Hubble Engineering Repair Operation

Final Report

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Rev. ZG
December 6, 2004

Acknowledgements

Team HERO would like to thank the following people for their help and support throughout the design project.

Paul Fulford – MDR Course Coordinator

Tim Reedman

Ross Gillett

Tim Fielding

Perry Newhook

Professor Chris Damaren – U of T Course Coordinator

Luke Stras

Dr. Chad English - Neptec

Executive Summary

The Hubble Rescue Mission [2] planned by NASA has a primary objective to safely and reliably de-orbit the Hubble Space Telescope (HST) and a secondary objective to extend the useful scientific life of the HST. The mission will be performed by a Hubble Rescue Vehicle (HRV) which is to consist of a De-Orbit module (DM) which de-orbits the HST, and an Ejection Module (EM) which supports the Grapple Arm (GA) and Dexterous Arm (GA) and de-orbits them after the servicing phase is complete.

The following high-level requirements of a robotic servicing mission have been put forth from NASA Head Quarters:

1. Provide the capability to safely and reliably de-orbit HST at the end of its useful scientific life
2. Provide the capability to robotically extend the scientific life of HST for a minimum of 5 (TBR) years
3. Provide robotic installation of the WFC3 and COS instruments
4. Provide single-fault tolerance for the de-orbit mission
5. Ensure that Level I performance is not degraded by robotic servicing

As stated in MDR's request for proposal (RFP) [1], requirements 2, 3, 4, and 5 form the mission objectives for the Dexterous Robot (DR) system. Additionally, the DR will operate cooperatively with the Grapple Arm (GA), which provides a platform from which the DR will perform the servicing tasks.

The design described within this document has the necessary operations policies, systems architecture, control systems, electrical power supply, and mechanical design to achieve the above mission, and to satisfy all the necessary requirements.

The DR is able to perform all necessary work within worksites on the HST with an arm span of 4.8 m (2.4 m per arm) and 6 degrees of freedom in each arm. It will be moved from work site to work site on board the end effector of the GA. A general purpose manipulator arm is used to handle cables, doors and other fixures on the HST. A tool arm uses interchangeable specialized tools for tasks such as unscrewing, driving latches, and mating connectors.

The DR will achieve better than required performance through the use of autonomous abilities such as work site registration and active force control. The DR will compensate for perturbations during motions which are due to the flexibility of the combined DR/GA structure.

For reliability, the DR has a fully manual backup mode, and has been designed to a maximum level of redundancy with appropriate factors of safety. HST level 1 performance is preserved by the hazard mitigation strategy of stopping the GA and DR as soon as fault conditions are detected, and having ground controllers assess such situations for safety.

Finally, the DR meets all the requirements given by the customer and is the best solution to the given problem. In short, the DR Rocks!

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2 Abbreviations

Abbreviation	Definition
AFC	Active Force Control
C&DH	Command and Data Handling
CU	Control Unit
DR	Dexterous Robot
DM	De-Orbit Module
DOF	Degrees Of Freedom
EE	End Effector
EL	Elbow
EM	Ejection Module
EMI	Electro Magnetic Interference
EPS	Electrical Power System
EU	Electrical Unit
FMEA	Failure Mode Effects Analysis
FRGF	Flight Releasable Grapple Fixture
FTSU	Force Torque Sensing Unit
GA	Grapple Arm
GC	Ground Control
HRM	Hubble Rescue Mission
HRV	Hubble Rescue Vehicle
HST	Hubble Space Telescope
ICD	Interface Control Document
IR	Infra Red
IRED	Infra Red Emitting Diodes
LCS	Laser Camera System
MEU	Motor Electrical Unit
MH	Manipulator Hand
PWM	Pulse Width Modulation
RFP	Request For Proposal
RSS	Robotic Servicing System
RSU	Rate Sensing Unit
SP	Shoulder Pitch
SR	Shoulder Roll
TBD	To Be Determined
TBR	To Be Reviewed
TCS	Thermal Control System
WFC3	Wide Field Camera 3
WF/PC2	Wide Field / Planetary Camera 2
WP	Wrist Pitch
WR	Wrist Roll
WRT	With Respect To
WY	Wrist Yaw

3 Mission Overview

3.1 Mission Scope

The scope of the DR mission is limited to the robotic servicing portions of the Hubble Rescue Mission (HRM) as presented by the contractor, MD Robotics, in the Request For Proposal (RFP) [1]. It will consist of the robotic mechanisms and support systems required to perform the power augmentation, wide field camera change out, and gyroscope installation operations during the servicing phase of the mission.

The DR shall operate in concert with another robot, the Grapple Arm, which will serve as a mobile platform from which the DR will operate. Power and communications will be provided to the DR from the systems in place on board the EM component of the HRV, and the DR will be stowed on the EM when not in use.

3.2 Mission Objectives

3.2.1 Power Augmentation

The DR is responsible for connecting the power conduits to the +V2 and –V2 diode boxes. This conduit connects the HST solar panels to the new batteries on board the de-orbit module.

3.2.2 Replace aging Rate Sensing Units (RSUs)

The DR is responsible for installing new Rate Sensing Units (RSUs) to allow the HST to maintain pointing control when one of the remaining three RSUs fails. This will be accomplished by installing the Wide Field Camera 3 (WFC3) on which the new RSUs are mounted.

3.2.3 Extend Scientific Life

The repair of HST power and pointing systems will extend the scientifically useful life of the HST for a number of years. Additionally, the WFC3 will expand the capabilities of the HST, further increasing the scientific value and potential of the Hubble Mission.

3.2.4 Do No Harm to Hubble

During all parts of the mission, Level 1 performance of the HST must not be degraded. The DR will operate so as to do no harm to the HST.

3.3 Stakeholders / Users

The main user of the DR system is the NASA HST mission team. This team requires a reliable and effective robotic servicing system to fulfill their mission objectives. The operators of the DR will be specially trained NASA mission personnel responsible for directing the DR in the servicing operations.

Indirect stakeholders in the DR are the members of the scientific community who will benefit from the extended life and enhanced scientific capabilities of the HST. Also, the space robotics industry stands to benefit from the technologies developed for this mission, and from the experience gained in performing orbital robotic servicing.

3.4 Mission Profile

3.4.1 Mission Phases

The role of the DR in context of the Hubble Rescue Mission's phases is described in Table 3.1. The scope of DR primary operations is within the servicing phase of the mission. The DR acts as a payload on board the EM during the remainder of the mission.

Phase	Duration	DR Operations	Purpose
Launch	2 hours	Off	*Payload*
Pursuit	2-12 days	Off	*Payload*
Proximity Operations	1-2 days	Off	*Payload*
Capture	2 hours	Off	*Payload*
Servicing	30 days	Activation Service Ops	*Augment EPS* *Install RSUs* *Install WFC3*
EM Jettison & Disposal	4 days	Shutdown	*End of Life (Payload)*
Science Operations	5 years +	*None*	
De-orbit	4 days	None	

Table 3.1 – Mission Phases and Systems

3.4.2 Mission Systems

The major systems involved in the execution of the Hubble Rescue mission, other than the Dexterous Robot, are as follows:

3.4.2.1 Hubble Rescue Vehicle (HRV)

This spacecraft is made of two components, the De-Orbit module (DM) and Ejection Module (EM). The HRV will transfer from its initial low earth orbit to perform a rendezvous with the HST, allowing the robotic systems to perform the capture and servicing operations.

3.4.2.2 De-Orbit Module

This spacecraft will carry out the primary objective of the HRM, namely the controlled de-orbit of the HST. However, prior to this terminal phase of the mission, it will serve as the structural attachment between the HST and the EM (and thus the RSS). It also contains the auxiliary batteries that will extend the functional life of the HST.

3.4.2.3 Ejection Module

This spacecraft contains the GA and DR robots, as well as the electrical power systems (EPS), communications hardware, and new HST components. During launch, pursuit, proximity, capture, and de-orbit the DR is stowed as a payload on the side of this module. At the end of the servicing mission this module separates from the HST-DM unit, and is de-orbited along with the on board GA and DR.

3.4.2.4 Grapple Arm

This robot performs the mission critical capture operation, and brings the HRV into alignment for docking with the HST. Additionally, it serves as the primary platform from which the DR operates during the servicing phase. The GA positions the DR at the necessary work sites, provides a structural support, and is a conduit for the DR's electronics and data cables connecting it to the Ejection Module.

4 Dexterous Robot Overview

The purpose of the Dexterous Robot (DR) is to perform three main tasks. It must perform power augmentation operation, replace the old WF/PC2 camera with the new WFC3 camera and replace the RSU's in the process. We look at the DR from a systems point of view in this section. The basic functional and performance requirements were provided in the RFP [1] and these were broken down to give detailed functional and performance requirements.

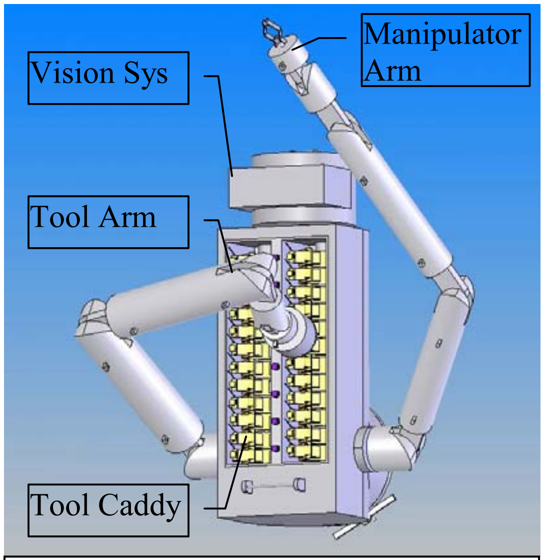


Figure 4.1 - DR Overview

The DR has the following major systems:

1) Vision
   The vision system is comprised of the LCS (3D laser scanner), four mini cameras and IR sensors enabling the operators and the DR to be aware of the environment.
2) Two manipulator arms
   Each arm has a span of 2.4 m with six degrees of freedom and a tip resolution of 0.025mm (translation) and 0.011 degrees (rotation), giving the DR the ability reach and access all parts of the workspace.
3) Communication
   The communication system enables the DR to constantly update ground control about the workspace situation and receive new commands and scripts.
4) Survival
   The survival system enables the DR to keep alive and maintain its system. This includes the thermal control and the fault monitoring and control system.
5) Control
   The control system controls the process and actions carried out by the DR to complete the mission.
6) Tools
   The tools enable the DR to interface with the HST in order to perform its mission.

These seven systems enable the DR to satisfy all given customer requirements.

In the following sections we present the customer requirements, system architecture, system block diagram showing the top level components of our system, physical architecture and the summarized power and mass budgets.

4.1 Top Level Requirements

The top level requirements were derived from the RFP and these were broken down further to get the system requirements on which our DR design was derived. The sections that follow present these requirements and the top level system architecture designed to satisfy these requirements followed by a system block diagram that outlines these systems.

4.1.1 Functional Requirements

The DR shall be able to perform the following operations:

DR.F1 Power augmentation
    DR.F1.1 Tap SA3 power at P6A and P8A on both HST diode boxes.
    DR.F1.2 Rout SA3 power to DM via new harness
    DR.F1.3 Harness Attachments (12 locations) to hold down conduit
DR.2 WFC3 installation
    DR.F2.1 Attach new ground strap stowage fixture
    DR.F2.2 WF/PC2 Interface plate
    DR.F2.3 WF/PC 2 blind mate release
    DR.F2.4 Release and secure Ground strap
    DR.F2.5 Release A latch
    DR.F2.6 Remove and stow WF/PC2
    DR.F2.7 Retrieve and position WFC3
    DR.F2.8 Install WFC3 into telescope
    DR.F2.9 Replace latch A
    DR.F2.10 Replace ground strap
    DR.F2.11 Replace blind mate
    DR.F2.12 Final stow WF/PC2
DR.F3 Gyro data and power augmentation
    DR.F3.1 486 - 1553 data bus installation (J9 connector on HST bay 1)
    DR.F3.2 Power for Gyros supplied by harness from DM to WFC3
DR.F4 All the above functions have to be performed while being supported by the GA and therefore have to satisfy interface requirements from the GA team

4.1.2 Performance Requirements

The DR shall:

DR.P1 Capable of maneuvering arm/s anywhere in the workspace
- accuracy of ± 1° relative to commanded position
- resolution better than 0.1” and 0.1°

DR.P2 Torque drive of 50 ft-lb and
    DR.5.1 track the progression of tool by counting turns and monitoring torque
DR.P3 Be capable of stopping a 1000lb mass from maximum commanded tip velocity within 2” and 2°
DR.P4 DR shall be capable of limiting forced normal to constrained translational paths to no more than 10lbs and delivering up to 25lbs along those paths
    DR.P4.1 Shall have a six axis force and torque sensor near end effector to sense the torque and force at end effector with accuracy of less than ±2lbs and ±2ft-lb as measured at end effector
DR.P5 Consume less than 300W that has been assumed to be the current power budget.
DR.P6 Weigh less that 500Kg which we assumed is the mass budget allowed.

The detailed requirement tree derived from these requirements can be found in Appendix 2

4.2 System Architecture

4.2.1 Functional Decomposition

The following are the basic functions that the system needs in order to complete the mission.

Vision system

The DR will be equipped with two camera systems that include one laser camera system (LCS) and four mini cameras.

The LCS by Neptec provides xyz workspace data. The LCS has a range of 30m and an accuracy of ±2mm within a 5m range. See Table 6.1 for details. Two mini cameras will be located at each end effector. These will be used to provide video feedback to GC.

System Interfaces

To perform the required operations the DR has to interface with the surrounding systems including HRV, HST, GA, and GC. The most important interface for the mission is the interface between the GA and DR. This interface is basically a modification of the FRGF. The details of the ICD can be found in Appendix 10.

Communication System

The communication system has three parts:

1) Communication within DR
   The various parts of the DR have to be able to communicate with each other and the CPU. Most of the components of the DR are connected to the central computer via a MIL –1553 data bus. The LCS requires a high data transfer rate and high processing power. Thus it will have a separate CPU and will be connected to the vision system CPU using a separate MIL – 1553 data bus. The vision system CPU and the main CPU will be in communication with each other in the avionics box.
2) Communication with GA
   The DR CPU and the GA CPU will be in communication to notify each other of new coordinates and emergency halt commands.
3) Communication with GC
   The communication with GC will be achieved using the EM communication module. This is necessary to keep GC aware of the current situation and to receive and new scripts and commands from GC.

Survival system

The purpose of our survival system is to ensure that the DR is not damaged or rendered inoperable during launch or operational phase. This system includes thermal control and fault monitoring.

The heating system uses thermocouples located at thermally sensitive locations to determine whether active heating is necessary. Unless active heating is necessary the temperature is maintained using passive heating and cooling. The heating element will be Kapton heaters (see Appendix 8.5) and to prevent over cooling MLI insulation blankets will be used. Since the DR has to be single fault tolerant most vulnerable systems are duplicated and the survival system will detect failure to any of these components and switch to the backup. Such systems include the electrical cabling, data bus, lights, mini cams, motor winding and others.

Other sensing capabilities

We decided to provide the DR with two other sensing capabilities that are

1) IR sensors: The IR sensors are located in specific locations on the DR that are not in the field of view of the LCS or the mini cams. The purpose is to detect if those parts are too close to the Hubble.
2) We will also use touch/pressure sensor in the tool caddy to register whether the tools are in position. When the tool arm acquires the tool it applies a pressure that stimulates the release of the right tool.

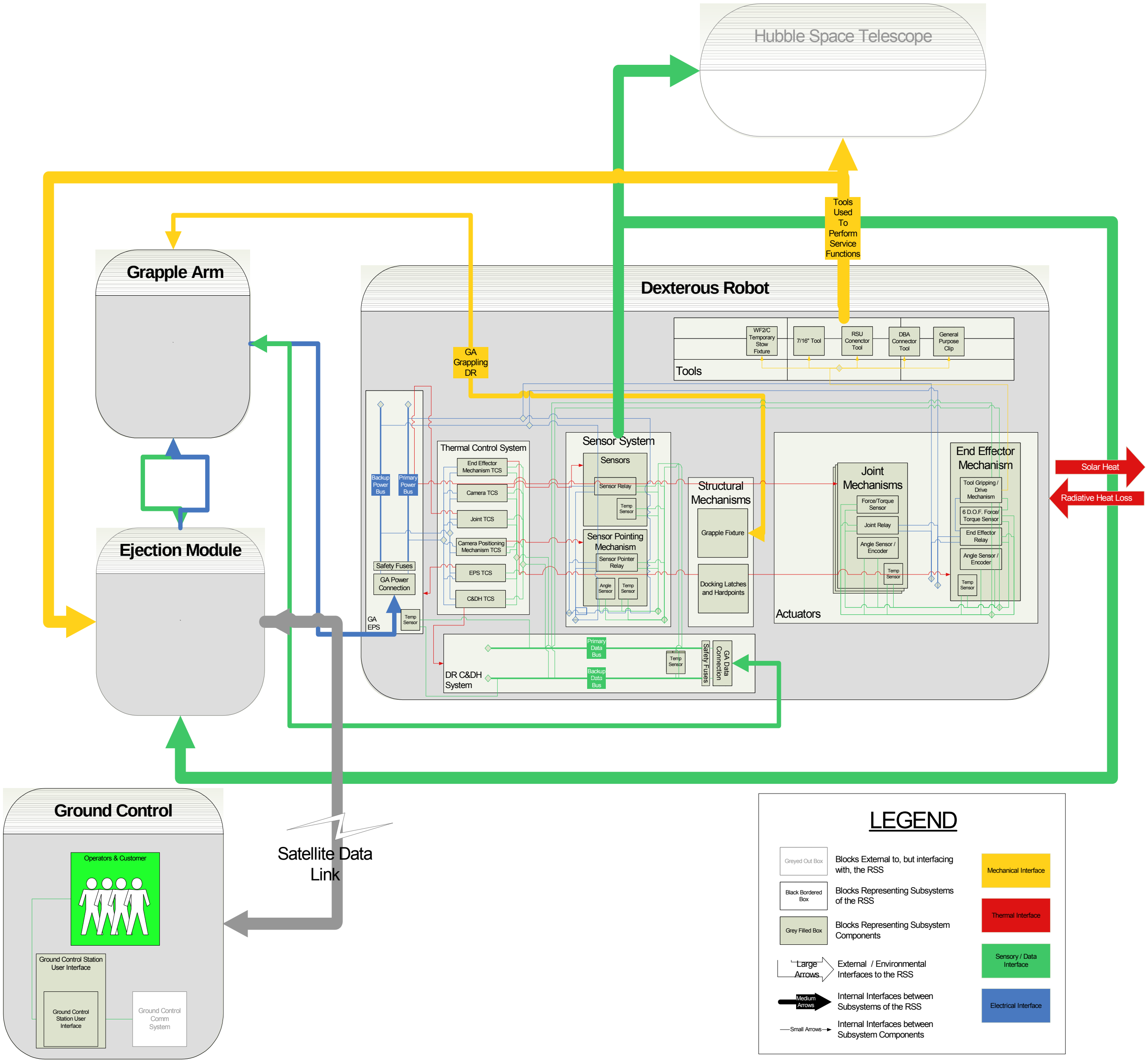
Control system

The control system of the DR is comprised of the various sensors that report telemetry to the C&DH where software processes this data and produces output signals to actuators/devices that creates the necessary response. The major part of the control software is the control of the motors. According to the calculated response time and due to the fact that we decided that absolutely no overshoot is acceptable we decided use a second order control transfer function with simple P control with data from the resolvers forming the feed back loop.

Central C&DH

The central CPU will be located in the avionics box in the EM. Since the vision data processing requires large processing powers we decided to have a separate CPU to perform model matching and analyzing the data from the LCS and the four Mini Cameras.

4.2.2 System Block Diagram



4.3 DR Characteristics

4.3.1 Physical Architecture

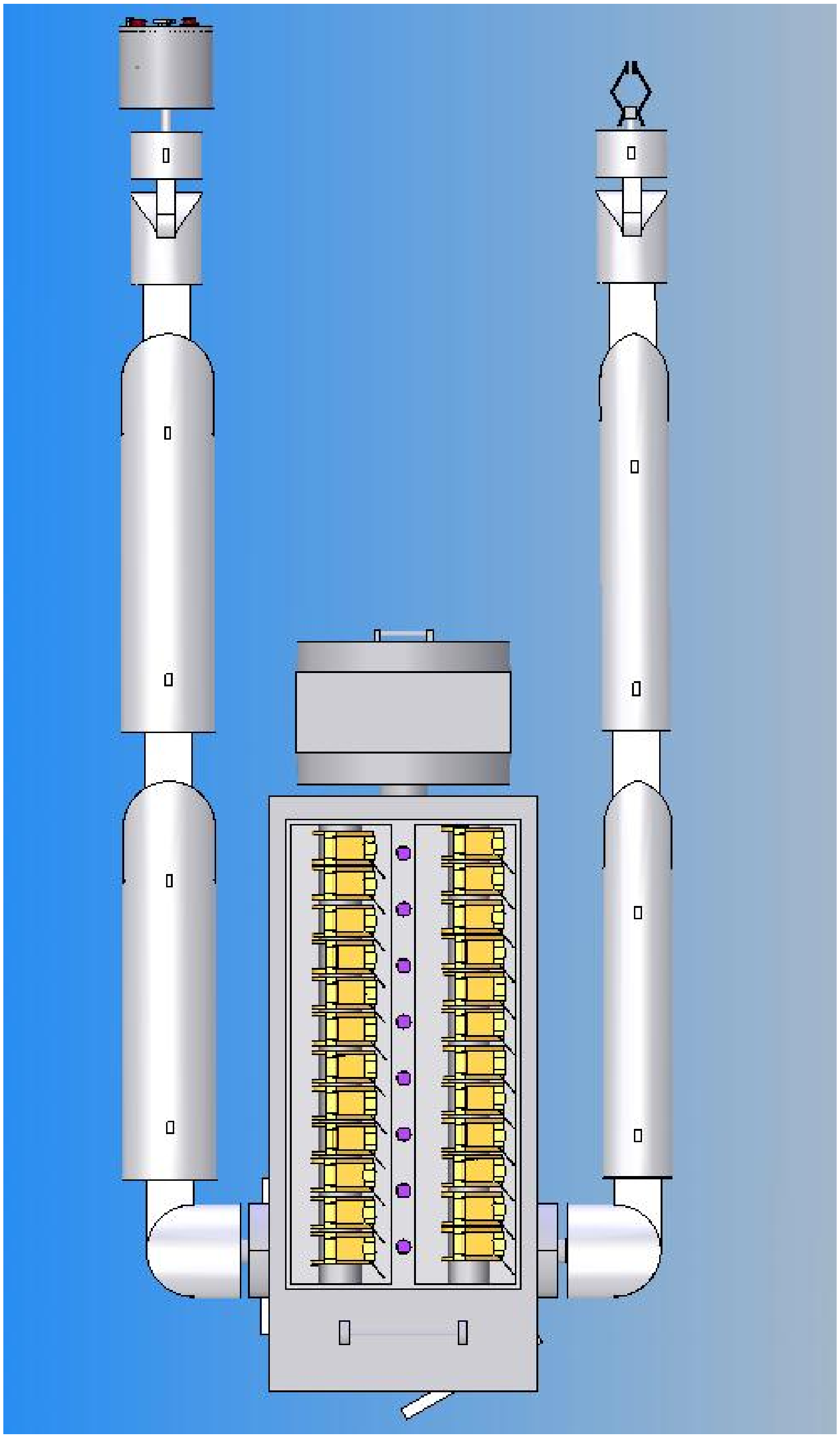


Figure 4.2 Front view of DR

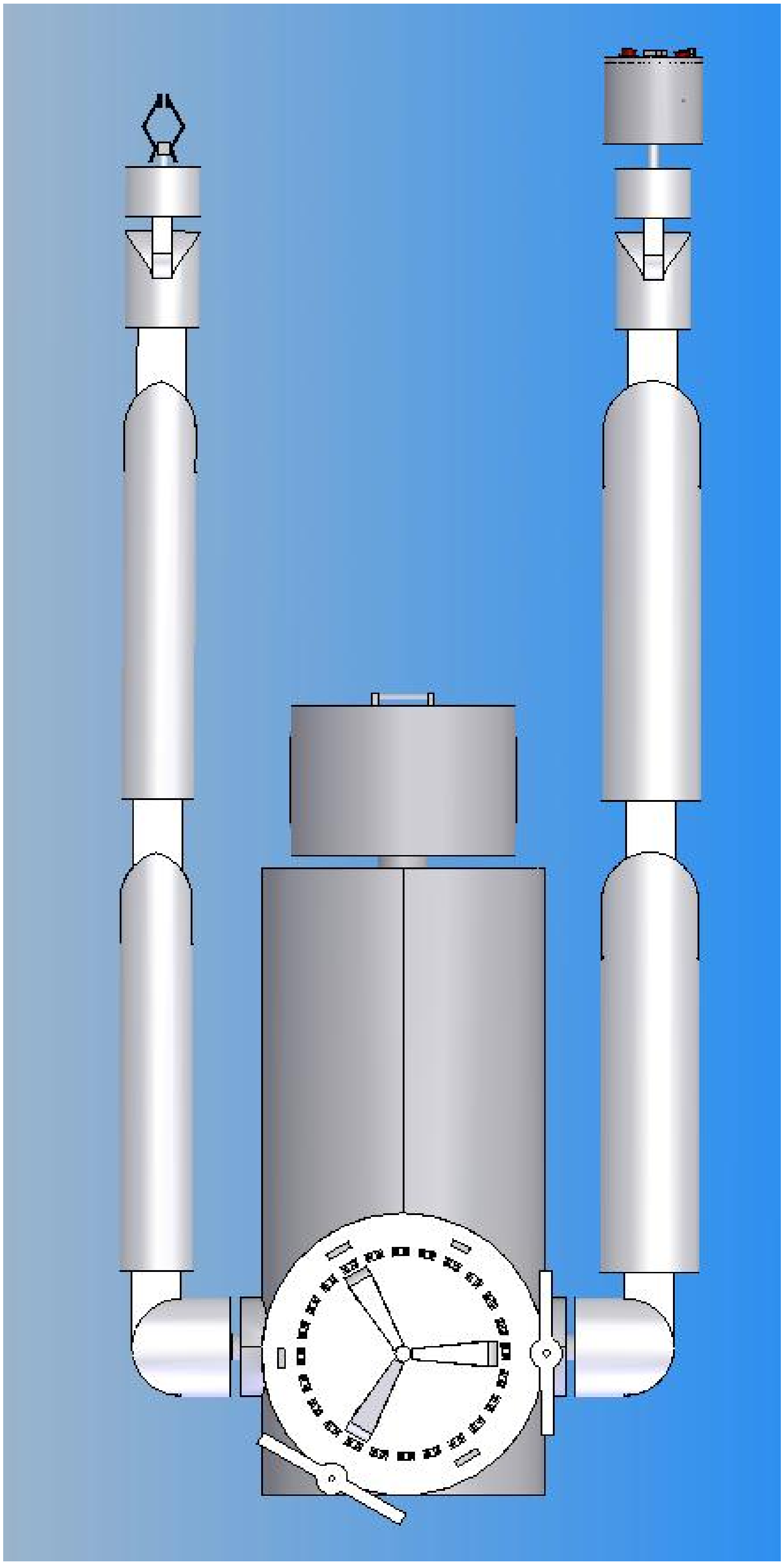


Figure 4.3 Rear View of the DR

This section summarizes the physical architecture of the DR. and briefly describes the five major physical structures, the main body, tool arm, gripper arm, head (housing the LCS) and grapple fixture. **Figure 4.2** shows the front view of the DR. Here the six joints of both arms are visible along with the tool caddy and the LCS mounted on the head. We can also see the various stowage fixtures. **Figure 4.3** shows the rear view of the grapple fixture with the two target points, two power connectors and two data connectors.

The body houses the tool caddy the two shoulder roll motor and the power and data busses going to the arms and the LCS. The length of the body is 140 cm and has a diameter of ~ 58cm.

The arms have a total span of ~2.4m. They have 3 main segments shoulder, arm booms, wrist and end effectors. The arm booms each have a length of 85 cm. The shoulder and wrist roll motors have a range ±180°, the shoulder pitch, the elbow and the wrist pitch and yaw motors each have a range of ±135° giving the DR the range of motion necessary to complete the mission.

The LCS, mounted on the head, is controlled by two motors, enabling it to pan ± 90° and tilt ±45°. This ability gives the LCS a large field of view, which is highly beneficial for the mission.

The grapple fixture is a modified version of the FRGF. The chief modifications being two targeting points, two data bus connectors, two power bus connectors and 24 gripping teeth. The purpose of the gripping teeth is to prevent rotational motion while mated to the GA.

The DR has two specialized end effectors; one for handling tools and payloads and the second is a general purpose gripper to hold loose objects stabilize payload and assist vision system with its two cameras.

4.3.2 Power Budget

The total average power needed for the DR servicing mission is 145 W.

4.3.3 Mass Budget

The total mass of the DR is 340 kg.

4.4 System Conclusion

The HRV mission presents several engineering challenges. On-orbit robotic servicing will require significant improvements in control, communications, imaging systems and machine vision. While NASA has requested that the HRV not be an R&D project, it is apparent that some new technologies like the LCS are needed in order to carry out the mission. We had to consider technologies that have not been verified for use in space. This is especially important given that NASA needs to have the HRV in a timely fashion and in a form that it is reliable enough to service the one of the most valuable space assets in orbit.

5 Operations

This section describes the operations and procedures followed by the DR and its controllers in carrying out the mission tasks identified in section 3 (above). Hazard mitigation and system autonomy are also discussed.

5.1 Operational Overview

5.1.1 Operational Policies

In order to maximize the likelihood of the success of the primary and secondary mission objectives, the DR is required to have limited single fault tolerance. We designed the functional flow of the mission to accommodate appropriate fail-safes, redundancies, and contingency scenarios.

It is paramount that the DR does not degrade the Level 1 performance of Hubble during servicing operations. Appropriate control precision, reliability, safe-modes and abort scenarios were therefore designed. Additionally, we designed the DR to prevent orbital debris production, so as not to create a hazardous debris cloud around the HST.

5.1.2 Operational Constraints

The DR operates on power supplied from the EM's on board Electrical Power System (EPS). The DR shall interface with communications systems found on the EM for data communication with Ground Control. It is assumed that the EM communication system will be sufficiently reliable and have sufficient bandwidth to allow operation of the DR during all mission phases.

The configuration of the HST is fixed, and therefore all operations are designed to be performed successfully within the envelopes defined by the HST work sites.

Due to the performance demands of the mission, and the lag in radio communications to LEO, the DR is capable of performing simple scripted tasks such as tip motions or tool actuation in an autonomous fashion. These scripted tasks will always be initiated by ground control.

The mission must be completed prior to the expected failure date of one of the remaining three RSUs so as to prevent the HST from entering an uncontrolled and unrecoverable spin. This puts the servicing phase of the mission no later than mid 2009.

5.1.3 Operational Environment

When launching the HRV, thrusts from the rockets will pulsate and cause the rocket and HRV to vibrate. The HRV must withstand these vibrations and reach HST unharmed.

HST is a Low Earth Orbiting (LEO) satellite; its orbit is in the thermosphere (HST is at an altitude of approx. 600km) [3]. The pressure at this altitude is very low (almost zero) and temperature gradients during each HST orbit can vary over 100°F as the Earth blocks out the sun's light. Temperatures range at this altitude from 300°F to –300°F. The DR has been designed to regulate its temperature to ranges that are survivable by its subsystems (see appendix 8.5).

The mission needs to be carried out without blocking Hubble's solar arrays, communication receivers/transmitters or the Tracking and Data Relay Satellite System (TDRSS).

At Hubble's altitude, the overhead atmosphere (the exosphere) does not provide any significant radiation protection. We have therefore designed the systems of the HRV to withstand this harsh radiation environment.

5.2 Functional Flow

The operational process is described in detail in Appendix 1. The HRV is to be first packaged securely on the rocket launcher so that it survives the launch loads and vibrations. After launch, the rocket separates and the HRV will pursue the HST using its guidance/navigation systems. The DR remains in a keep-alive mode until the GA has captured the HST and docked the HRV on its berthing pins.

The GA will then mate to the DR, allowing it to power up and detach from the EM. The GA will then position the DR as required to perform servicing operations that include power augmentation, installation of the new Wide Field Camera 3 and RSU connections. During servicing, the DR will have to ensure that all loose parts are stowed properly and not set adrift in open space. At the completion of servicing task, all tools and components removed from the HST will be properly stowed on the EM.

After servicing is complete, the GA will stow the DR back onto the EM, placing it within its stow fixtures and releasing the grapple fixture once the DR has powered down. Once GA has stowed itself, the EM will jettison from the HST/DM and will be de-orbited. The De-Orbit module will remain attached to the Hubble for future controlled de-orbit of the HST/DM complex.

5.2.1 Operations Timeline

This section describes the basic timeline of DR operations. We decomposed the Functional Flow Block Diagrams from the mission objectives, and detailed them sufficiently to allow the identification of all significant functional requirements imposed on the DR by its mission.

Listed below are the top levels of functional flow during the major parts of the DR mission. A more detailed functional flow of the DR system is presented in the detailed Functional Flow in Appendix 1.

1. Launch
    1.1. Pre-launch system check
    1.2. DR enter keep-alive mode

5. Servicing
    5.1. Deploy DR
        5.1.1. Activate GA
        5.1.2. Move to DR stow site
        5.1.4. Grapple DR
        5.1.5. DR Wake up & Checkout
        5.1.6. DR standby

        - 5.1.6.1 DR switches from Normal to Sleep Mode
        - 5.1.6.2 Await command signal from ground control
    - 5.2. Power Augmentation
        - 5.2.1. Conduit Deploy
        - 5.2.2. Diode Box -V2
        - 5.2.3. Diode Box +V2
    - 5.3. WFC3 Operations
        - 5.3.1. Remove Ground Strap
        - 5.3.2. Remove and Temporarily Stow WF/PC2
        - 5.3.3. WFC3 installation
        - 5.3.4. Permanently Stow WF/PC2
        - 5.3.5. WFC3 Support Hardware

- 6. EM Jettison and De-Orbit
    - 6.1. DR shutdown
        - 6.1.1. Activate GA
        - 6.1.2. Activate DR
        - 6.1.3. Move GA/DR to DR stow site on EM
        - 6.1.5. Configure DR for stowage
        - 6.1.6. GA Positions DR in large capture envelope of main stow fixture
        - 6.1.7. GC engages main stow fixture, aligning DR with other fixtures.
        - 6.1.8. GA tilts DR to position it within capture envelope of remaining stow fixtures
        - 6.1.9. GC engages remaining stow fixtures as required
        - 6.1.10. DR shuts off power completely
        - 6.1.11. GA releases DR
        - 6.1.12. GA standby
    - 6.2. GA shutdown
    - 6.3 EM Jettisons and Carries out De-Orbit maneuver

Upon the completion of primary and secondary mission objectives the Ejection Module carrying the RSS will be disposed via separation and subsequent de-orbit. The HST will continue to produce useful scientific data for an expected period of 5+ years after the end of the DR mission.

5.3 DR/GA Interaction

This section describes the coordination of the DR and GA operations and explains how the two robots interact. The DR and GA will interact in four major ways during the mission:

5.3.1 DR grappling and activation

The DR will be in keep-alive mode until the capture phase of the mission is complete. Once the GA is ready, it will move to the DR stow site on the side of the EM, and position itself to grapple the exposed DR Grapple Fixture (GF). To simplify the operation, we designed the GF on the DR to emulate a standard FRGF like those on the HST and positioned it so that it is exposed and easy to reach.

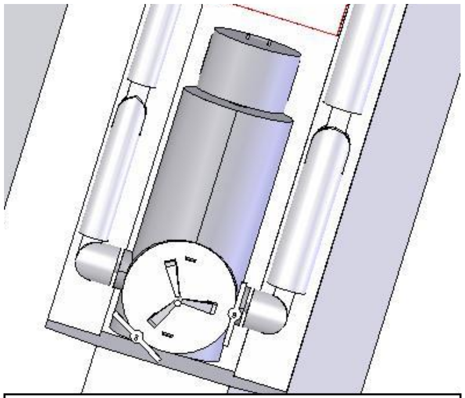


Figure 5.1 - DR is stowed face down with GF exposed for easy access.

The DR will be a passive target during this phase, as its primary systems will be un-powered until the GA has made the power and data connection. DR ground control will await confirmation of successful structural and connector mating, and will then activate the main power and data systems of the DR. This will supply power to the robotic part of the DR via busses running along the GA. Once the DR has been activated and tested, the stow fixtures will release, and the GA will move the DR clear of the EM for final testing.

5.3.2 DR repositioning during servicing

During servicing operations the DR will need to be moved from work site to work site by the GA. The DR has an arm span of about 4.8 m (2.4 meter arms), so it is capable of reaching all necessary parts of a given work site while executing servicing tasks. However, the servicing operations take place at various sites, necessitating DR mobility.

Combined motion will be accomplished by the series of operations described in the second ‘Combined GA/DR Move’ Command and Control Flow Down diagram in Appendix 2. In essence, the DR will assume a static configuration, the GA will move to the new location, and then the DR will resume operations

5.3.3 DR / GA emergency stop

In the event of a contingency situation arising, we have identified a full stop of activities as being the best hazard mitigation strategy (See 5.5 – Safety below) . For this reason, the DA and GR will coordinate emergency stops so that both systems halt completely in the event of some fault being detected.

5.3.4 DR stow and un-grappling

The DR needs to be re-stowed prior to jettisoning of the EM. We have designed the stowing operation to account for the accuracy capabilities of the GA (See ICD in appendix 10) by making the first stow fixture have a large capture envelope. The DR will be configured for stowing, and the GA will then need to place the matching fixture on the DR into the initial stow fixture.

DR GC will then engage this initial fixture to force the DR into alignment with the remaining connection points. The GA will then pivot the DR around the closed stow fixture until the remaining ones are aligned and can be engaged. Once the DR is secure, it will shut down all systems in anticipation of power being severed one the GA un-grapples and moves into its own stow position.

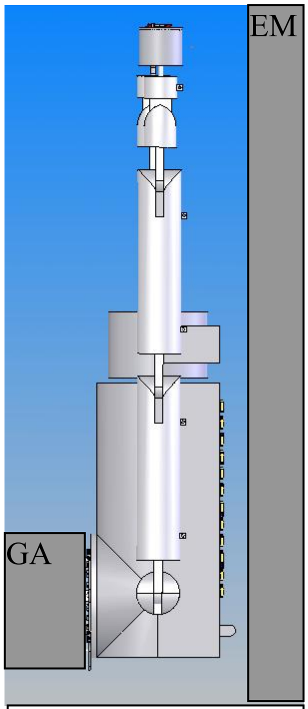


Figure 5-1 DR ready configuration for placement in stow fixtures on EM

5.4 Operating Modes

5.4.1.1 Keep-alive Mode

In this mode the DR be essentially inactive. All CPUs, motors and vision systems will be shut down to conserve power, aside from the minimum necessary to run the Thermal Control System

(TCS). This mode will be used during the launch, pursuit, proximity, and capture phases while the DR is a payload on the EM.

5.4.1.2 Standby Mode

In this mode the DR will monitor its temperature and power heaters as needed to maintain its minimum temperature. All processors are on, and the DR is essentially just awaiting the next command from ground control.

5.4.1.3 Normal mode

In this mode the DR will perform its servicing operations making use of its full set of on board autonomous capabilities. Arm motions and forces will be autonomously corrected as outlined in section 5.5 below.

5.4.1.4 Manual mode

In this mode operators will be able to control some, or all, subsystems on the DR directly in the event of primary control systems failure or if some contingency operation calls for it.

5.4.1.5 Safe Mode

In the event of a fault being detected on the DR, it shall cease all motion to ensure no harm comes to the HST, send a notification signal to the GA and to GC. The DR will then send telemetry to GC and await instructions. In the event of a stop during some major operation, ground controllers will need to decide an appropriate course of action sufficiently quickly to prevent damage such as having the system freeze to death.

5.5 Safety

5.5.1 Operational Scenarios

Many different operating scenarios may take place during the mission. The nominal operations scenario is outlined in detail in 1.Appendix 2. In case of failure, the general operating scenario is defined as follows:

1. DR automatically enters safe mode
2. DR resets systems
3. DR performs safety and operational self tests
4. If problem successfully eliminated then return to nominal operations
5. If unsuccessful, DR awaits further instructions from GC
6. GC identifies solution
7. Solution is implemented
8. DR performs safety and operational self tests
9. Nominal operations resume

The operations procedures used to mitigate a set of specific failures characteristic of the potential operational disruptions are discussed in Appendix 1.2

Mechanical failure of the 7/16” tool – Appendix 1.2.1
Failure of the main power system – Appendix 1.2.2
Communications black out due to solar interruptions – Appendix 1.2.3

5.5.2 Failure Modes and Effects Analysis

In response to the mission requirement that the DR do no harm to the Hubble Space Telescope, we performed Failure Modes and Effects Analysis (FMEA) on the operations performed by the DR. The table shown in Appendix 4 illustrates this analysis as broken down into the following steps:

5.5.2.1 Hazard Identification

First, we identified the various categories of maneuvers performed by the DR. For each of these actions, a frequency index was assigned based on the scale given in Appendix 4.1. We then identified the key input and how damage will be caused to the HST. Following this, the failure modes and effects were listed. The severity of all potential DR failure effects was very high due to the importance of not harming the HST. See Appendix 4 for the severity index scale.

5.5.2.2 Hazard Mitigation

The second part of the FMEA involved outlining strategies for controlling each hazard. The potential causes of the failures were outlined, completing the identification and organization task.

We first considered ways to eliminate the hazards from the mission entirely. If this was not possible, design features were identified that could remove or control the hazard. Finally, in some instances neither of these options was possible, so we considered methods of reducing the damage caused by the hazard. See Appendix 4.1 for the control index.
We then assigned a risk index to each series of control actions based on the three categories discussed above. This allowed for easy identification of the most serious risks to the mission.

All but one of these high-risk failures fall into the group of communication failures during operations of the DR. These pose the highest risk to the mission because short of having an entirely redundant communication system, the possibility of failure cannot be eliminated. Furthermore, the frequency of these actions is very high, increasing the likelihood of a failure during their operations. Therefore our overall hazard control strategy is to have the DR cease all motion and await further instructions from ground control.

The last high risk factor falls into the group of command corruption, and we have decided to mitigate this by having all mission commands and signals use a double-positive system. This way no single failed channel, or misinterpreted signal, can lead to uncommanded control input to the DR.

5.6 Ground Control Architecture

This section defines the ground control architecture that will govern how operators carry out the Dexterous Robot’s repair mission. DR ground control is responsible for all mission tasks, while the DR subsystems will govern low-level operations that maintain basic functions like thermal control.

We have reducing the DR to a minimum level of autonomy, as this preserves the same overall mission capabilities while eliminating failure points, including a number of catastrophic scenarios (i.e.- a runaway robot completing servicing tasks incorrectly and causing damage to the HST).

The onboard systems of the DR will not be truly autonomous, though they will provide real time corrections and adjustments while executing the commands issued by ground controllers. Details of the DR's autonomy are discussed in section 5.4 (below). The following is a discussion of how the human controllers of the DR command and control the robotic system during its various activities.

Below is a table identifying what the mission tasks initiated by GC, and those performed by on board systems without an operator in the loop.

Mission Tasks	Ground Control (Manual)	DR (Automated)
Operational Command Tasks		
Grapple DR	x	
Deploy DR	x	
DR Self Test	x	
Performance Asessment	x	
Manual operations (I.e. drive a motor)	x	
Service Operation	x	
Grapple tool	x	
Move DR EE to target location	x	
Have GA move DR to a new Work Site	x	
Stow DR	x	
GC Communication Tasks		
Establish Communications	x	
Video/LCS downlink	x	
Telemetry Transmission		x
Update DR software	x	
Low-level continuous tasks		
DR Keepalive		x
Initialize/Refresh Workspace Registration		x
Collision/Fault Detection		x
Emergency Stop Signal		
Mechanical Sensors (resolvers)		x
Thermal Control		x

Table 1 – Mission Task Initiators

Below is a diagram outlining the subsystems that play a role in the command flow within the DR system. It also places them in context with external systems that have command interactions with the DR during its mission.

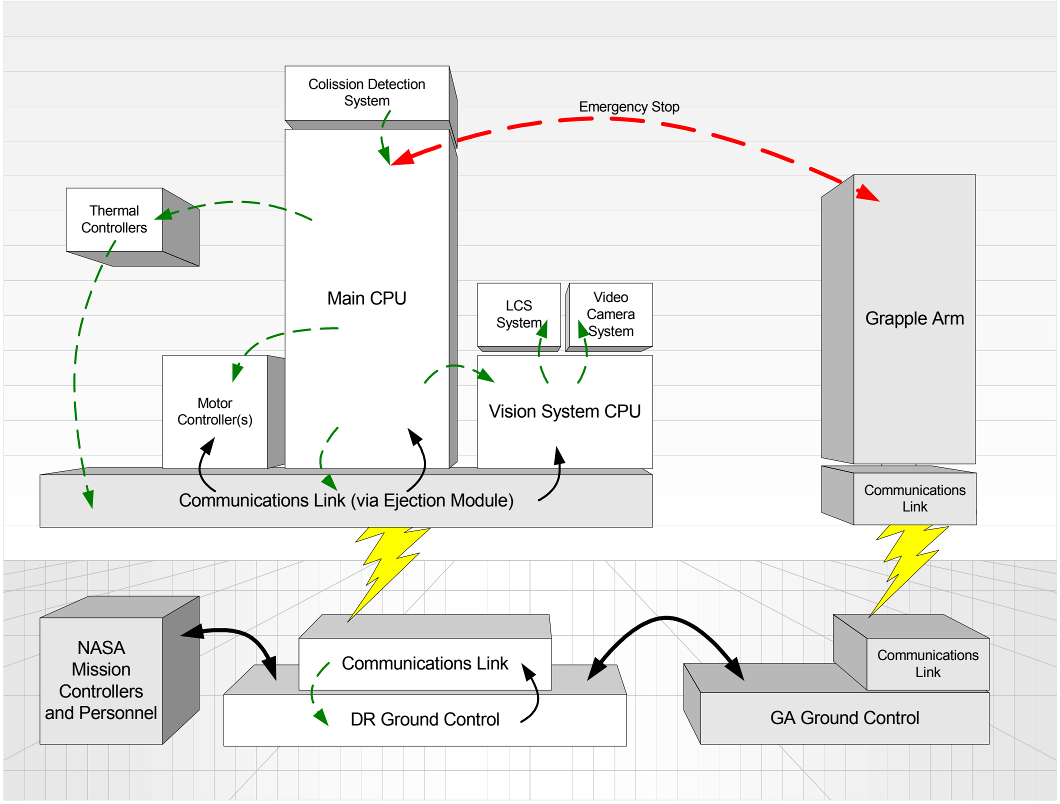


Figure 5-2 - Ground Control Architecture (Solid arrows indicate commands from GC. Dashed Arrows indicate autonomously command signals initiated by the DR. Thick solid arrows indicate external interfaces with GC. Grey blocks are systems and actors external to the DR.)

5.6.1 Initiation of Mission Tasks (Internal Interfaces)

DR operations such as servicing tasks will be orchestrated by ground control sending combinations of available command types to the DR. This methodology can be likened to giving the DR a script to follow, and telling it when to carry out a particular line. By tailoring the scripts, which the DR executes on orbit, ground controllers maintain control of the robot at all times but still benefit from its real-time control capabilities that it uses while executing a particular given script. Typical commands are an EE move, where ground controllers could specify a destination point, or a constrained path along which the EE should travel.

For example, to remove a bolt, ground controllers would first initiate a combined move of the GA/DR. Then they would have the DR acquire the correct tool. Next they would command the DR to position the tool on the bolt, an operation that would make use of the DR’s greatest on board autonomous capabilities. While moving the tool from its original location to its final position on top of the targeted bolt the DR will use its vision system to provide registration (calibration of the tool position relative to the target location) and correct for any perturbations in its position. Next ground controllers would command the DR to drive its wrist motor to turn the bolt the desired number of times.

Ground control would upload a part of the above instruction set to the Main CPU on the DR, which would then execute the instructions by coordinating subsystems on board the DR. In this manner, by stitching together the various commands that are used to trigger mission tasks on board the DR, ground controllers will ensure that the mission objectives will be met.

In the event of CPU failure, ground controllers have the capability to command joint motors and other subsystems directly in manual control mode. This mode provides extra reliability, but does not offer the same level of performance since the real-time autonomous functions performed by the CPU are unavailable.

5.6.2 External Interfaces

Ground control needs to interact with NASA mission controllers and operators while performing servicing tasks on the HST. In the likely event that operations need to be modified or updated due to unforeseen complications during the mission, DR GC will collaborate with HST specialists and operators to lay out the functional flow and objectives of any necessary operations.

Ground control also needs to interact with GA Ground control to coordinate the operations of the two robotic elements of the RSS. The following information will regularly be exchanged between DR and GA ground controllers during the operational life of the DR:

DR GC To GA GC:

- Readiness to grapple, prior to un-stowing.
- Readiness to be moved away from open stow fixtures.
- Desired position and orientation to which the GA should move the DR
- Envelope and mass of the DR and any payload prior being moved.
- Resolution of Emergency Stop condition
- Readiness to be placed in open stow fixtures.
- Readiness to un-grapple after stowing. (Ready to power off)

From GA GC:

- Successful grapple of DR.
- Successful mating of connectors on DR GF. (Ready to power on)
- Resolution of Emergency Stop condition
- Arrival at requested location.
- Successful un-grapple and de-mating of connectors on DR GF.

5.6.3 Personnel Needs

The GA and DR are both mainly autonomous systems; however, human interaction with the robotic manipulators is required at many points in during the mission. First, a team will be required to prepare the GA and DR for launch, performing manual safety and operational checkouts and finally stowing the robots on the HRV. This group should have a broad technical skill set for the installation. Also, these persons should have a thorough understanding of the procedures to be performed during the mission, in order to effectively test the robotic arms.

During the mission, from launch to the EM Jettison, a team will work from the ground to direct the phase transitions of the GA and DR, as well as to initiate robotic sequences. This team is also responsible for manually operating the arms in the case of failure. Members of this team need to be trained and practiced at using the communication equipment. They should also be flexible and creative, in case of deviations from the mission plan. All personnel associated with this mission should have a multidisciplinary engineering and problem solving background.

5.6.3.1 Personnel Profile and Activities

The execution of tasks during the HRV mission will be performed by robotic arm. However, a ground team is needed to monitor and support the actions of the GA and DR.

Specialized personnel will be needed to prepare the GA and DR for launch. These people will perform manual safety and operational checkouts and stow the DR on the HRV. This group should have a broad technical skill set for the installation. Also, these people should have a thorough understanding of the procedures to be performed during the mission, in order to effectively test the robotic arms.

During the mission, from launch to the EM Jettison, ground controllers will direct DR. This team is also responsible for manually operating the robot in the event that the primary control system fails. Members of this team need to be trained and practiced at using the communication equipment and in controlling and commanding the various DR subsystems. They should also be flexible and creative, in case of deviations from the mission plan. All technical personnel associated with this mission should have a multidisciplinary engineering and problem solving background.

The remainder of the team should be populated with mission specialists, payload experts and various management personnel. Together this team should be capable of effectively and efficiently coordinating DR operations with other teams in the HRM (like the GA), and dealing with all situations that arise during the HRV mission.

5.6.3.2 Organizational Structure

The DR mission control should consist of teams focused on individual mission components will make up the larger DR Ground Control team. A mission controller who facilitates interaction between the DR, GA, and EM will coordinate DR operations.

DR and GA ground control should be co-located to facilitate the effective communication and coordination that will be required during all phases of the DR mission.

5.6.4 Existing Support Environment

It may be necessary to undergo staff training for this system; we assume NASA has the resources and capital needed for this mission. Ground operations will require a suitable facility such as the Goddard Space Center, which has the necessary communications infrastructure for this mission.

5.7 Autonomy

This section describes in detail the nature and level of autonomy required of the DR, to give an idea of the overall level of autonomy of the mission. The reader should gain an understanding of what actions the DR is responsible for initiating in each of its operating modes. The tasks performed autonomously by the DR are either ongoing closed loop functions, or are triggered by a task such as end effectors motion commands.

5.7.1 Autonomy Requirements

The autonomy laid out in the above section imposes a number of functional requirements on the DR. These requirements are decomposed into performance specs in the relevant detailed design sections of this report.

- The DR shall be capable of performing an Emergency Stop to ensure that the HST is not harmed.
    - The DR shall be able to detect conditions requiring an emergency stop, and halt all motion prior to a potential collision.
    - The DR shall have sensors to detect whether there are any objects within an unsafe distance of the DR.
    - All DR commands other than an operator override shall have a lower priority than Emergency Stop
    - DR shall and halt all motion within 10.6 mm and 0.4°. (Negotiated total stopping distance with GA)
    - The DR CPU shall have a connection to the GA that allows it to signal when an emergency stop is required.
    - The DR CPU shall signal to ground control that an emergency stop has occurred.

- The DR shall have a backup mode allowing full manual control in the event of primary control systems failure. (Single Fault Tolerance)
    - DR shall have a direct command link between GC and DR subsystems
    - GC shall have an explicit option to override the DR Emergency Stop

- The DR shall be capable of coordinated joint motion when controlling either of its arms.
    - DR CPU shall be capable of doing 6 Degree of Freedom (DOF) inverse kinematics to solve joint angle changes to achieve commanded EE locations.
    - DR shall be capable of simultaneously powering and commanding all 6 joint motors in one arm
    - DR shall be able to command its motors at a continuous range of speeds from zero up to the maximum speed of a given joint.
    - Motor commands shall have a lower priority than Emergency Stop

- The DR shall be capable of moving its end effector along a constrained path while applying a force, as during the insertion of the WFC.
    - DR CPU shall be capable of doing the 6 Degree of Freedom (DOF) inverse kinematics and joint rate adjustments required to solve joint motions for a constrained end effector path.

- The DR shall use active force control to limit off axis forces to prevent jamming of the WFC.
    - DR shall stop motions if forces at the end effector exceed limits set by the operators. (TBD)

    - DR Shall have a force and torque sensor at each end effector capable of metering 200% of the expected forces and torques.
    - DR Shall use active force control to limit off axis forces to 10 lbs

- The DR shall use a vision system to correct user commands for perturbations due to GA/DR structural flexibility
    - DR shall have a 'vision system' to provide accurate position info WRT work site.
    - DR shall use a model matching algorithm to compute its delta vector (distance from actual DR position to reference DR position used in operator commands)

- The DR shall report telemetry such as temperature data, joint positions and speeds, forces/torques, and other engineering data to ground control.
    - DR CPU shall initiate the communication connection upon which telemetry is transmitted to GC.

5.7.2 Autonomous Architecture

5.7.2.1 Subsystem Controllers – Manual Mode

At its most primitive level, the DR will allow ground controllers to directly command each individual joint. This basic level of functionality ensures mission success even in the event that the more capable CPU controllers fail.

5.7.2.2 Main CPU – Motion Control

At its normal operating level, the DR will be augment user commanded motion with autonomous control that will significantly improve performance during normal operations. The main CPU of the DR will be able to compute appropriate motor commands for each of the 6 joints per arm, to achieve coordinated motion at the end effectors. We determined that this functionality is desired since the several seconds of communications lag between GC and the DR precludes real-time control. Additionally, coordinated control of joints is required to achieve motion along constrained paths as during the insertion of the WFC3.

5.7.2.3 Main CPU – Active Force Control

In addition to computing the joint motions required for a given commanded tip motion, the DR will be able to intelligently correct motions if it is perturbed by deflections of the flexible DR/GA system. In effect the DR need to 'Register' its workspace, determine its displacement relative to its expected location, and produce a delta vector that allows it to correct motions in real time. Details of how this capability improves the performance of the DR is found in Section 6 - Control System (below).

5.7.2.4 Main CPU - Active Force Control (AFC)

At its the primitive (manual) level of DR, operators inputting commands at less than real time are unlikely to have great success preventing jamming while moving the WFC3 along the constrained path of the rails. This problem is likely to be exacerbated by motion of the DR and GA as loads are applied. The backup manual mode would achieve path following by monitoring forces and stopping the DR if load limits are exceeded. However, this requires GC to reassess and re-plan the motion many times during the operation.

We have decided to enhance the DR's autonomous capability so that it can to modify the joint torques in real time during the insertion motion. This will improve the DR performance during WFC operations considerably, by allowing it to correct for misalignment during insertion before jamming occurs. This capability will require additional computational power on the Main CPU, as well as data from force torque sensors placed at each end effector. However, we believe that this is achievable since AFC has been used on other robots, most notably the SPDM, as well as being used in robotic manufacturing [7] and surgery [8]. For this reason we felt this technology is both appropriate and feasible for the DR.

5.7.2.5 Main CPU - Telemetry Reporting

The Main CPU will report telemetry to ground control whenever the DR is in an operating mode. This process will take place continuously without being initiated by controllers, since we desire continuous data collection. The CPU will initiate commands to the EM communications system when it needs to transmit data.

The separation of telemetry transmission from central robot functions means that telemetry signals could be displaced from the communication bus in the event of higher priority signals. This could lead to loss of telemetry at times, but can be mitigated by appropriate use of interrupt priorities and scheduling rules.

5.7.2.6 Collision Detection System – Emergency Stop

The collision controller will continuously monitor the space available around the DR structure and halt operations when a collision is about to occur. It does not receive any commands from other systems on the DR or from ground controllers.

The moment of approaching any physical object beyond the safety limit that collision sensors detect should cause the collision controller to automatically send the halt command to DR CPU. This will trigger the Main CPU to stop any motor commands, put the DR into safe mode, and to signal the GA via the dedicated emergency stop communication bus. Upon stopping, the DR shall report its status to ground control, and wait in safe mode for operators to assess and resolve the situation.

Ground control will be able to override the emergency stop signal if for some reason the system is triggers a halt and operators determine that it is safe for the DR to continue.

5.8 Operations Tradeoffs

Minimum vs Maximum Autonomy

Greater autonomy could be used to enhance the overall performance of the DR, but we believe that the cost in terms of mission risk and complexity would be too high. An autonomous system has more failure modes and thus would be more dangerous in close proximity to the HST. For this reason we have designed the DR to use the minimum necessary.

Active Force Control vs. Purely Scripted Motion

Operators using only scripted motion are likely to have great difficulty in performing the WFC due to the small tolerances on each rail (+-0.1”). They would have to do stop and go control; finely tuning the commands to unstick the rails. Active force control, while complex, is current technology, and is well suited to this application. We felt that the extra demands on the DR software were justified by the increased mission safety resulting from speeding up the WFC installation so that it is not in danger of freezing while it is stuck and partly inserted.

6 Control System

This section discusses the DR control system. The major requirements that drove various design decisions are itemized and are listed from general to specific (and hence more quantitative). The control system architecture is then outlined through a discussion of our control philosophy and how the requirements contributed to its design. The software architecture is then discussed and supported by a number of software architecture diagrams. The requirements that the software imposes on the hardware are listed in addition to a number of key computer hardware components that we feel will be necessary to fulfill the software requirements.

6.1 Control Requirements

6.1.1 Functional

The DR shall control:

- The position of the tool manipulator
- The position of the general purpose manipulator
- The camera orientation at each end effector
- The LCS system orientation

6.1.2 End Effector Position Accuracy

The DR shall:

- Have an accuracy of ± 1" and ± 1° relative to the commanded position.
- Have a tool end effector such that can apply a torque of at least 50 ft-lbs with an accuracy of ± 15%

6.1.3 End Effector Position Resolution

The DR shall:

- Have end effector tip resolution better than 0.1" and 0.1°

6.1.4 Vision System Sensor Requirements

The DR shall:

- Have two cameras on each end-effector to provide a single fault tolerant means of obtaining viewpoints of the workspace.
- Provide the vision system software data to register and track objects to within the aforementioned accuracy in all lighting conditions.
- Be able to visualize the entire workspace with no regions that cannot be visualized by either moving the end effector cameras or pivoting the LCS.
- Have an LCS lens, mounted on the top of the body, capable of +/- 90 degrees of pan and +/-45 degrees of tilt

6.1.5 Time Domain Requirements

The repair operation will occur slowly over the course of a month; therefore, a system that responds in an ultra-fast fashion is not required and is likely to add complexity to our system. Given this, we have decided upon the following time domain response:

6.1.5.1 Settling Time:

In order to complete the HST servicing operations in a reasonable amount of time, the lag time should be no greater than 5 seconds

6.1.5.2 Rise Time

The rise shall be less than 2.5 seconds. This is deemed to be an acceptable rise time

6.1.5.3 Bed Time

This shall gradually increase without bound while $I = n\psi$.

6.1.5.4 Steady State Error Requirements

The steady state error is interpreted as the cumulative error in tip position caused by the steady state angular errors of each joint in the arm. For a cumulative error less than 1", as requested by the customer, a higher accuracy is required at the shoulder joints as compared to the wrist. However, we have decided to apply the highest-level constraint to each joint, to improve the overall accuracy of the arm. Given our arm's length, the steady state error allowed in each joint is +/- 0.0466 degrees.

6.1.5.5 Frequency Domain Requirements

The control system shall be stable for obvious reasons, and this necessitates that there be no poles in the right hand plane or exactly on the imaginary axis. Moreover, from the requirement that the HRV shall do no harm to the HST, it is apparent that any overshoot of the desired position by the DR will not be tolerated. In order to accomplish this, the system must be critically or slightly over-damped, such that $\zeta >= 1$.

6.1.5.6 Bandwidth

We may need to compensate for small oscillations in the tip position as the result of vibrations in the GA and DR as whole, therefore our bandwidth shall be able accommodate our highest predicted natural frequency, 107Hz. Appendix 8 contains the details of the modal analysis.

6.2 Control Architecture

6.2.1 Control Philosophy - Distributed controllers and Centralized Coordination

Each controlled device will have its own micro controller that will handle all low-level operations. Conversely, all command operations and advanced data handling will be accomplished by a centralized CPU. In this 'dictator style' control, the central controller does not need to spend its processing power on low-level monitoring operations. Instead, the CPU simply requests data from a device specific micro controller, when required.

6.2.2 Controlled Devices

To achieve the functional and system specifications the following components need to be controlled.

1. Arm motors (to control the precision positioning of the end effector)
2. LCS orientation motors (to control the direction the LCS is pointing at)
3. Control torque applied by end effector motor
4. Temperature (to ensure minimum survival temperature is maintained)

Human operators at ground control will command the dexterous robot. However, several subsystems on the dexterous robot, and the GA, which interfaces with the DR, are capable of autonomous actions, and thus are capable of influencing the DR independently of Ground Control. This section lists these actors, and describes their autonomous functionality.

6.2.3 Controller Overview

6.2.3.1 Arm Motor Control

The absolute coordinate system will be as follows. The z-axis is along the cylindrical axis of HST, the x-axis is orthogonal to the z-axis along the length of the solar array boom, and the y-axis is orthogonal to both axes. This coordinate system has been chosen to be on HST since this way we can pre-determine the required positions of the workspace from the Hubble model available.

The ground controllers are going to be in control of the ultimate position of the end effector. From the LCS feedback, GC can locate the end effectors as well as identifiable features on the Hubble. From this data the ground control computer will calculate the relative position and orientation of the end effectors. Using the existing 3D model of Hubble, GC will calculate the position of the end effector relative to the fixed coordinate system mentioned above. This way GC is going to be aware of the exact location and orientation of the end effector relative to the fixed coordinate system.

To move the arm the GC will upload desired Dx, Dy, Dz and Dq1, Dq2, Dq3 to the DR CPU. The CPU will then calculate the desired motor angles and command the motor micro-controllers to rotate the motor. The motors will have resolvers that are will used to identify the amount of turn. This data will be fed back to the micro-controller to form a closed loop feedback. This data will also be fed back to the main CPU and transmitted to GC.

While moving the arm the CPU continuously uses real time readings from the collision detecting IR sensors so that the minimum clearance from the HST is not violated. In the case that the IR sensors detect a violation, the CPU will command the micro controllers to immediately halt all power supply to the motors.

Fine-tuning of end effector position will be done at GC with the feedback of the mini cameras and the LCS once the end effector is in workspace vicinity.

6.2.3.2 LCS Motor Control

The LCS will have 2 degrees of freedom, a yaw motor and a pitch motor. Since the GA will not be fully rigid, GC will have to register the position of the end effector before a move,to generate the Dx, Dy, Dz and Dq1, Dq2, Dq3, and after a move, to ensure correct positioning and apply corrections if necessary. Once the motion is complete and the end effector is in position the LCS will be used to register the workspace for servicing operations.

The LCS motors will be controlled using motor angles as input. The resolvers will form the feedback loop. GC will control the orientation of the LCS view.

The motor micro controllers will receive the following commands:

- Move Joint at speed X

- Move Joint to angle X
- Apply Force X to Joint

The motor micro controllers will give the following commands:

- Control signals to the internal hardware (release brakes, voltage to motors, read sensors)
- Position/Rate/Torque telemetry to the CPU and ground control

6.2.3.2.1 Level of Autonomy

The motor controllers perform some autonomous operations, in that they operate as closed loop feedback system. They operate until they achieve the desired position/rate/force given by the controlling actor (GC or DR CPU).

6.2.3.2.2 Performance Impact

The low level autonomy in the motor units increases reliability and responsiveness to input commands, as there will not be any internal processes that could cause a control lock. Additionally, it allows various agents to control the same physical mechanism while still providing a sufficient level of abstraction, which encapsulates the details of internal hardware and electronics.

6.2.3.3 Control torque applied by end effector motor

Ground control will determine the torque to be applied to the tool. The processor will receive the required torque via the communications, and pass the data to the micro controller. This will determine the duty ratio of the pulse width modulation that is applied to the motor drive circuits. The motor drive circuits will receive the PWM signal through a MOSFET gate node, which allows the current through the drain-to-source to be controlled directly through PWM. The motor is in series with the drain and hence we can control the torque of the motor directly. Relays can be used for directional control. Figure 6.1 shows the motor control circuit.

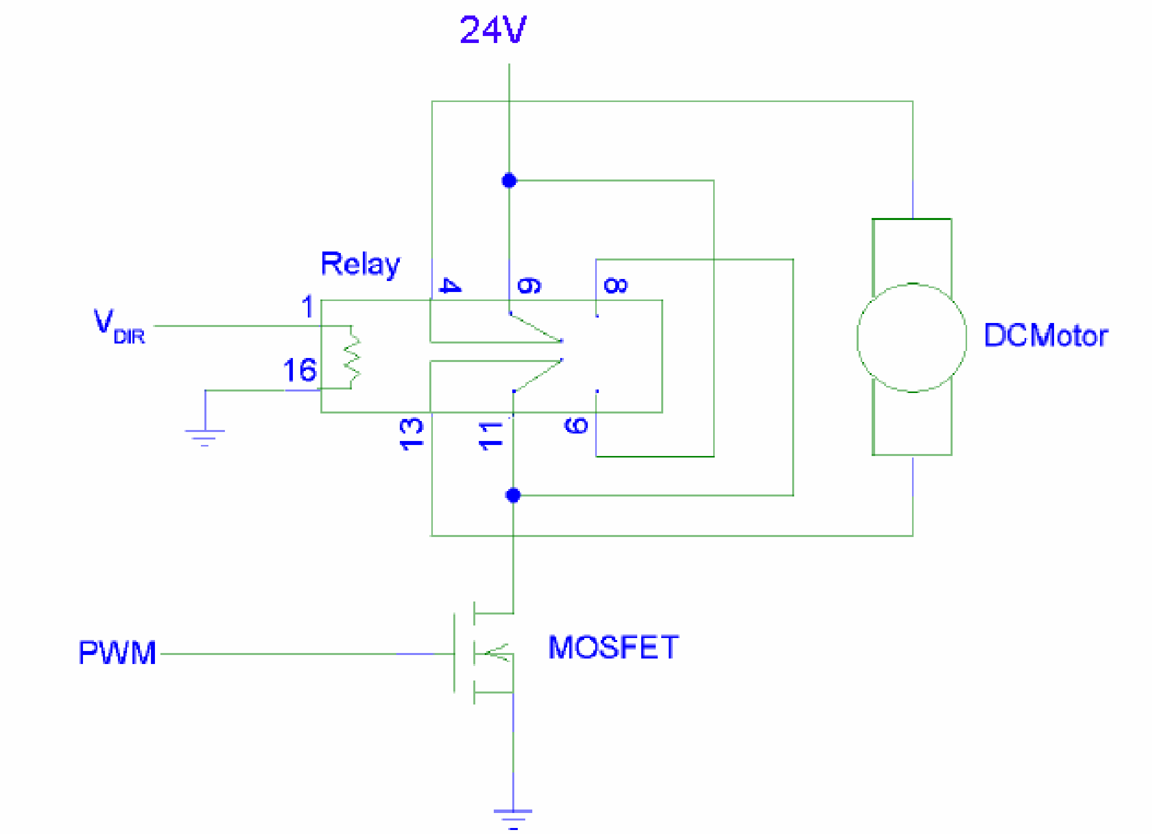


figure 6.1: motor control circuit

6.2.3.4 Thermal control

Temperature control is necessary to protect the electronic components. Active heating is needed to prevent the temperature from falling below -15°C. The temperature control system is fully autonomous. The CPU on the DR will receive inputs from the thermocouples and switch on the power to the heaters as and when necessary. The thermal control system measures and compares the temperatures to decide whether to power the heaters. The autonomous nature of the thermal control system ensures that any failures will be immediately dealt with, decreasing the chance of damage occurring to the DR. See Appendix 6 for a model of the thermal control block diagram.

6.2.3.5 DR Main CPU

The DR CPU is responsible for sending and receiving commands and signals to ground control as well as all of the other DR actors with the exception of the LSC, video cameras and telemetry controller. It performs high-level tasks, which coordinate most of the autonomous systems on the DR.

The CPU will give commands to the following systems:

Vision System Processor
- Update the workspace definition- these tasks are actually carried out by separate visions system controller.

Motor Controllers
- Start/stop
- Required angles

- Required speeds
- Perform test
- Enter stow configuration.

Communication

- Establish Data Link with Ground

Sensors

- Power up
- Perform test

GA

- Emergency Stop

Self

- Switch into desired mode

6.3 Vision System Architecture

The DR vision system includes a suite of sensors, which it uses to perceive its workspace. The sensor data is interpreted by a dedicated vision system processor, which, through machine vision algorithms, locates the DR relative to the HST and provides essential feedback for the control system. The primary vision sensor will provide the data for workspace registration and a secondary system will provide additional camera angles, and close up views of specific objects. We have selected a pair of NepTec LCSs to act as our primary vision sensor (with one in reserve as a back-up to provide single fault tolerance). Two Toshiba mini-cameras will be mounted on the end of each end effector and will provide additional camera angles and limited stereoscopic ability (our system however does not require this capability).

6.3.1 Selection of a Primary Vision System Sensor

There are a number of requirements on the DR design, which will directly influence the selection of a vision sensor. These are outlined below:

Accuracy

The DR must achieve:

- Closed loop accuracy of 0.16” or 4.06mm
- Angular accuracy of better than 1°

While this could be accomplished by simply having accurate sensors in the DR arms in the form of resolvers, the addition of feedback provided by a vision system will make this goal significantly easier to achieve, and makes the system more robust in the presence of transient disturbances to the DR arms. Any vision sensor selected should be able to determine the location of a target point to about the same level of accuracy quoted above. This statement neglects the full extent of the information that a vision system provides, in that not only does it provide xyz coordinates for specific points, but also determines corner locations, edge locations and the orientation of a ‘rigid body’ etc. To restrict our scope and given that machine vision is a topic with a considerable amount of depth (well beyond our space to examine it here), it will suffice to say that our visual sensor will have an accuracy equivalent to the DR requirements.

Range

The DR vision sensor does not require an extensive range, since the majority of its operations will be conducted within and ‘arms reach’ of the DR. Hence the range should not exceed 5m.

The vision sensor should however have a wide field of view such that the DR is capable of viewing its entire workspace despite being in close proximity to it.

Lack of Markers or Digital Landmarks

The DR vision sensor will not have the benefit of special purpose markers attached to any of the HST components to aid in their identification and position/orientation measurement. The vision sensor(s) used must be able to provide enough information to the image processing software such that it is able to identify each DR and HST component and its position and orientation. Certain vision sensors such as a single camera may have difficulty doing this and may require the use of a second camera to gain full depth information.

Current Technological Options

There are two major DR vision sensor alternatives that will provide position xyz information:

- Traditional visual-spectrum cameras;
- **Laser based scanners**

Both of these technologies have been demonstrated in space applications, with the former being extensively applied on both the Canadarm and Canadarm2 and the latter only in limited proof-of-concept tests on STS-105. The laser scanner was selected for the DR's main vision sensor.

The conventional camera technology is limited in that it requires a second camera to gain depth measurement without the aid of fudicials (markers). Space cameras also suffer from the effects of inconsistent lighting during orbital operations as a result of the ultra-high contrast between light and shadow rendering the vision sensor information useless. This would mean that despite being a fully proven technology, RSS operations would have to be dependent on lighting conditions, introducing an element of unreliability that is not acceptable.

Laser-based scanners are a new technology that was first developed for aerial surveying tasks and has been recently introduced into space operations. They have the advantage of being almost completely immune to the lighting effects of the sun, and are also capable of operating in complete darkness (given that the sun appears to rise and set 16 times a day in LEO, this is essential for long duration servicing operations). The accuracies quoted for laser scanners are also comparable to the photogrammetric results obtained using a conventional camera with special target markers [9].

There are two laser-based vision sensors that have been designed for the space environment- NepTec's LCS (Figure 6.3) and MDR/Optech's RELAVIS (Figure 6.4). RELAVIS is intended to work at extremely long ranges so that it would be useful for rendezvous operations, and LCS has been design for shorter range use, and is currently being considered to inspect tiles for the OBSS project (see Table 6.1 for RELAVIS and LCS comparison). Because NepTec's product is already partially adapted to the DR's needs, it was selected as the primary vision sensor.

Figure 6.3 NepTec LCS

Figure 6.4 MDR/OpTech RELAVIS

	Instrument	
Parameter/Feature	RELAVIS (Goals)	NepTec LCS
Flight Tested?	no	Yes
Primary Technology	Optech LIDAR	Laser 3D auto synch scan
Range	500m-5km	30m
Range accuracy	1cm	0.1mm @ 1m, 2mm @ 5m, 10mm @ 10m, 80mm @ 30m
FOV	30x30	30x30
Data Rate	10000-50000 point/s	Unknown
Volume	6-10L	13.32L
Mass	6-8 kg	12.1 kg
Power	35 W	65 W

Table 6.1 RELAVIS- LCS comparison [10][11]

A scaled down version of the LCS could be produced that would take advantage of the short-range requirement (<5m) and could operate on the DR's power. This would take more development resources than using a conventional camera, but given the advantage of being able to operate in any lighting condition, the added cost is worth the benefit. The field of view (FOV) would also have to be expanded so that the vision system could keep both arms in view at the same time. To complement this FOV expansion, the LCS will be mounted on a platform which will allow pan-tilt operation.

6.3.2 Video Cameras

The video cameras produce a standard 2-D image of whatever they are pointed at to provide the vision system as well as ground controllers with a full motion visual representation of the site at which the cameras are pointed. The cameras act in response to being turned on via the vision system controller. The cameras are low level autonomous, constantly producing a stream of video output as long as they are turned on. Low level single function autonomy in the cameras increases their reliability as a subsystem, and offloads the burden of the low-level image capture tasks away from the Vision System Controller.

The following commands are received by the video cameras

- Vision System Controller - Turn On

The following commands are given by the video cameras

- Control Internal Hardware (focus, capture image, encoding it, and transmitting it along the video bus)

6.3.3 Vision System CPU

The vision system processor is to be designed such that it is to automatically react to requests from GC and CPU for workspace view. This reaction involves the vision system processor to command LCS and the mini cams to capture the image of the workspace. The vision system processor shall automatically receive LCS and video data directly as soon as the data and the appropriate bandwidth are available. The most demanding level of autonomy for the processor is to coordinate the data to calculate the relative coordinate system of each vision field from Mini cams and LCS for meaningful mapping. This processed data is to also be fed back to DR CPU and GC upon requests.

The following commands are received by the vision system processor.

- DR GC – Acquire view of workspace.
- DR CPU – Request 3D mapping workspace registration.

The following commands are sent by the vision system processor.

- LCS – Capture image
- Video Cameras – Capture video of workspace.

6.4 Software Architecture

6.4.1 Software Requirements

The DR software must fulfill a number of fundamental requirements such that it is usable by the HRV ground controllers. These requirements however do not necessarily contribute the most to its complexity, difficulty of implementation or to the demands it places on other systems. As a result two lists of requirements have been produced, the first ranked in order of fundamental functionality and the second in terms of the complexity induced by the requirement. These two lists can be combined in a matrix format, whereby we will be able to correctly rank each requirement based on both its core functionality and complexity factor. The various requirements, not in any particular order are stated below:

a. The DR software shall be capable of accessing the communications system on the EM and communicating with ground control.
b. The DR software shall be capable of operating all actuators and devices on the DR.
c. The DR software shall use a vision system to locate all elements of the workspace including their orientations and positions relative to the DR
d. The DR software shall be capable of commanding the DR arms to any location and orientation and along any required trajectory, and apply corrections accordingly based on vision system feedback
e. The DR software shall have the ability to solve multi degree of freedom movements to avoid collisions or critical occlusions with HST or the DR itself.
f. The DR software shall complete machine vision processing tasks in a timely fashion such that it does not unduly prolong servicing operations.
g. The DR software shall be sufficiently stable such that it does not crash or malfunction during servicing operations.
h. The DR software shall have a situational awareness model that incorporates data from DR sensors (ie. motor encoders), the DR vision system, and internally stored data (self knowledge).
i. The DR software shall interface with the GA software such that it is capable of commanding the GA to move the DR to any desired position and orientation as well as halting such motion at any time.
j. The DR software shall have a minimum level of autonomy such that it is able to detect a collision and take appropriate actions to prevent the following (in order of priority)- 1) do no damage to the HST 2) do no damage to the HRV (GA/DR) 3) do not prevent success of RSS mission.

k. The DR software shall be capable of a self-assessment to ensure to the integrity of its executables.
l. The DR software shall be capable of downloading patches and bug fixes via the GC comm. system to correct errors in its programming
m. The DR software shall be capable of interfacing with the HST system via the EM comm. system such that it can trigger internal mechanisms of the HST such as the detector vent valves.

Ranking these in terms of their respective core functionality generates the following:
b,a,c,g,d,e,i,h,j,m,f,k,l

Ranking in terms of complexity:
h,c,j,f,e,d,l,g,i,m,b,a,k

This produces the following matrix,

	complexity												
functionality	1	2	3	4	5	6	7	8	9	10	11	12	13
1											b		
2												a	
3		C											
4								g					
5						d							
6					e								
7									i				
8	h												
9			j										
10										m			
11				f									
12													k
13							l						

By adding the row and column number in quadrature ((x^2+y^2)^0.5) we can derive a single 'importance number' for each requirement, which serves as the basis for our final ranking: C,D,E,H,G,J,B,I,F,A,M,L,K.

Hence our top ten software requirements are:

1. The DR software shall have machine vision algorithms that will be able to match a xyz data from the LCS system and stereoscopic information from the video cameras with a 3d model.
2. The DR software shall be capable of commanding the DR arms to any location and orientation and along any required trajectory, and apply corrections accordingly based on vision system feedback
3. The DR software shall have the ability to solve multi degree of freedom movements to avoid collisions or critical occlusions with HST or the DR itself.
4. The DR software shall have a situational awareness model that incorporates data from DR sensors (ie. motor encoders), the DR vision system, and internally stored data (self knowledge).

5. The DR software shall be sufficiently stable such that it does not crash or malfunction during servicing operations.
6. The DR software shall have a minimum level of autonomy such that it is able to detect a collision and take appropriate actions to prevent the following (in order of priority)- 1) do no damage to the HST 2) do no damage to the HRV (GA/DR) 3) do not prevent success of RSS mission.
7. The DR software shall be capable of operating all actuators and devices on the DR.
8. The DR software shall interface with the GA software such that it is capable of commanding the GA to move the DR to any desired position and orientation as well as halting such motion at any time.
9. The DR software shall complete machine vision processing tasks in a timely fashion such that it does not unduly prolong servicing operations.
10. The DR software shall be capable of accessing the communications system on the EM and communicating with ground control.

Requirements M, K, and L were eliminated from the top-ten list as a result of this procedure.

6.4.2 Level 0 - Rationale

Our overall software architecture consists of two distinct elements: the main command module and the vision system module. This division was chosen because each software element will reside on an independent processor and will be carrying out vastly different tasks with differing software and hardware requirements. Taken together, these modules interpret all sensory information provided by the data gathering systems on the DR and communicate the condition of the DR and its surroundings to the outside world (GC, EM, GA etc). This dual architecture is summarized is Figure 6.5 below.

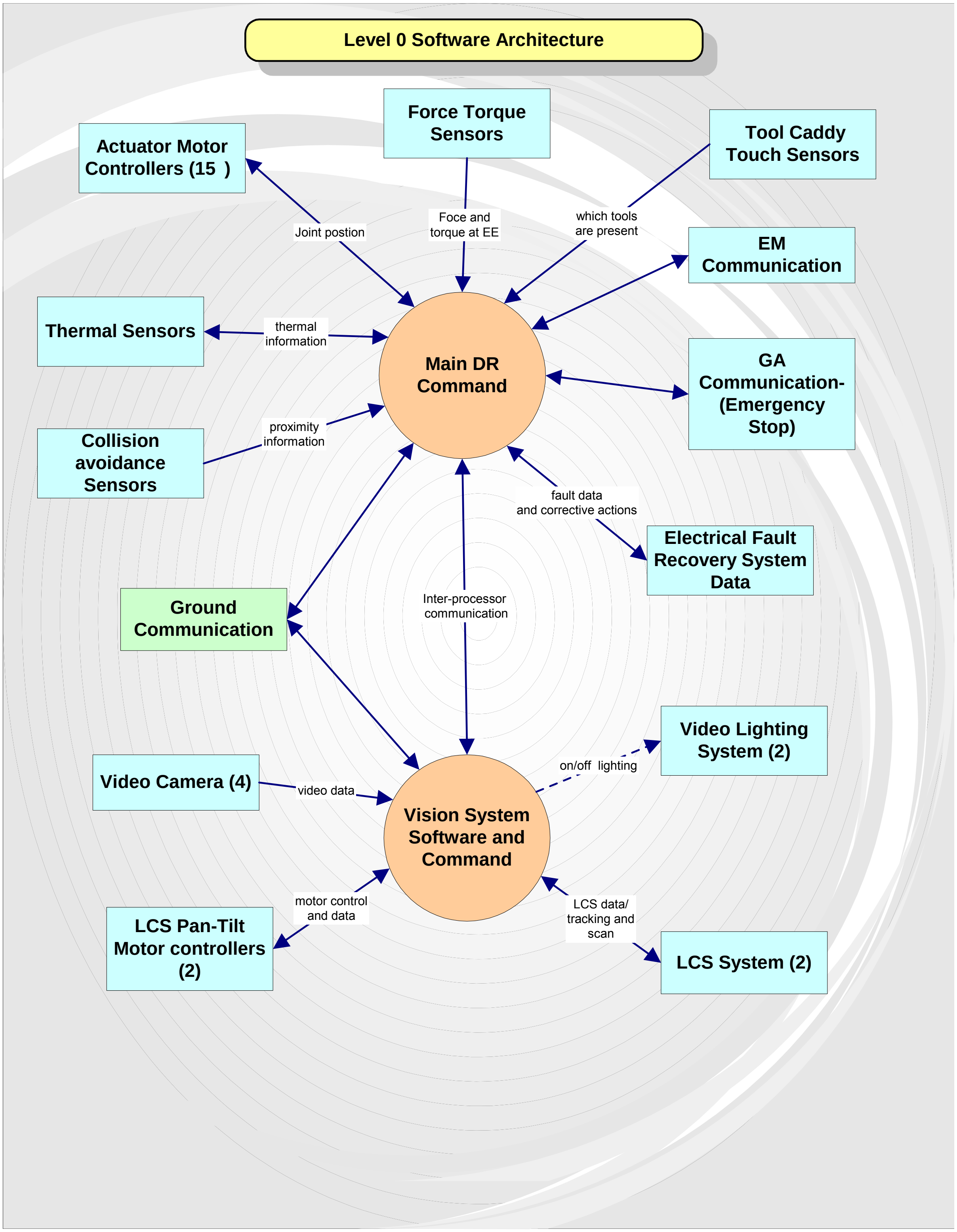


Figure 6.5 Level 0 Software Architecture

6.4.3 Level 1 Breakdown

Our dual architecture can be broken down further into software nodes contained within each of the main control and the vision system. Please see Figures 6.6 and 6.7.

6.4.3.1 Level 1: Main DR Command

The main command module will handle all non-vision operations of the DR. The main command modules will individually process these tasks while the MCOS (Main Command Operating System) will handle the computer system resources and the lower level tasks. The main command module will contain the following software modules:

- Redundancy Control - This module will only be active if there has been a failure detected in the DR's power or data bus system. The redundancy control system will take corrective action, engaging backup systems and coordinating this complex switching task with the power regulation module.
- Power Regulation System - This module will act as the central governor of all power on the DR. It will know how much power is available and will supply power to devices based on requests from their respective commanding modules (i.e. the motor command module would request power for a motor, and then would handle the control of that motor) and will have control of the central switching mechanisms. Each commanding module in the main controller must interface with the power controller and hence, this module is of central importance and should require extensive verification and validation. By having all power controlled through one software module, we can avoid the possibility of an error leading to the DR exceeding its power limit and potentially damaging other systems on the HRV.
- Collision Avoidance - This software element interprets data from the infrared emitting diode (IRED) sensors and heavily preprocessed data from the vision system and detects a potential collision situation. This information and is reported to GC and GA via the communications module and immediate corrective actions are sent to the motor command module (generally a full-stop).
- Thermal Control - This module handles the monitoring the thermocouple sensors and requests that various heaters be turned on in order to maintain a optimal operating temperature.
- Communications - This module coordinates all communications with EM,GA, and GC. GC communications are routed through the radios on the EM while communications with the EM, and GA are handled internally within the HRV.

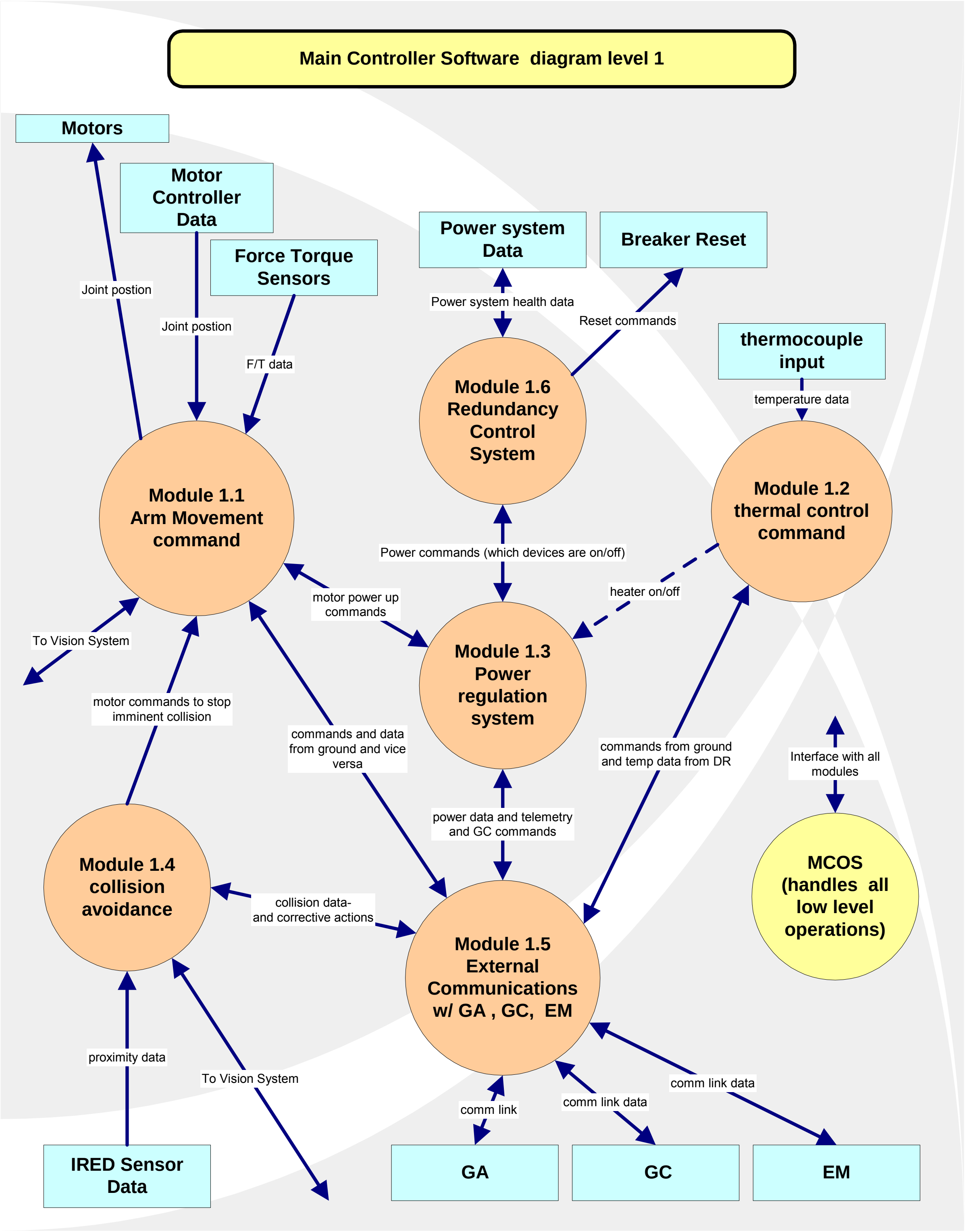


Figure 6.6 Level 1 Main Control

6.4.3.2 Level 1: Vision System

- Vision operating system - The vision system requires a dedicated OS to help it manage the system resources, and handle the deluge of data that must pass through the visions system's limited data bus bandwidth. It also coordinates all the communication between each software module within the vision system.
- LCS Controller - Directly controls the LCS, receives data and disseminates it accordingly through the VSOS.
- LCS Pan Tilt Movement - This module commands the movement of the LCS pan-tilt mount based upon commands received from the LCS system controller or the GC via the VSOS.
- 3D Model Matching Engine - This module generates 3D models of the DR's workspace using full-scan data from the LCS. This data is received directly from the LCS control module and the results are sent to GC and various other modules via the communications interchange.
- Stereoscopic Engine - Solves for depth of field information given the two video streams from each camera and known baseline between the cameras
- Collision Detection Engine - Analyzes the latest model update and tracking data for imminent collisions and communicates the results through VCOS to all interested parties.
- Video Camera Controller - This module controls the video cameras and their associated lighting on each end effector. It alters the focus accordingly and receives and preprocesses visual data so that it can be sent to the stereoscopic engine.
- External Communication - The vision system is able to communicate directly with GC via this module, which interacts with the radios on the EM. Video data are compressed by this module and any other operations
- LCS Edge Tracking Engine - This module contains the algorithms required to deal with the LCS tracking mode. The edges identified by the LCS will be fitted to models of the objects in question and a coarse determination of the position and orientation of each object will be determined.

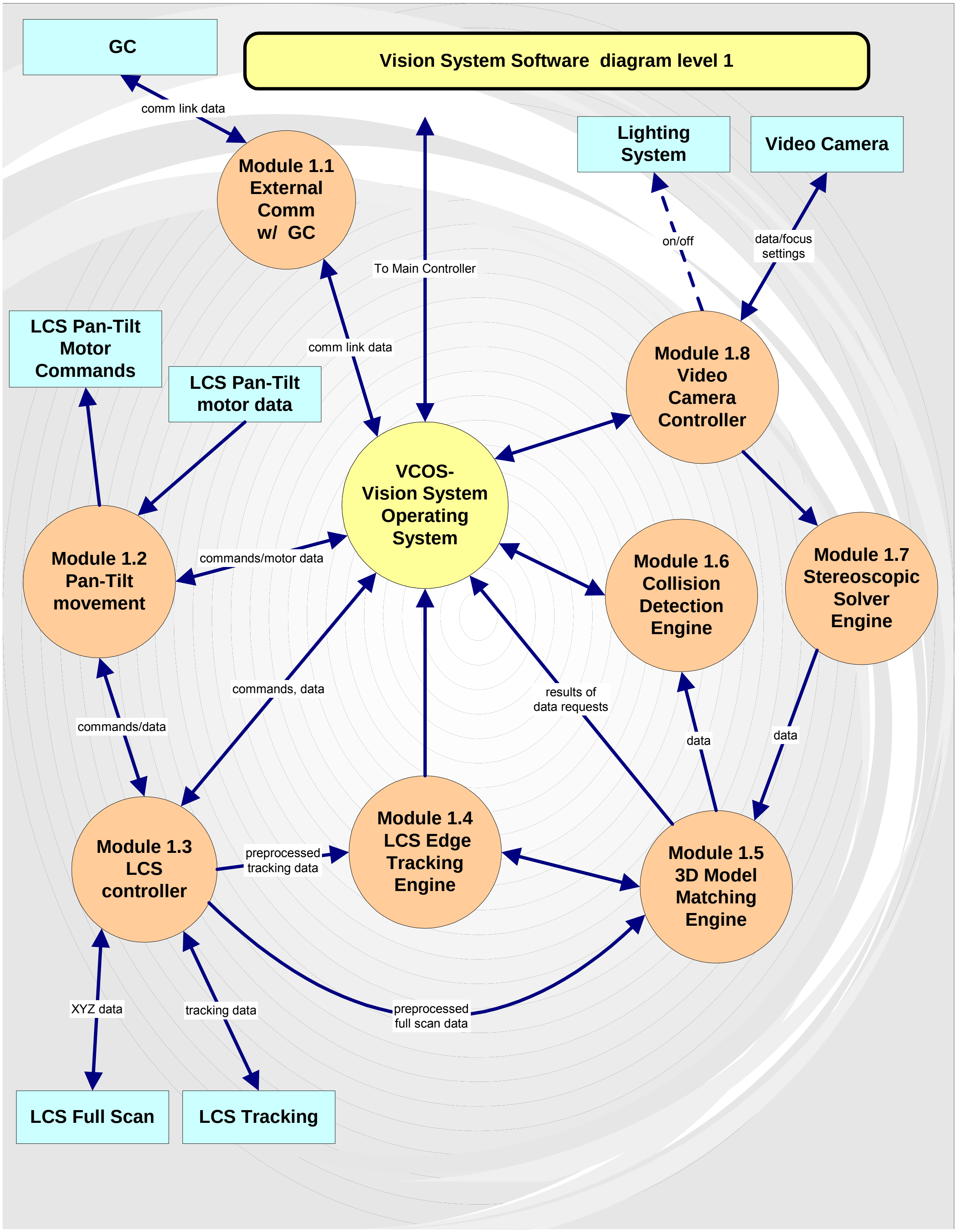


Figure 6.7 Vision System

6.4.4 Level 2 breakdown

For reasons of brevity we have not developed every software module to the detail of a level two breakdown. However as an example, we do present level two breakdowns for both the motor controller and the thermal control modules.

6.4.4.1 Level 2 (example): Motor Command

Please see Figure 6.8

- Force Torque Monitor - This module will continuously loop over the Force torque sensor data and report processed data to the overload monitor, the command interpretation module (so that it may send the data to the GC) and to the motor command calculator.
- Overload Monitor - Compares force/torque data to overload values and signals the GC and the main controller if we exceed the specified safe limits or each joint.
- Command Interpretation - This module will take in all external commands to the motor controller module and interprets them accordingly- it will also send out data from the motor controller to other modules and GC.
- Motor Command Calculator - This module will take in data from the power request module, F/T monitor, overload monitor, motor/shaft position monitor, and determine an appropriate motion for the arm as a whole or a specific motor. These instructions are then sent out to the appropriate device after its power request has been satisfied.
- Motor/Gearbox Output Shaft Monitor - This module will continuously monitor the output data of each resolver and calculate the current angle, angle rate and angle acceleration. This data will be communicated externally via the Command Interpretation module
- Power Request Module - The power request module will interact with the power regulation system in requesting power for motors. While the power regulation system does not directly control the function of the motors, it does control which devices are currently have a full power supply and which are in standby.

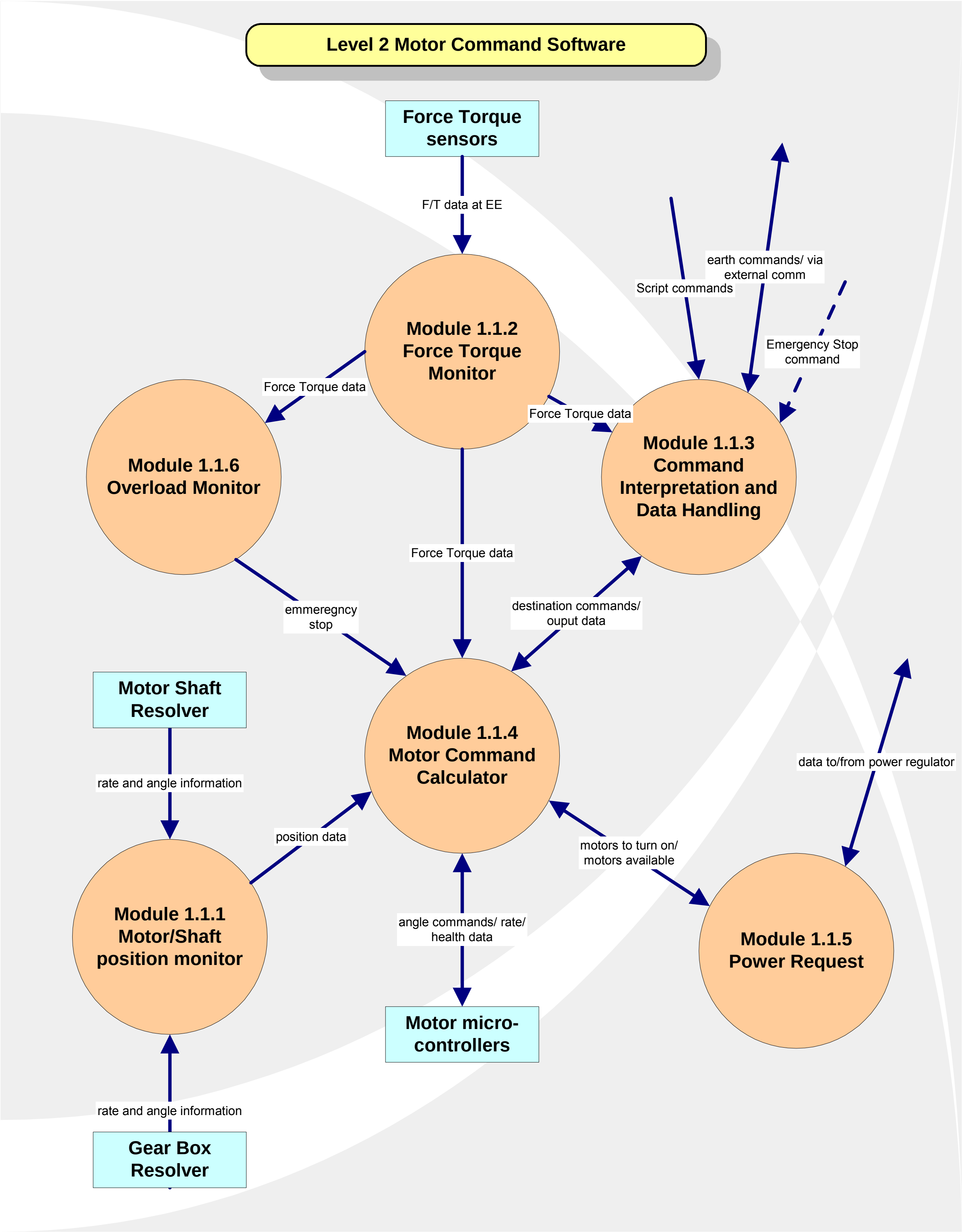


Figure 6.8 Motor Control

6.4.4.2 Level 2 (example) Thermal Control

Please see Figure 6.9

- Monitor Temperature - This module continuously loops over the data from the thermocouples and processes this data for communication to the Adjust Temperature module
- Command and Data Handling - This module interprets thermal commands form the other modules and the GC and sends them on to the temperature adjustment module.
- Adjust Temperature - Based on data received from monitor temperature and commands received from the CD&H this module will adjust the temperature on a specific device accordingly by switching on the appropriate heating element. This is accomplished by making a request to the power regulation system.

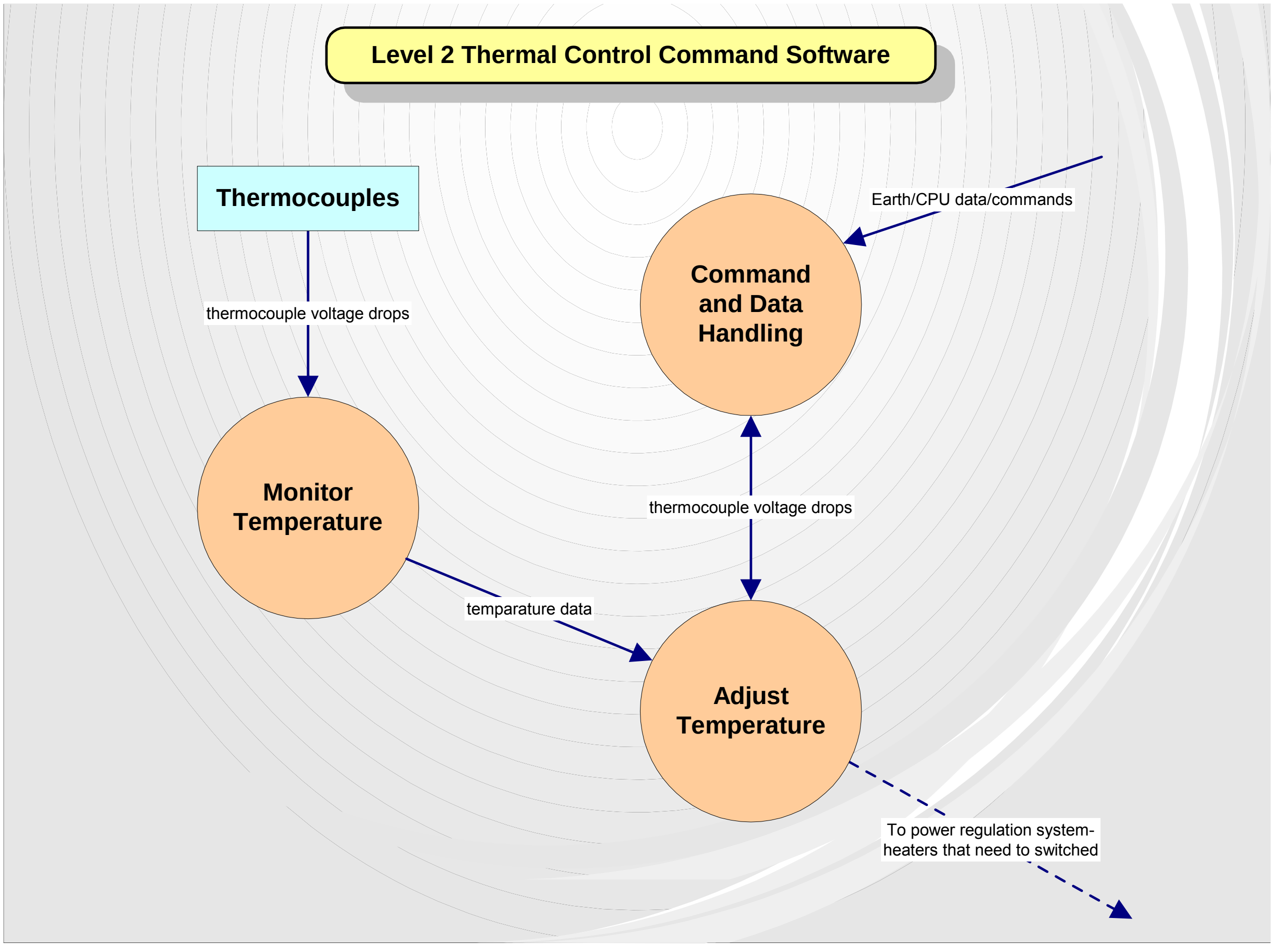


Figure 6.9 Thermal Control

6.4.5 Example Software Mini-Spec

See Appendix 6

6.4.6 Data Dictionary

See Appendix 6

6.4.7 Software 'Push Down' Hardware Requirements

In order to complete its requirements the software shall:

Since the processing power of conventional radiation hardened CPUs is comparatively small compared to their earth-bound brethren, and large quantities of rad-hard memory are unavailable, the DR software must be designed such that it does not overwhelm the resources of its supporting hardware. This imposes limitations on operations that require large computational power and especially impact vision systems activities.

We have determined that the most computationally significant operation carried out by the DR software is the registration of the workspace using the LCS. The LCS scans the workspace and generates a 3D model of the workspace. The workspace is then registered using model matching, which is an iterative and computationally intensive process. Due to this factor we decided to have a separate CPU for vision system. We will need to store quite a large bit of data for the operation especially when handling the model matching as a result we need a high volume of data storage space. Typical model matching applications being researched at Princeton University [12] needed 256 MB of RAM.

The CPU and memory requirements led to the choice of the SCS 750A computer by Maxwell Corporation. Operating at 800MHz and accompanied by 64KB of L1 cache and 256 KB of L2 cashe and 256MB of RAD hardened SDRAM.

Capabilities of CPU have to be chosen based on software complexity and will determine the power required by the CPU. This will impose requirement on our power budget. The Maxwell CPU and Memory board requires 7-25 W of power depending on the clock rate and MIPs requirements.

For reasons of simplicity, this processor (although vastly over-computationally-powered) was also selected as the CPU for the Main command CPU.

See Appendix 9 for detailed specification of the system CPUs and memory board.

7 Electrical Subsystem

7.1 Electrical Requirements

- The DR shall have single fault tolerance in its electrical subsystem
    - The DR electrical subsystem shall use resettable circuit breakers for overcurrent protection
    - The DR electrical subsystem shall be completely redundant
    - Motor redundancy shall be obtained through dual windings
- The DR cables bundles shall be small enough in size so that the force required to bend them is less than 10 N
- The DR cable bundles shall have 0.15 m slack at the joints to allow for full mechanical range of motion (shoulder roll ±180, shoulder pitch ±135, elbow ±135, wrist roll ±180, wrist pitch ±135, wrist yaw ±135)
- The DR cable mass shall not be more than 5% of the total DR mass
- The DR electrical subsystem shall be capable of supplying power to all 6 joint motors in one arm simultaneously
    - The tool arm power buses shall provide a maximum of 142 W to the motors
    - The manipulator power bus shall provide a maximum of 108 W to the motors
    - The DR power bus system shall carry 24 volts over the length of the arms.
- The DR shall be able to command its motors at a continuous range of speeds from zero up to the maximum speed of a given joint.
    - The motor electrical units shall vary current to change the motor speeds over the ranges given in Appendix 8.3.7

7.2 Electrical Architecture

7.2.1 External Interfaces

7.2.1.1 DR to EM

During the Launch, proximity and capture operations, the DR is stowed aboard the EM. In order to prevent damage to the electronics, the thermal subsystem must be active during these phases. To accomplish this the DR will have a primary and redundant electrical connection to EM. Both power and data will be transferred by these connectors.

The power for the DR is drawn from the batteries on board the EM. Cables are passed through the GA to two 20-pin connecters at the interface to the DR. The DR's main CPU is located on the EM, requiring data busses to pass through the GA to the DR micro controllers and components. Power and data will both be connected to the DR when it is grappled by the GA.

7.2.2 Cabling Layout

Cabling will be routed along the exterior of the arms, with 0.15 m slack loops at each joint to allow sufficient flexibility of the arm. At each drop point a connector will rout the necessary wires from the main bus to the specific EPCE.

7.2.2.1 Power Cables

There will be two primary and two redundant 24V busses for each arm, and a primary and redundant 24V pair for the body. These 10 (5 primary, 5 redundant) busses will supply power to the joint and gripper motors in the arms, the LCS orientation motors and the main LCS unit.

For the lower power devices, there will be two primary and two redundant 12V busses on each arm, and a primary and redundant 12V pair for the body. These 10 (5 primary, 5 redundant) busses will supply power to the electronics, heaters, sensors and the tool caddy.

7.2.2.2 Data Cables

Data will be supplied to and retrieved from the motors, sensors, heaters and the LCS via MIL-STD-1553 busses. There will be a set of primary and backup busses for each arm and the body. Couplers and stub connections will be used to connect components to the buses.

Video data from each of the four mini cameras (two at each end effector) will be transmitted along dedicated primary and redundant video busses.

The complete cable layout has been included in Appendix 7.1. The map illustrates both arms below each other because of space limitations for presenting the map. The actual design will have the body and head in the middle of the robot, and the arms come out of either side. The boxes that are diagonally hatched in the cabling layout diagrams represent the external interfaces for the DR. These systems have links with the DR but are not physically part of the DR. The cable layout diagram has been broken down into 6 subsections, listed in Table 7.1 below for clarity. A map of the DR has been provided to show the integration of these subsections.

Diagram	Title	Appendix
	Cable Layout Map	7.1.1
Layout and Cabling 1	Lower Tool Arm	7.1.2
Layout and Cabling 2	Upper Tool Arm	7.1.3
Layout and Cabling 3	Lower Manipulator Arm	7.1.4
Layout and Cabling 4	Upper Manipulator Arm	7.1.5
Layout and Cabling 5	DR Body	7.1.6
Layout and Cabling 6	EM	7.1.7

Table 7.1 Cable Layout Breakdown.

7.2.3 Functional Block Diagrams

The complete electrical functional block diagram of the DR is seen in Appendix 7.2. A high level diagram shows the location of all subsystems and the connections between them. These electrical subsystems have been further decomposed to show the connections and redundancy of the EPCE on the DR. The characteristic subsystems are listed in Table 7.2 with their corresponding appendix.

Diagram	Title	Appendix
	High Level??	7.2.1
EFBD 1	Motor EU	7.2.2
EFBD 2	Thermal Control System	7.2.3
EFBD 3	LCS EU (Control Unit)	7.2.4
EFBD 4	Tool Caddy EU	7.2.5
EFBD 5	Tool Gripper MEU	7.2.6
EFBD 6	Clamp MEU	7.2.7
EFBD 7	Vision Processor	7.2.8
EFBD 8	CPU	7.2.9
EFBD 9	Force/Torque Sensing Units	7.2.10
EFBD 10	Mini Camera	7.2.11

Table 7.2 EFBD Breakdown.

The following component descriptions are characteristic of those seen in the EFBD's

7.2.3.1 Circuit Breakers

Each electrical unit will have two circuit breakers, located between each unit and its power bus. One breaker will be primary and the second backup, forming the connections to the primary and redundant power busses. In the event of an overload, the breaker will trip, sending a signal to the bus controller. At this point, either the backup bus will be activated, or the breaker will be reset. The breakers will be capable of being reset by the bus controller, discussed below.

7.2.3.2 Bus Controllers

Every electrical unit will contain a primary and backup bus controller. The job of this controller is to facilitate the transfer of information between the micro-controller(s) and the data bus. In addition the bus controller will receive a signal directly from the circuit breaker if an overload has occurred.

7.2.3.3 Voltage Regulators

Voltage regulators are located after each circuit breaker (primary and backup for each electrical unit). If necessary, regulators drop the bus voltage to that required by the electronics. In addition, the voltage regulators ensure the input to electronics is within their specified limits by increasing or decreasing the voltage by small amounts as required.

7.2.3.4 EMI Filters

EMI filters are used in the electrical units of the motors and the LCS. These components are 'noisy' and in order to prevent propagation of this noise into the rest of the system, EMI filters are used.

7.2.3.5 Analog to Digital Converters

These are used to convert analog data from various sensors to a digital signal that can be received by a micro-controller.

7.2.3.6 Collision Avoidance Sensors

The collision avoidance sensors will be located near each electronics box (MEU), with each box providing the required data and power connections. In this way a separate connection to the power and data bus is not required. The redundant hardware in each electronics box will support its own collision detection system. Since each collision detector is composed of an IR emitter and detector (both of which are small and consume little power) it is acceptable to have a redundant collision system on each joint to correspond to the redundant hardware/busses.

7.3 Electrical System Implementation

7.3.1 Power Busses

7.3.1.1 Interfaces

The power for the DR is transferred from the EM, via cables through the GA. Two 20-pin power connectors are located on the grapple fixture to route the power to the DR. Each connector will carry a full set of cables, allowing the DR to fully function in the event of a connector fault.

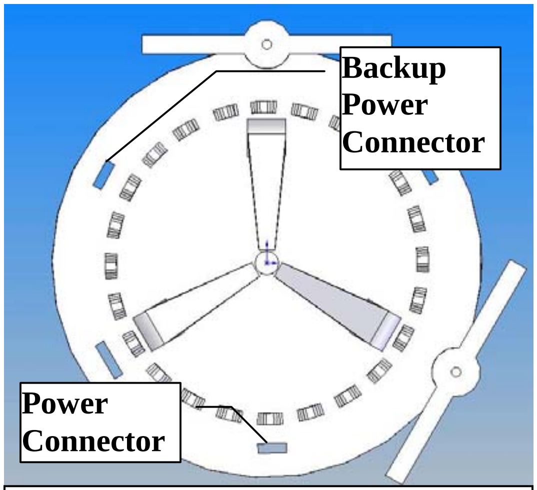


Figure 7.1 - Power Connector Locations

7.3.1.2 Design

The electrical devices on DR have been divided between the buses in such a way so that the noise and back EMF associated with motors and other actuators cannot affect sensitive electronic components. Therefore, motors and electronics will not be drawing their power from the same bus. Additionally, the DR heating units can draw large amounts of power and for reasons of limiting the wire gauge required, are connected to their own independent power bus. Exceptions to this paradigm are the heaters in the body of the DR, which have been included on the same bus as the LCS system for reasons of limiting the buses required and matching.

Since all the motors could not be placed on the same bus for reasons of limiting the wire gauge, it was also decided to stagger the connections such that if a bus failed and its backup also failed, a critical joint such as the shoulder would not be rendered completely inoperative. In this worst-case scenario, at least one DOF in the shoulder would still be active and provide the ground control with some options as to removing the arm from Hubble. Although one might think that this is an example of ‘scope creep’ we feel that this added error tolerance is essentially ‘free’ as the motor power needs to be divided between two busses in any case, and changing the order in which the connections are distributed adds no additional complexity cost to the system.

The power bus voltages have been selected based on the specifications provided for each component: i.e. 24 Volts for motors and 12 V for electronics. The electronics boxes will have their own transformers to step down the 12 V according to specialized needs of the hardware. The heater power bus requires 12V as well. An additional consideration taken into account when selecting voltages is the gauge of wiring required to supply power to each of the devices.

7.3.2 Data Busses

7.3.2.1 Interfaces

The data busses are routed from the CPU on the EM, through the GA. Two 32-pin data connectors are located on the grapple fixture to transfer the data busses to the DR. The pin set consists of 16 1553 data bus connections and 16 video bus connections. Each connector will carry a full set of data cables, allowing the DR to maintain functionality in the event of a connector fault.

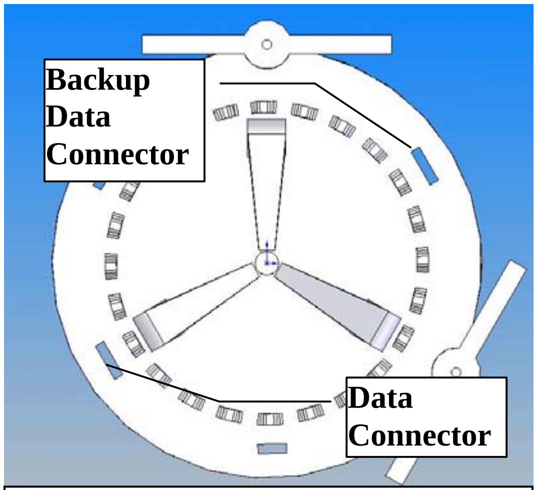


Figure 7.2 - Data Connector Locations

7.3.2.2 Design

Given the large amount of data expected from the video cameras and the LCS (the LCS can output a maximum resolution image size equivalent to 1Mb), we expect that they will likely need a dedicated bus to handle this heavy data transfer. A similar arrangement will be followed for the video cameras, with each video camera having a separate independent bus. Since there are two video cameras on the end of each arm, each camera serves as the other's back-up and there is no need to have back-up data bus for each camera.

7.3.3 Electrical Mass Budget

The total mass of cabling in the DR is 14 kg. The details of these calculations are found in Appendix 7.4. This number includes wire insulation, bundle shielding and connectors at all bus drop locations. The wire gages were adjusted to accommodate the derating of the cable bundles.

Since the power and control center of the DR is located on the EM, cable-carrying requirements are imposed on the GA. The total cabling mass imposed on the GA is 4kg. The details of these calculations are located in Appendix 7.5

7.4 Fault Tolerance

7.4.1 Automatic Breakers and Fault Recovery

There shall be a bus controller in each electronics box that controls all breakers. Each actuator has its power breaker contained within its controlling unit, such that the breaker for the control unit and actuator are co-located and do not necessitate a separate breaker bus line going to both locations.

The recovery bus will be redundant like the power and data busses, with each recovery bus RA and RB providing breaker control to the corresponding power bus, PA and PB. The 1553 standard will be used and will pass through the GA and will be connected to the main avionics box where its bus controller will be located. The main computer will provide command and control of the breaking functions.

7.4.2 Power Bus Redundancy

Each of the busses is electrically isolated from each other such that any shorting between the two busses is completely avoided. This will prevent the majority of single fault failure modes and comply with customer requirement of single fault tolerance, whereby a single fault in one bus could potentially corrupt both busses and render the DR inoperative.

Unfortunately this electrically isolated redundancy requirement has significant ramifications for the overall system design. There now has to be a doubling of most electronic components that represent a critical loss in performance should they fail. All MEU's and SEU's shall contain two identical sets of components connected to their own power bus (one serving as the backup of the other). We now require that our motors have dual windings, such that either bus can drive the motor without having to physically switch the power connections between the busses or requiring a complicated clutch to switch between independent motors.

7.4.3 Data Bus Redundancy

The data busses in the DR will be redundant in a similar fashion as the power busses. Each hardware string will be connected to its data bus (whether primary or backup) and there will be no interconnections between the data busses on the external component level (ie outside the CPU). This will prevent most of single point failures and the interconnection at the CPU could be designed such that a failure is unlikely. Given the low power usually found in data busses, the likelihood of a short at the CPU interconnect (not a direct connection, however both busses are connected to the same processor), which would render both busses un-operational, is also unlikely.

7.5 Power Demand

The power demand during key mission tasks was evaluated by summing the max power of the active components. All of the EPCE and their corresponding power requirements are listed in Appendix 1.3. A graph of the peak power demand vs. time with is given in Figure 7.3. Key mission tasks are identified and described in Table 7.3

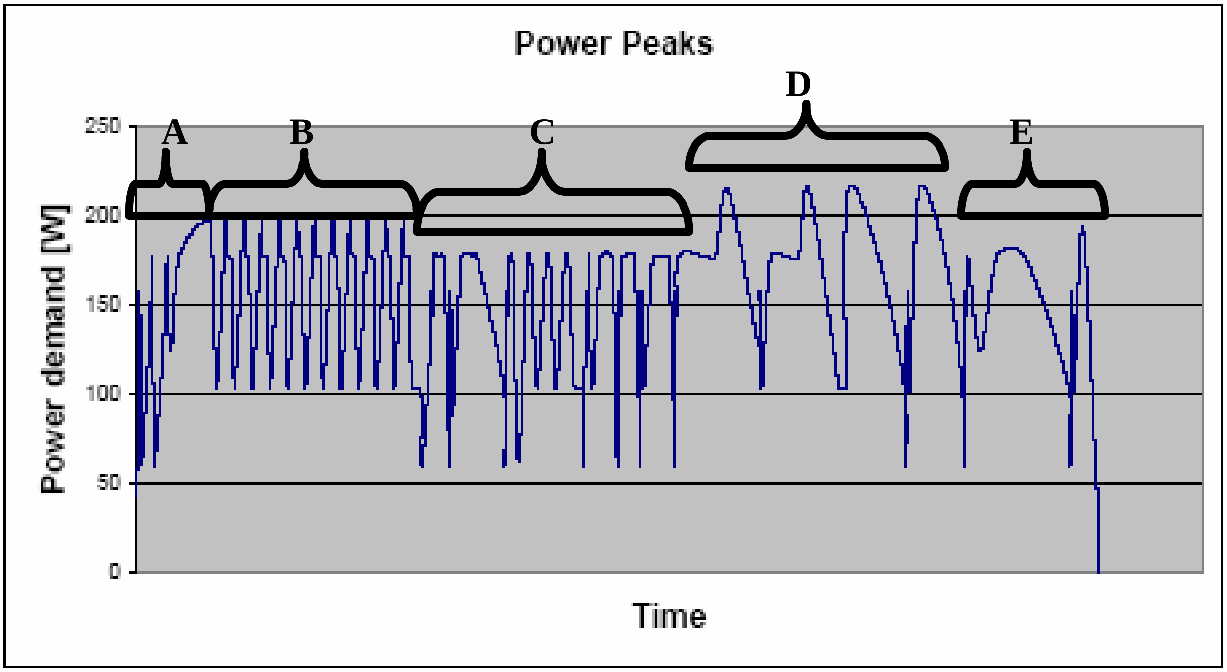


Figure 7.3 Peak power demand vs. Time

Label	Mission Operation
A	Start up and checkout
B	Conduit Deploy
C	Diode Box Ops
D	WFC Ops
E	Shutdown

Table 7.4 Key Mission Operations

The average power needed during the mission is given in Figure 7.5. The overall mission average power is given by the horizontal line as 145 W. This graph illustrates the power demand at each mission step. To determine these values, a list of components that will be drawing power at each step was made and the power added up for each stage to give the total power demand during that stage.

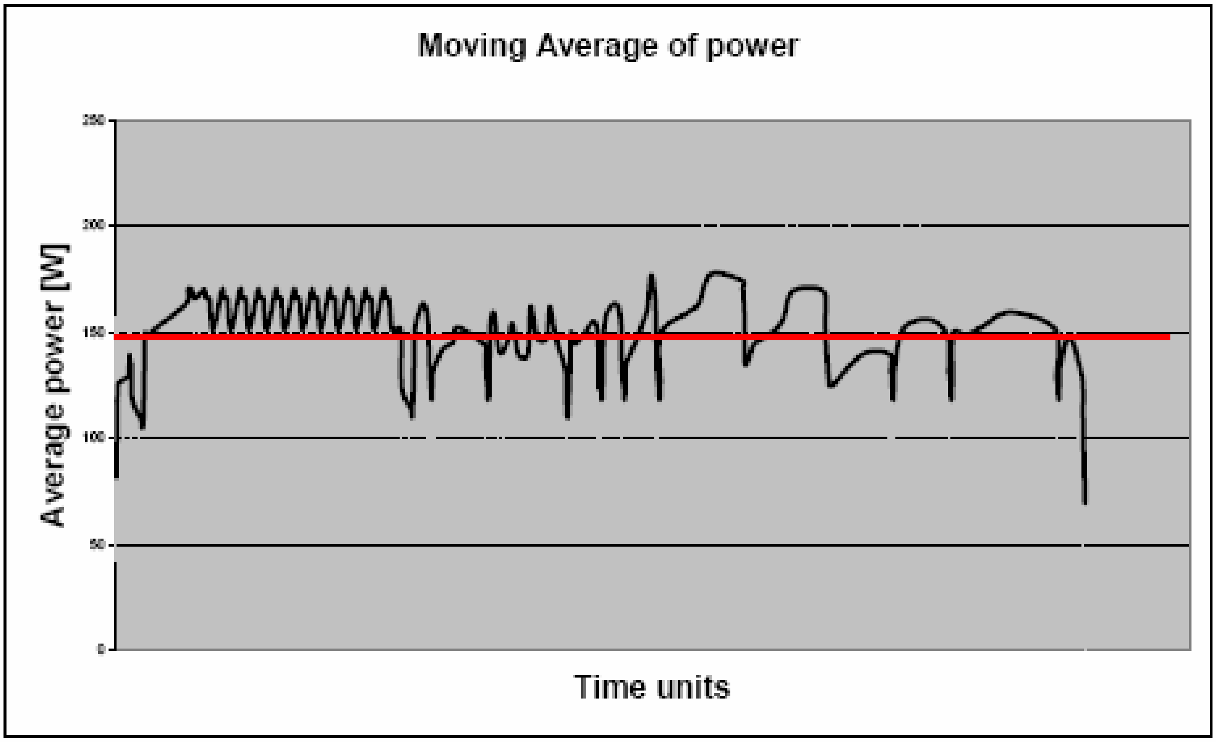


Figure 7.5 Average Power Demand

7.6 Design Tradeoffs

7.6.1 **Complex Multiple Redundancy vs.** Redundancy through Duplication

It was decided to go with a simple failure tolerant system whereby all electrical systems are duplicated in order to exclude the possibility of introducing unknown or poorly understood failure modes. Additionally, the duplication of primary systems as backups allows for simpler analysis, which increases confidence in the predicted performance of the system.

7.6.2 **Centralized Device control vs.** Distributed Device Control

A distributed architecture was chosen for devices such as motor electrical controllers, sensor controls, and TCS control units. This was selected in order to reduce the number of micro controllers producing heat in a centralized location (i.e. CPU) as well as to increase the reliability of the control system by spreading tasks across a large set of specialized micro-controllers. Additionally, the co-location of devices and their associated controllers reduces overall cabling. A distributed arrangement requires only one data bus running along the robot, rather than a host of cables to allow each sensor to communicate with centrally located micro-controllers.

8 Mechanical Subsystems

8.1 Mechanical Requirements

The mechanical requirements imposed on the design to meet customer's request are listed below:

1. The DR shall have closed loop accuracy of 0.16"
2. Linearly retract WF/PC II 7.5' in the plane of WF/PC II
3. The DR's tool actuator shall be capable of applying 50 ft-lb of torque
4. Resolution accuracy of Force/Moment at end effector shall be at least ±2lbs and at least ±2ft-lb
5. The DR should not weigh more than 500 KG.
6. The DR motion should have a resolution of 0.1 inch and 0.1 degree
7. The DR motion should be accurate to +/-1 degree and +/- 1 inch.
8. The DR must be able to stop a 1000lb mass from the maximum commanded tip velocity within 2 inches and 2 degrees

8.2 Physical Architecture

8.2.1 Overview of Mechanical Design

The dexterous robot will have a pair of arms, approximately 2.4 meters in length, each with 6 degrees of freedom. The main segments between shoulder and elbow and between the elbow and wrist will be 85 cm in length. One arm will project from each side of the DR body, allowing for a full range of motion on either side of the robot. Figure 8.1 depicts the overall look.

This configuration allows the DR to fully retract/install the wide field camera in a single continuous motion, without requiring re-positioning of the base. See Appendix 8.2 for a diagram demonstrating the maneuver used to determine arm sizing.

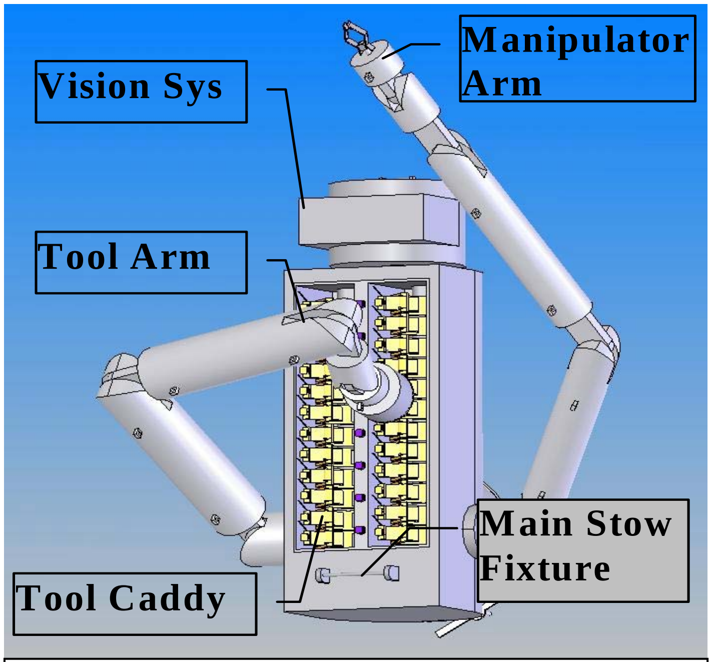


Figure 8.1 - DR Overview

The six degrees of freedom will be accomplished with a set of two one-axis joints in the 'shoulder', one joint at the 'elbow', and three more at the 'wrist'. One arm will have a tool grappling mechanism at its end, allowing it to pick up and drive the various tools used to service the HST. The other arm will have a general purpose manipulator. Details of both arms are in sections 8.3.1 and 8.3.2 respectively.

8.2.2 DR/GA Interface

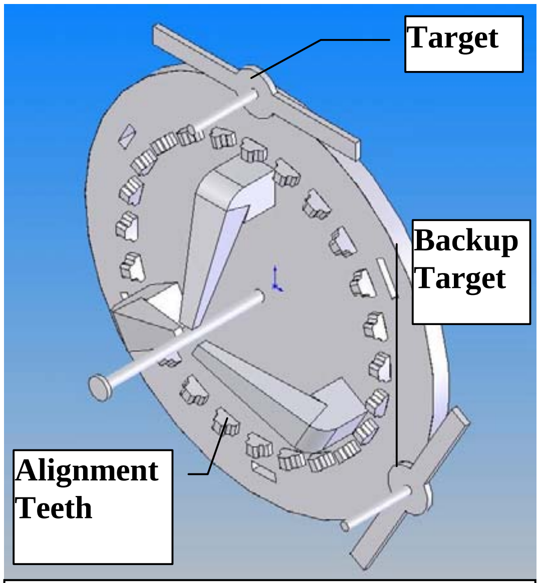


Figure 8.2 - DR Grapple Fixture

8.2.2.1 Grapple

The standard grapple fixture designed for the CanadArm 2 is used, as per requirements from the GA. The detailed specification of the grapple fixture is found in the ICD in Appendix 10. Modifications were made to the fixture including the elimination of the clamping feature that was originally designed to allow the grapple end effector to act as a shoulder. This kind of structural support is not necessary for the mission and thus the clamps will be discarded.

8.2.2.2 Load Transfer

The dominant interface force is 226 N and results from applying 50ft-lb of torque at the DR end effector. The dominant torque is 288 Nm and results from stopping a 1000lb mass. Note that these numbers include a factor of safety of 1.75. The interface will have the necessary stiffness and strength to withstand these loads. The details of these calculations can be found in Appendix 8.3.7.

The DR also imposes a cable load requirement on the GA, requiring 4 kg of cabling and associated accessories to be routed through the GA. This imposes structural requirements as well as adding to the force required from each of the motors. Using the estimation that a 100- wire bundle requires 5 Nm of torque (given by Ross Gillett), we have 5.2 Nm of torque needed for the 104 wires.

8.2.2.3 Stopping Distance

The stopping distance requirement imposed on us is to stop within 2 inches and 2 degrees from the maximum tip velocity when manipulating a 1000lb mass. The GA has a much longer structure and so we have agreed with them that they will take 80% of this stopping distance budget. This leaves 0.4 inches and 0.4 degrees for the DR, imposing a 288 Nm torque on the GA as discussed above in section 8.2.2.2 Load Transfer. The calculations is shown in Appendix 8.6.

8.2.2.4 Release

The GA will release the DR on the EM exterior for stowing. The mechanical force for mating and demating will be approximately 10-20 N, which the GA can perform.

8.2.3 DR/EM Interface

The DR will be stowed on the exterior of the EM during launch, proximity and capture operations. This location was chosen over an interior bay to simplify the removal and return of the DR. Exterior stowage eliminates the need for doors to be manipulated, simplifies the configuration of the DR and gives the GA a wider work area when grappling the DR. In order to secure the DR to the EM, clamps will be located on the EM and corresponding 'towel bars' on the DR. The GA will signal ground control when it has securely grappled the DR and the stowage clamps will be opened by ground control. Similarly, when the GA has returned the DR to the stow location, a signal will be sent and the clamps closed. The stowed configuation is shown in Figure 8.2.

Figure 8.2 Stowed Configuration

To stow the body and the arm securely, it has been decided that the joints need to be held securely to prevent pivoting. The boom structure is a thin carbon composite tube while the joints are titanium, having stow fixtures at the booms might cause fracture because the boom structure is thin. Nine stow fixtures will be needed to have a fixed body. Two at each wrist, one at each elbow, one at the head pivot and two for the body will be sufficient. Drawings detailing the stowed configuration can be found in Appendix 8.1.

The stow fixtures are to be released from a signal from the DR ground control team once the GA team has confirmed successful grapple and mating is done.

8.3 Mechanical System Implementation

8.3.1 Tool Arm

8.3.1.1 Interfaces

The tool arm will interface with all tools and manipulate the WF/PC2 and WFC3. As well, during stowage the arm will interface with the EM via three stow fixtures, one in the elbow and two in the wrist.

8.3.1.2 Requirements

The requirements of the tool arm come from the specified functional requirements:

1. The DR shall have closed loop accuracy of 0.16”
2. The DR motor gear ratio will be sufficiently great to allow minimum input to stack up to required resolution.
3. Linearly retract WF/PC II 7.5' in the plane of WF/PC II
4. The DR's tool actuator shall be capable of applying 50 ft-lb of torque
5. Resolution accuracy of Force/Moment at end effector shall be at least ±2lbs and at least ±2ft-lb
6. Stow away tools and parts not in use.
7. The DR motion should have a resolution of 0.1 inch and 0.1 degree
8. The DR motion should be accurate to +/-1 degree and +/- 1 inch.
9. The DR must be able to stop a 1000lb mass from the maximum commanded tip velocity within 2 inches and 2 degrees

8.3.1.3 Design and Performance

The tool arm will be able to achieve a tip speed of 0.04 m/s or 2°/s when maneuvering a 1000lb payload, and can move faster when moving smaller loads. Table 8.1 lists the DR tool arm characteristics and the details are found in Appendix 8.3.

Main Boom Lengths	0.85	m
Arm Diameter	0.15	m
Arm Offset from Body Center	0.45	m
Total Arm Length	2.6	m
Tip Translation Speed @ 1000 lbs	0.04	m/s
Tip Rotation Speed @ 1000 lbs	2	°/s
Mass (structure and motors only)	138.6	kg

Table 8.1 DR Tool Arm Characteristics

The material selected for the arm was carbon composite. The arm will have six degrees of freedom to be able to perform its tasks. Motors and gears performance for the tool arm is summarized in Appendix 8.3.7. The calculations were based on satisfying the requirements imposed on the tool arm.

Our design utilizes two gearboxes coupled together to provide the appropriate output speed and torque required. The motor is attached to a primary worm gearbox, which is inherently nonbackdrivable (the ramifications of this are discussed below). The output shaft of this box is then coupled to a secondary planetary gearbox, which completes speed reduction and is coupled to the output shaft. Since our gearboxes are non-backdrivable, we do not require actual brakes on the DR. This necessitates that our boxes have greater strength and ability to safely absorb the energy of a stopping maneuver. We believe that with sufficient design effort this problem can be adequately solved without developing any new technologies.

The tool arm end effector is shown below in Figure 8.3

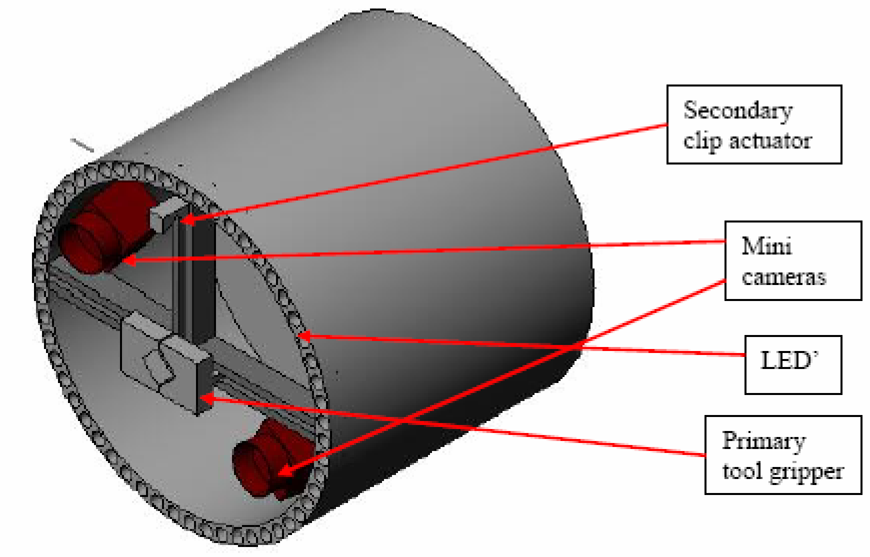


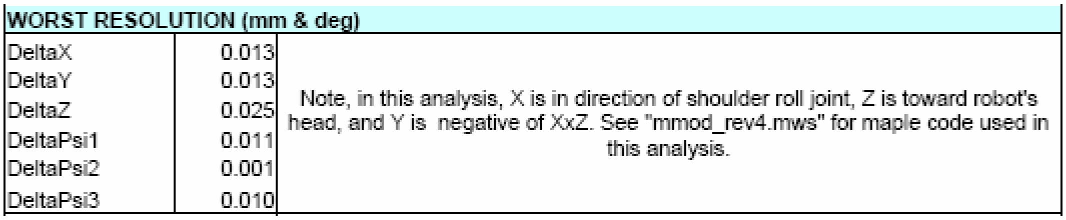
Figure 8.3 – Tool arm end effector

The tool end effector will consist primarily of a gripper mechanism and two mini cameras. The gripper design includes a primary tool gripper that will actively hold any tool while it is being manipulated. This is where the common tool interface is grappled. As well, there is a secondary actuator designed to open the multi-purpose clip tool.

With this gripper in the open position, the primary gripper is able to grab the clip tool such that the secondary actuator is in position to open the tool. By activating only the secondary grip, the clip tool can be opened and closed while still held securely by the end effector.

The mini cameras are oriented 180° from each other, tilted inwards. In this configuration, the cameras can view worksite immediately in front of the end effector. A ring of white LED's, mounted in the outer shroud of the end effector, will illuminate the workspace.

The sensitivity of the end effector position to resolver error was analyzed in various arm configurations to determine the expected resolution of the end effector. Calculations are based on the resolvers selected, which have a manufacturer quoted error of ±4 arc-minutes. A MATLAB code which computes the end effector position as a function of joint angles and boom lengths was written and used to determine the error in tip position introduced by varying commanded inputs by the maximum error of 4 arc-minutes. Table 8.2 below outlines the results.

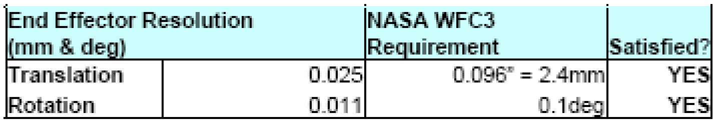


WORST RESOLUTION (mm & deg)		
DeltaX	0.013	Note, in this analysis, X is in direction of shoulder roll joint, Z is toward robot's head, and Y is negative of XxZ. See "mmod_rev4.mws" for maple code used in this analysis.
DeltaY	0.013	
DeltaZ	0.025	
DeltaPsi1	0.011	
DeltaPsi2	0.001	
DeltaPsi3	0.010	

Table 8.2 End Effector Resolutions

See Appendix 8.6 for a complete tabulation of configurations considered, the resultant errors, and the maple code used.

This analysis was not performed to include all possible symmetries, so the worst case for translation (ΔX, ΔY, ΔZ) and rotation ($\Delta\varphi_1$, $\Delta\varphi_2$, $\Delta\varphi_3$) are assumed to be the largest of each set, as shown in Table 8.3.



End Effector Resolution (mm & deg)		NASA WFC3 Requirement	Satisfied?
Translation	0.025	0.096" = 2.4mm	YES
Rotation	0.011	0.1deg	YES

Table 8.3 End Effector Resolution Requirements Met

Overall, we expect the DR to have an end effector resolution better than the cited values, since these are derived from analysis of cumulative worst-case errors in resolver data. However, we do not have a quantitative result for more optimistic performance figures.

8.3.2 Manipulator Arm

8.3.2.1 Interfaces

The manipulator arm will be required to open bay doors and hold objects when the tool needs to clip the conduit or ground strap. The EM will also interface during stowage. Three stow fixtures will be located on the arm, one in the elbow and two in the wrist

8.3.2.2 Requirements

1. The DR shall have closed loop accuracy of 0.16”
2. The DR motor gear ratio will be sufficiently great to allow minimum input to stack up to required resolution.
3. The DR motion should have a resolution of 0.1 inch and 0.1 degree
4. The DR motion should be accurate to +/-1 degree and +/- 1 inch.
5. The DR must be able to stop a 1000lb mass from the maximum commanded tip velocity within 2 inches and 2 degrees

8.3.2.3 Design

The DR general manipulator arm characteristics are listed in Table 8.4. Please refer to Appendix 8.3 for the detailed calculations

Main Boom Lengths	0.85	m
Arm Diameter	0.15	m
Arm Offset from Body Center	0.45	m
Total Arm Length	2.2	m
Tip Translation Speed @ 200 lbs	0.1	m/s
Tip Rotation Speed @ 200 lbs	3	°/s
Mass (structure and motors only)	118.6	kg

Table 8.4 DR General Manipulator Arm Characteristics

As with the tool arm, our design utilizes two gearboxes coupled together to provide the appropriate output speed and torque required. The motor is attached to a primary worm gearbox, which is inherently non-backdrivable (to eliminate the need for brakes). The output shaft of this box is then coupled to a secondary planetary gearbox which completes speed reduction and is coupled to the output shaft. Motor and gearbox details are found in Appendix 8.3.7.

8.3.3 Body

The body will be where all other parts interconnect. The shoulders for the arms, the head for the LCS, the tool caddy and the GA power/data interface will all be in the body. The EM will also interface when stowing or releasing the body.

8.3.4 Tools

8.3.4.1 Interfaces

The tools carried on board are needed by the DR to perform certain tasks required by the customer. These tasks require that tools can interface with:

1. The tool end effector
2. The blind mate connector (7/16” hex interface)
3. The A-Latch (7/16” ex interface)
4. The bolt holding the ground strap in place
5. The J9 and 1553 terminator plugs.
6. P6A/P8A connectors
7. Ground strap
8. The conduit, to harness to the handrail

The end effector interface will be common to all tools to simplify the design. The tools will have the end shown in Figure 8.4 for gripping, which matches the end effector design discussed later

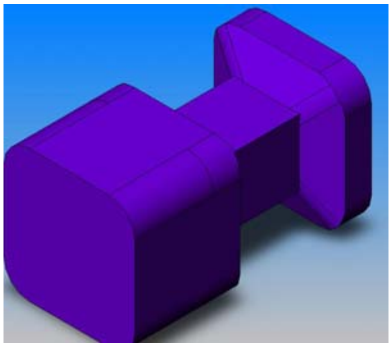


Figure 8.4 Tool/EE interface

8.3.4.2 Tool Requirements

- The 7/16” tool will be 2” long to reach the blind mate connector.
- The 7/16” tool will have a 7/16” hexagonal male interface.
- The 7/16” tool will interface with the tool end effector on the DR.
- The 7/16” tool will be able to turn the blind mate connector 5 turns.
- The 7/16” tool will be able to turn the A-latch 22.5 turns.
- The ground strap release tool will have a 7/16” hexagonal female interface.
- The ground strap release tool will have end dimension less than or equal to 1.25” in diameter. (in order to clear the surrounding structure when turning)
- The ground strap release tool will interface with the tool end effector on the DR.
- The RSU connector tool will grapple the terminator plugs.
- The RSU connector tool will securely hold the terminator plug while moving it to new location.
- The RSU connector tool will interface with the tool end effector on the DR.
- The diode box connector tool will grapple the P6A/P8A connector.
- The diode box connector tool will be able to rotate and unscrew the P6A/P8A connector
- The diode box connector tool will securely hold the P6A/P8A connector while moving it to new location.
- The diode box connector tool will interface with the tool end effector on the DR.
- The harnessing tool shall to fix the conduit in place securely
- The ground strap stowing tool will need to stow the ground strap temporarily.
- The clip tool shall have a target for the DR end effector to locate.

8.3.4.3 Design and Performance Specifications

Un-powered tools were chosen in order to eliminate the need for an electrical interface between the end effector and the tools. Since no connectors need to be mated, the accuracy involved in the tool capture procedure is reduced. Furthermore, the tools themselves become much less massive, as no motors, electronics or cables are housed in them.

The wrist roll joint will provide the necessary torques to the tools, however its range of motion is limited to ±180° due to the cables. In order to accomplish the multiple turns needed to operate the blind mate connector and A-latch, the 7/16” hex tool will be ratchet style, allowing the wrist to apply multiple turns of 360°, without removing the tool.

8.3.4.3.1 7/16” Hex Tool

The 7/16” hex tool is used for the blind mate connector and the A-latch. Figure 8.5 below shows the basic tool design. A ratchet style tool will be used as discussed above. Both a right hand and left hand tool will be required in order to enable clockwise and counter-clockwise torques.

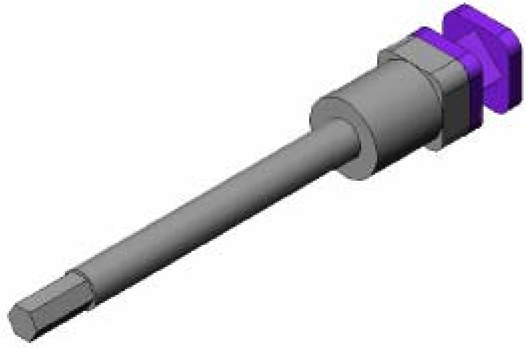


Figure 8.5 - 7/16” Hex Tool

8.3.4.3.2 Ground Strap Tool

The ground strap tool is used to torque the bolt holding the ground strap in place. The design is shown in Figure 8.6. A circular end shape was chosen to maximize the area, while remaining 1.25” in diameter. The 7/16” female connector was filleted at the opening to facilitate its placement on the ground strap bolt. Also, the tool uses the common interface identified above.

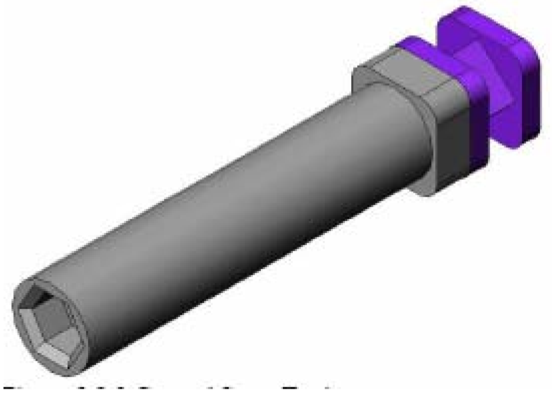


Figure 8.6 Ground Strap Tool

8.3.4.3.3 RSU Tool

The RSU tool manipulates the J9 and 1553 terminator plugs.

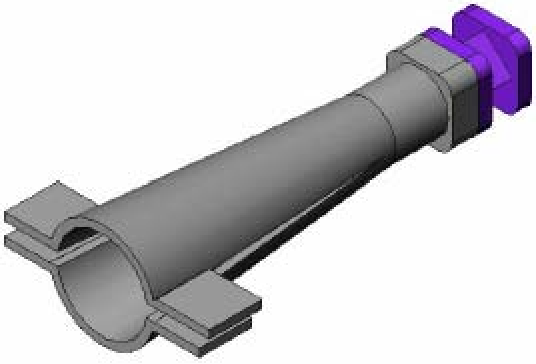


Figure 8.7 RSU Tool

8.3.4.3.4 Right Angle Tool

Figure 8.8 shows the right angle tool design. The shape was chosen to encompass the terminator plug, holding it with pressure during movement. The tool uses the connector wing tabs as a means of applying the torque needed to unscrew the connector. Again, the tool uses the common interface.

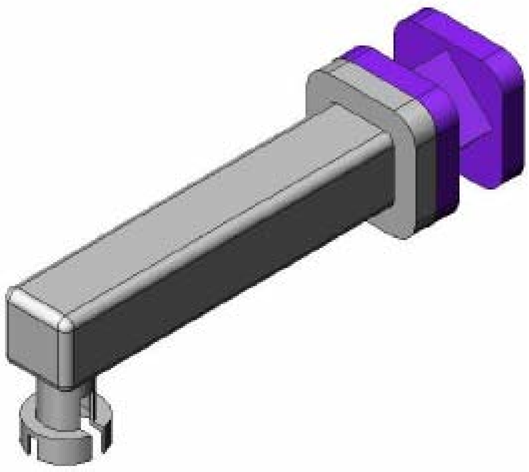


Figure 8.8 Right Angle Tool

8.3.4.3.5 Multi Purpose Clip Tool

The general-purpose clip has been redesigned to account for the different clipping envelopes for gripping the ground strap and the conduit. The new clip has a circular end that will allow the gripping action to be more flexible and versatile. When clipping the conduit to the handrail, the circular end is sized such that it closes to rigidly grip them in place. As for the ground strap, the redesigned clip is allowed to close beyond the horizontal pivot line so that it can enclose smaller clipping envelopes for gripping the ground strap to the handrail.

One hand of the clip will have the typical (tool)-(end effector) interface for the end effector to grip. This is seen in Figure 8.9 below, labeled Tool/EE interface. The other hand of the clip will have a circular ‘towel bar’ that will allow our secondary gripper to open the clip when it strokes the two clip hands together. The reason to the towel grip design is because the stroke motion will follow a radius of curvature, and so the towel bar design can interface with the end effector while allowing the radius of curvature to be followed without inducing stresses on the end effector or the clip.

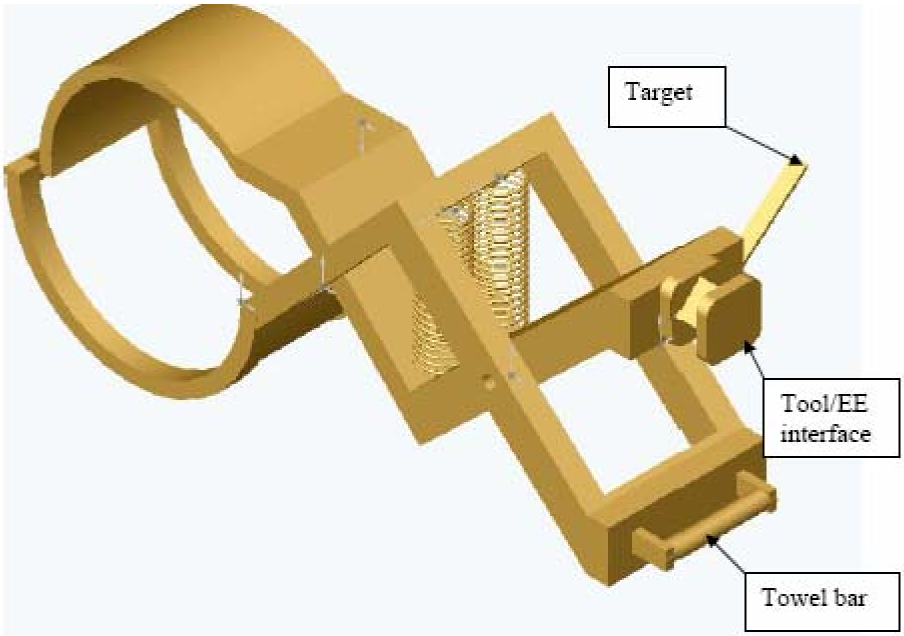


Figure 8.9 Multi Purpose Clip Tool

The springs in the clip will always be in compression and so will always apply a force to close the clip in place. The springs have to be designed such that when the clip is closed all the way in the tightest position, the springs are still in compression. An appropriate force that the clamp should withstand in the most closed position while the springs are in compression is about 10 N. In the clip design, the distance between the pivot and the springs is a quarter of the distance from the pivot to the clip end. This means that, when balancing moments, the springs should provide a force of 4 x 1 = 4 lb-ft in tension. To have this tension force in a relatively small tensile displacement for the springs, such as 0.5 inch, we need an effective spring constant to be:

$k_{eff} = f/x = 4/0.5 = 8$ lb-ft/inch. = 1400 N/m.

Two springs, each with the above spring constant, are included for redundancy. The spring will be directly welded to the titanium clip. The clip should be made from titanium to have them as light as possible, because we will have 24 of them as seen below:

Harnesses needed	**Number needed**
Conduit	12
Diodebox connectors	8
Ground strap	1
Conservative addition	3
Total	**24**

Table 8.5 Clip tools

8.3.5 Tool Caddy

The tool caddy consists of 2 rails, holding the multipurpose clips and a center console, designed to house the remaining tools. Pressure sensors will be located at the base of each tool inset, to ensure proper removal and storage. The tool interfaces protrude from the body of the DR to facilitate capture by the tool end effector. A diagram of the tool caddy, with the tools loaded can be found in Appendix 8.1

8.3.6 Thermal

8.3.6.1 Requirements

The thermal control system (TCS) needs to keep the DR in the survival range at all times when off and in the operational temperatures at all times when it is on. These temperature ranges are given in Table 8.6.

	Operational mode (°C)	Survival mode (°C)
Power/Fuses	-10 to 20	-15 to 35
C&DH	-20 to 70	-40 to 85
Electronic components	-20 to 65	-50 to 70
Joint actuators	-20 to 70	-65 to 80
End effector actuators	-20 to 70	-65 to 80
Camera/sensors	-20 to 65	-50 to 70
Structure	-15 to 65	-45 to 65

Table 8.6 Operational and Survival Temperatures

This imposes that the EM provide power to the DR thermal system when the DR is stowed. This will occur through dedicated 'keep alive' connectors on the DR.

8.3.6.2 Design

The TCS 'isolates' the DR from space by using a MLI blanket. The MIL blanket is painted white on the outside to minimize the heat absorption when the sunrays are in direct exposure. The MIL blanket results in a reduced radiation heat loss from the DR body, making the net power requirement for all of the heaters 20 W. The detailed calculations have been included in Appendix 8.5.

To have an approximate duty ratio of 70 %, we design the heaters to have a maximum capacity of 30 W. When requiring a 20 W average power, the duty ratio will be 20/30 = 67 %. This allows moderate power consumption when the heaters are on, and also leaves room to increase our power need by increasing our duty ratio. Increasing the duty ratio may be required because of degradation of the heaters or unexpected cold cases & heat loss. A total of 18 heaters are needed. This comes from needing 14 heaters to be evenly distributed among the joints, 7 heaters on each arm, and 4 on the body. Each heater will be approximately dissipate 1.7 W when on.

8.4 Fault Tolerance

The fault tolerance requirement is to be single fault tolerant. While we have done so in most subsystems, it is unfeasible to fully meet the requirement mechanically. Adding an extra tool arm or an extra body would have been analogous to carrying an extra engine in a car to make the car single fault tolerant. Our calculations have a high safety factor of 1.75, and we believe that well manufactured gearboxes and motors should eliminate the need to double the number of gearboxes and motors. The booms can be made sufficiently strong to prevent buckling or any mechanical failure during the mission

8.5 Mass Budget

A detailed mass budget for the DR may be found in Appendix 8.7. For those components for which the mass was difficult to estimate, a number of assumptions had to be made. These are outlined and justified below.

8.5.1 Cabling and Connector Mass

These figures were generated from a previous analysis of the cabling mass for the DR, and are based upon expected motor and other power system loads. These estimates could be refined further, given our updated mass budget and our improved fully three-dimensional performance analysis in an iterative procedure. However, given the time constraints on this project, it was felt that our current estimates are sufficient for a design in the PDR stage.

8.5.2 Boom Structure/Fairings

The links between the DR joints were assumed to be perfect hollow tubes with a circular cross section. An appropriate thickness was calculated based on stiffness calculations with predicted load cases. The mass of the booms was simply calculated from the density of the chosen material (carbon composite) and material volume of the boom. These calculations are detailed in Appendix 8.3.

8.5.3 Joint Structure

Without a detailed design, the mass of the joint structure was largely an educated guess. We selected a mass that would be comparable, in that such a mass would be likely be able to accommodate the load cases. A large margin ratio (20%) was also used to further buffer our estimate in the event that in reality we may require a larger joint. It was felt that because we had neither the time nor the resources to conduct a full fledged joint design, and conclusive joint mass was extremely difficult to produce.

8.5.4 Resolver Mass

The mass of the resolver could not be found on the manufacturer's website, so a comparable resolver of similar proportions (standard size 11) was used for the mass number [5].

8.5.5 Tool Mass

We estimated our tool mass based on their volume (calculated from the solid models) and the density of the selected material (titanium) to gain a first order approximation of the tool mass. Given the preliminary nature of our design, this was deemed to be sufficient.

8.5.6 Motor Electronics

This was estimated by searching for a terrestrial version of the electronics required to control the motors and searching for their mass. Masses of circuit boards of seemingly similar capability varied largely any where from 25g to 200g, therefore a middle estimate of 100g was chosen. The overall contribution of the electronic components is small and therefore a rough estimate such as this one can be made, given a large margin of 20%.

8.5.7 Thermal Protection System

We found it extremely difficult to locate masses for commonly used solar blanket materials such as aluminized mylar or beta cloth. Therefore, we selected a more terrestrial material; a heavy camping tarp which was highly likely to have a larger mass per m^2 than the solar blanket materials. We applied five layers of our thermal blanket to the outer surface of the DR body and arms to protect its internal components. Mass was calculated accordingly using the figures for the terrestrial tarp material [13].

8.5.8 A Final Note

Any components of our system located in the GA or EM were not included in our mass budget. These items (mostly cabling the GA and computers in the EM) are relatively small and will be given a more thorough examination in a more detailed design. That said, however, the cabling mass present in the GA due to DR needs has been communicated to the GA team for inclusion into their mass budget.

8.6 Design Tradeoffs

8.6.1 Joints

8.6.1.1 **Varying Joints** vs. Standardized

Having all joints the same size was considered but rejected as it is not a mission requirement to be able to change out a joint, nor is it realistic for the robot to achieve that level of self-reparability. Since the driving reason for uniform joint size would be to make spares interchangeable, there is no reason for the DR joints to be uniform in size. Diminishing joint strengths were selected as this allows for an overall reduction of mass along the arm, and thus reduces the loads on the joints and booms

8.6.1.2 **Titanium** vs. Aluminum

Titanium has a CTE much closer to Steel than Aluminum, and so a joint housing made from titanium will have much lower thermal stresses between the housing and steel bearings/shafts/gears within the motor. By keeping thermal stresses small it is expected that the friction to drive the joints will be kept at a reasonable level, well within the loads specified for the motors.

Material:	CTE [2]:
Steel	12.6 µm/m-°C
Aluminum	24 µm/m-°C
Titanium	8.7 µm/m-°C

8.6.1.3 **Single Axis Motors** vs. Tendons

Since precision (stiffness and controllability) is the driving constraint for the arm, it is necessary to have the both precise and simple to control actuators. A tendon driven arm will be far too flexible for the DR application, and for this reason, a tendon system is ruled impractical.

8.6.2 Booms

8.6.2.1 **Same Arm Sizes** vs. Differing Sizes

While it is possible to operate such that one arm performs the more structurally demanding tasks while another does only fine manipulation, doing so increases mission risk in the event of one arm experiencing a failure. By having two arms with identical performance envelopes, many operations can be performed by either arm.

8.6.2.2 **Straight** vs. Tapering

Consistent size allows for simpler manufacturing and analysis, as well as providing consistent paths for routing cables etc. By maintaining a maximum diameter along the length of the arm, the second moment of area, and thus stiffness, is maximized.

8.6.2.3 **Carbon** vs. Aluminum

The loads on the booms of each arm can be easily withstood by all of the suggested space materials, and so we make the choice of carbon based on secondary criteria. Carbon fiber composites have excellent mechanical properties, including high stiffness, low density, and extremely low coefficients of thermal expansion. A low CTE is desirable in reducing end effector positioning error due to thermal drift. While composite structures are harder to manufacture than metals, the demands of the DR do not require any exotic structural design outside of the current state of the art.

9 Conclusions

This document has presented the operations, systems, controls, electrical, and mechanical design of a Dexterous Robot that meets the requirements set forth in MDR's request for proposal. The robot performs at the required precision needed to perform the difficult task of WFC insertion, and has the mobility and dexterity needed to complete all the servicing tasks. It is small enough and light enough to be transported economically to the HST, and can be powered and controlled effectively.

9.1 Possible Improvements

The obvious area for improvement in this design is the application of more time and resources to the analysis of the various systems, so that the many approximations can be improved, and more exact performance parameters could be determined.

With more time and specialized engineering experience, the details of the design would be optimized and improved to a far greater extent than was possible in the time allocated for this project. In particular, nobody on our team had a substantial electrical engineering background, which made the electrical, computer, and software portions of the design much more challenging.

We found that the main constraint on the design was the distinction between Grapple Arm and Dexterous Robot, which created the need for a more complicated DR than could do the job if the two systems were operationally and physically integrated into one design.

More work should be done in our overall tracking and proving of requirements. Since the DR mission is of such a complex nature, there is an enormous number of requirements which are interconnected.

Our present methods also limit the design, as we were unable to perform proper mechanical analysis of the joints which would have allowed us to better assess performance. Also, we did not have the means to simulate all of the operations (both manpower and computer power) which would validate our Functional Flow, or perhaps allow us to identify better operations concepts.

The most limiting specifications were those requiring accuracy and precision at the end effectors in order to achieve alignment of the WFC3 rails. We proposed the shortening of one WFC rail to allow us to get the process started on one side first, rather than having to simultaneously align two rails with tight tolerances.

What specifications are most limiting or where could they reasonably be modified or best clarified to simplify or improve the design?

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Appendix 1 Functional Flow

Appendix 1.1 Functional Flow Listing

Chronological sequence is in the downward direction as indicated by the numbering of the items. The hierarchy of the functional flow is represented by nested numbering and by the indentation of the lines. Please note that this information is presented textually instead of in block form. We decided to leave it like this because it was easier to maintain and update the functional flow in text, and producing blocks from this large a set of steps would take a large number of hours while adding little actual content to this section.

Appendix 1.1.1. Launch Phase Functional Flow

1. Launch
    1.1. Pre-launch system check
        1.1.1 DR stowed in fixtures on EM
        1.1.2 Keep alive power connection activated
    1.2. DR enter keep-alive mode
        1.2.1. Shut down Actuators
        1.2.2. Shut down Sensors
        1.2.3. Shut down Communications
        1.2.4. Shut down Processors
        1.2.5. Activate Thermal Control Loop

Appendix 1.1.2. Pursuit Phase Functional Flow

2. Pursuit
    The DR is in keep-alive mode during this phase

Appendix 1.1.3. Proximity Phase Functional Flow

3. Proximity Operations
    The DR is in keep-alive mode during this phase

Appendix 1.1.4. Capture Phase Functional Flow

4. Capture
    The DR is in keep-alive mode during this phase

Appendix 1.1.5. Approach Phase Functional Flow

5. Servicing
    5.1. Deploy DR
        5.1.1. Activate GA
        5.1.2. Move to DR stow site
        5.1.4. Grapple DR
            5.1.4.1 Move arm until GF inside capture envelope
            5.1.4.2 Grapple manipulator to DR GF
            5.1.4.3 Verify physical connection was made
            5.1.4.4 Rigidize connection and engage power/data connectors
            5.1.4.5. Signal successful connection

- 5.1.5. DR Wake up & Checkout
  - 5.1.5.1 DR GC shuts off keep-alive system
  - 5.1.5.2. DR GC powers up DR via main connection across GA
    - 5.1.5.2.1 DR Switches from Keep-Alive to Normal operating mode
    - 5.1.5.2.2 DR powers up processors.
    - 5.1.5.2.2 GC and DR establish communications
    - 5.1.5.2.2 Guidance online
    - 5.1.5.2.3 Power up sensors
    - 5.1.5.2.4 Power up actuators
  - 5.1.5.2. Perform static self test (while stowed)
    - 5.1.5.2.1 Perform sensor static self test
    - 5.1.5.2.2 Perform arm static self test
    - 5.1.5.2.3 Perform joint static self test
    - 5.1.5.2.4 Perform manipulator static self test
  - 5.1.5.3. Release Stow Fixtures
    - 5.1.5.3.1 DR GC trigger stow fixture release
    - 5.1.5.3.2 Verify latches released (sensors and video feed)
    - 5.1.5.2.3 GA moves DR clear of stow fixtures.
  - 5.1.5.4. Move GA/DR to home position
  - 5.1.5.5. Perform DR dynamic self test (motion and performance)
  - 5.1.5.5.1 Perform joint dynamic self test
  - 5.1.5.5.2 Perform manipulator dynamic self test
- 5.1.6. DR standby
- 5.1.6.1 DR switches from Normal to Sleep Mode
  - 5.1.6.1.1. Moves arms to standby configuration at safe distance from HST
  - 5.1.6.1.2. Power down motors
  - 5.1.6.1.3 Power down sensors (other than thermal and collision)
- 5.1.6.2 Await command signal from ground control

5.2. Power Augmentation

- 5.2.1. Conduit Deploy
  - 5.2.1.1 Activate GA
  - 5.2.1.2 Activate DR
    - 5.2.1.2.1 GC commands DR to switch from Sleep Mode to Normal Mode
    - 5.2.1.2.2 Power up sensors
    - 5.2.1.2.3 Power up actuators
    - 5.2.1.2.4 DR Self Check
  - 5.2.1.3 Move GA/DR to conduit stow site
  - 5.2.1.4 Remove conduit stowage fixtures
  - 5.2.1.5 Grapple conduit with manipulator arm.
  - 5.2.1.6 Repeat installation procedure for each attachment point (as required)
    - 5.2.1.6.1 Move GA/DR to conduit attachment work site
    - 5.2.1.6.2 Acquire a clip tool from tool caddy
    - 5.2.1.6.3 Attach conduit to rail using a clip tool
  - 5.2.1.7 Stow loose conduit cables for next tasks
  - 5.2.1.8 DR standby
  - 5.2.1.9 GA standby
- 5.2.2. Diode Box -V2

- 5.2.2.1. Attach connector interface plate
    - 5.2.2.1.1 Activate GA
    - 5.2.2.1.2 Activate DR
    - 5.2.2.1.3 Move GA/DR to diode box opening fixture stow site
    - 5.2.2.1.4 Grapple -V2 diode opening fixtures
    - 5.2.2.1.5 Open -V2 diode box
    - 5.2.2.1.6 Stow opening fixtures
    - 5.2.2.1.7 Move GA/DR to conduit connector plate stow site
    - 5.2.2.1.8 Remove connector stowage fixtures
    - 5.2.2.1.9 Grapple connector
    - 5.2.2.1.10 Install conduit attachment point to DBA II
    - 5.2.2.1.11 Stow any remaining fixtures
    - 5.2.2.1.12 DR standby
    - 5.2.2.1.13 GA standby
- 5.2.2.2. Attach cabling harnesses to HST handrails
    - 5.2.2.2.1 Activate GA
    - 5.2.2.2.2 Activate DR
    - 5.2.2.2.3 Attach Cable 4 points (repeated)
    - 5.2.2.2.3.1 Move GA/DR to harness attachment work site
    - 5.2.2.2.3.2 Acquire a clip tool from tool caddy
    - 5.2.2.2.3.3 Attach harness to rail using a clip tool
    - 5.2.2.2.4 Stow any remaining fixtures
    - 5.2.2.2.5 DR standby
    - 5.2.2.2.6 GA standby
- 5.2.2.3. Complete diode box power connection
    - 5.2.2.3.1 Activate GA
    - 5.2.2.3.2 Activate DR
    - 5.2.2.3.4 Grapple right angle tool from caddy
    - 5.2.2.3.5 Move Tool Arm End Effector into position inside diode box
    - 5.2.2.3.6 Remove P8A connector from diode box
    - 5.2.2.3.7 Connect P8A connector to interface plate
    - 5.2.2.3.8 Repeat P8A ops for P6A connector
    - 5.2.2.3.9 Stow right angle tool in caddy
    - 5.2.2.3.10 Stow any remaining fixtures
    - 5.2.2.3.11 Close diode box -V2
    - 5.2.2.3.12 DR standby
    - 5.2.2.3.13 GA standby

5.2.3. Diode Box +V2

- 5.2.3.1. Attach connector interface plate
    - 5.2.3.1.1 Activate GA
    - 5.2.3.1.2 Activate DR
    - 5.2.3.1.3 Move GA/DR to diode box opening fixture stow site
    - 5.2.3.1.4 Grapple +V2 diode opening fixtures
    - 5.2.3.1.5 Open +V2 diode box
    - 5.2.3.1.6 Stow opening fixtures
    - 5.2.3.1.7 Move GA/DR to conduit connector plate stow site
    - 5.2.3.1.8 Remove connector stowage fixtures
    - 5.2.3.1.9 Grapple connector

        - 5.2.3.1.10 Install conduit attachment point to DBA II
        - 5.2.3.1.11 Stow any remaining fixtures
        - 5.2.3.1.12 DR standby
        - 5.2.3.1.13 GA standby
    - 5.2.3.2. Attach cabling harnesses to HST handrails
        - 5.2.3.2.1 Activate GA
        - 5.2.3.2.2 Activate DR
        - 5.2.3.2.3 Attach Cable 4 points (repeated)
            - 5.2.3.2.3.1 Move GA/DR to harness attachment work site
            - 5.2.3.2.3.2 Acquire a clip tool from tool caddy
            - 5.2.3.2.3.3 Attach harness to rail using a clip tool
        - 5.2.3.2.4 Stow any remaining fixtures
        - 5.2.3.2.5 DR standby
        - 5.2.3.2.6 GA standby
    - 5.2.3.3. Complete diode box power connection
        - 5.2.3.3.1 Activate GA
        - 5.2.3.3.2 Activate DR
        - 5.2.3.3.4 Grapple right angle tool from caddy
        - 5.2.3.3.5 Move Tool Arm End Effector into position inside diode box
        - 5.2.3.3.6 Remove P8A connector from diode box
        - 5.2.3.3.7 Connect P8A connector to interface plate
        - 5.2.3.3.8 Repeat P8A ops for P6A connector
        - 5.2.3.3.9 Stow right angle tool in caddy
        - 5.2.3.3.10 Stow any remaining fixtures
        - 5.2.3.3.11 Close diode box +V2
        - 5.2.3.3.12 DR standby
        - 5.2.3.3.13 GA standby

- 5.3. WFC3 Operations
    - 5.3.1. Remove Ground Strap
        - 5.3.1.1. Activate GA
        - 5.3.1.2. Activate DR
        - 5.3.1.3. Move GA/DR to Work Site at WF/PC2
        - 5.3.1.4. Release Ground Strap
            - 5.3.1.4.1 Grab hold of GS with manipulator hand
            - 5.3.1.4.2 Acquire ground strap tool from caddy
            - 5.3.1.4.3 Use ground strap tool and release ground strap by loosening bolt
            - 5.3.1.4.4 Put away ground strap tool
        - 5.3.1.5 Temporarily Stow Ground Strap
            - 5.3.1.5.1 Use Manipulator arm to position ground strap over rail
            - 5.3.1.5.2 Acquire a clip tool from tool caddy
            - 5.3.1.5.3 Attach GS to rail using clip tool
            - 5.3.1.5.4 Release GS from manipulator arm
        - 5.3.1.8. DR standby
        - 5.3.1.9. GA standby
    - 5.3.2. Remove and Temporarily Stow WF/PC2
        - 5.3.2.1. Activate GA
        - 5.3.2.2. Activate DR

        - 5.3.2.3. Move GA/DR to Work Site at WF/PC2
        - 5.3.2.4. Install WF/PC2 interface plate
            - 5.3.2.4.1 Acquire interface plate
            - 5.3.2.4.2 Position interface plate with guide studs
            - 5.3.2.4.3 Place interface plate
        - 5.3.2.5. Release blind mate connector on WF/PC2
            - 5.3.2.5.1 Acquire 7/16”counterclockwise ratchet tool from tool caddy
            - 5.3.2.5.2 Position tool for driving blind mate connector
            - 5.3.2.5.3 Drive tool until connector is released (5 turns)
        - 5.3.2.6. Release A-Latch
            - 5.3.2.6.1 Position 7/16” counterclockwise ratchet tool for driving A-Latch
            - 5.3.1.6.2 Drive tool until A-Latch is released (22.5 Turns)
            - 5.3.1.6.3 Stow 7/16” counterclockwise ratchet tool in caddy
        - 5.3.2.7. Grapple Interface Plate with Tool Arm
        - 5.3.2.8. Retract WF/PC2 7.5' from HST
            - 5.3.2.6.1 DR withdraw WF/PC2 from bay on HST
            - 5.3.2.6.2 DR maneuver WF/PC2 to safe distance from HST
        - 5.3.2.9. Stow WF/PC2 at temporary stow position
            - 5.3.2.7.1 DR/GA move to DR stow site while carrying WF/PC2
            - 5.3.2.7.2 Insert WF/PC2 in temporary stow fixture
            - 5.3.2.7.3 Release WF/PC2
        - 5.3.2.10. DR standby
        - 5.3.2.11. GA standby
    - 5.3.3. WFC3 installation
        - 5.3.3.1. Activate GA
        - 5.3.3.2. Activate DR
        - 5.3.3.3. Retract thermal/contaminant cover
        - 5.3.3.4. Stow cover on EM
        - 5.3.3.5. Release ground strap from EM (As above, with 7/16” clockwise ratchet tool)
        - 5.3.3.6. Release A-latch (As above, with 7/16” clockwise ratchet tool)
        - 5.3.3.7. Grapple WFC3 with Tool Arm (As above)
        - 5.3.3.8. Retract WFC3 7.5' from EM (As above)
        - 5.3.3.9. DR/GA move to HST WFC site while carrying WFC3
        - 5.3.3.10. DR Stabilize WFC3
        - 5.3.3.11. Position WFC3 for insertion into HST
            - 5.3.3.11.1 Align longer rail using video from manipulator arm.
            - 5.3.3.11.2 Engage longer rail (insert a bit)
            - 5.3.3.11.3 Align shorter rail using video from manipulator arm.
            - 5.3.3.11.4 Engage shorter rail (insert a bit)
        - 5.3.3.12. Push WFC3 7.5' into position in HST
        - 5.3.3.13. Drive A-latch into position
            - 5.3.3.13.1 Acquire 7/16” counterclockwise ratchet tool from tool caddy
            - 5.3.3.13.2 Position tool for driving A-Latch
            - 5.3.3.13.3 Drive tool until A-Latch is closed (22.5 Turns)
        - 5.3.1.14. Drive blind mate connector into position

        - 5.3.1.14.2 Position7/16” counterclockwise ratchet tool for driving blind mate connector
        - 5.3.1.14.3 Drive tool until connector is engaged (5 turns)
        - 5.3.1.14.4 Stow 7/16” counterclockwise ratchet in caddy
    - 5.3.3.15 Un-stow ground strap
        - 5.3.1.15.1 Capture GS with manipulator arm
        - 5.3.1.15.2 Capture clamp tool holding GS with tool arm
        - 5.3.1.15.3 Detach GS from rail by opening clamp tool
        - 5.3.1.15.4 Put away clip tool
    - 5.3.3.16 Install Ground Strap on WFC3
        - 5.3.1.16.1 Acquire ground strap tool from caddy
        - 5.3.1.16.2 Position ground strap on WFC3 using manipulator hand.
        - 5.3.1.16.3 Use ground strap tool and attach ground strap by tightening bolt
        - 5.3.1.16.4 Put away ground strap tool
        - 5.3.1.16.5 Grab hold of GS from manipulator hand
    - 5.3.3.17. DR standby
    - 5.3.3.18. GA standby
- 5.3.4. Permanently Stow WF/PC2
    - 5.3.4.1. Activate GA
    - 5.3.4.2. Activate DR
    - 5.3.4.3. Move GA/DR to Temporary Stow Work Site at WF/PC2
    - 5.3.4.4. Grapple Interface Plate With Tool Arm
    - 5.3.4.5. Release WF/PC2 from Temporary Stow Fixture
    - 5.3.4.6. Move GA/DR to WFC bay on EM while carrying WF/PC2
    - 5.3.4.7. Push WF/PC2 7.5' into position in EM bay (As Above)
    - 5.3.4.8. Release WF/PC2
    - 5.3.2.9. Drive A-Latch into position (As Above)
    - 5.3.4.10. DR standby
    - 5.3.4.12. GA standby
- 5.3.5. WFC3 Support Hardware
    - 5.3.5.1. Activate GA
    - 5.3.5.2. Activate DR
    - 5.3.5.3 Move GA/DR to WFC3 Work site on HST
    - 5.3.5.4. Engage blind mate connection (As Above)
    - 5.3.5.5. Open detector vent valves
    - 5.3.5.6. Mate harness from conduit/ECU to WFC3 for RSU
        - 5.3.5.6.1 Grapple connector on harness conduit/ESU
        - 5.3.5.6.2 Position circular connector on WFC3
        - 5.3.5.6.3 Complete Connection
        - 5.3.5.5.4 Release harness
    - 5.3.5.7. Mate 1553 bus from RSU to J9
        - 5.3.5.7.1 Open Bay 1
        - 5.3.5.7.2 Acquire RSU tool from caddy
        - 5.3.5.7.2 Uninstall J9 terminator plug
        - 5.3.5.7.3 Stow terminator plug
        - 5.3.5.7.4 Grapple 1553 connector
        - 5.3.5.7.5 Mate 1553 connector with 486 computer
        - 5.3.5.7.6 Return RSU tool to caddy

                - 5.3.5.7.7 Close Bay 1
            - 5.3.5.7. DR standby
            - 5.3.5.8. GA standby
        - 5.3.6. Have a smoke and pat self on back

Appendix 1.1.6. Jettison Phase Functional Flow

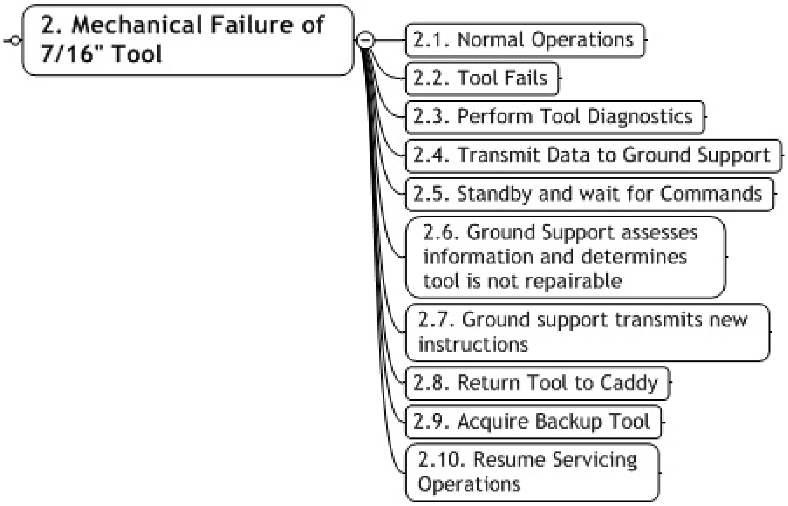
6. EM Jettison and De-Orbit
    - 6.1. DR shutdown
        - 6.1.1. Activate GA
        - 6.1.2. Activate DR
        - 6.1.3. Move GA/DR to DR stow site on EM
        - 6.1.5. Configure DR for stowage
        - 6.1.6. GA Positions DR in large capture envelope of main stow
        - 6.1.7. GC engages main stow fixture, aligning DR with other fixtures.
        - 6.1.8. GA tilts DR to position it within capture envelope of remaining stow fixtures
        - 6.1.9. GC engages remaining stow fixtures as required
        - 6.1.10. DR shuts off power completely
            - 6.1.10.2. Shut down Actuators
            - 6.1.10.3. Shut down Sensors
            - 6.1.10.4. Shut down Communications
            - 6.1.10.5. Shut down processors
            - 6.1.10.6. GC shuts off power connection from EM
        - 6.1.11. GA releases DR
        - 6.1.12. GA standby
    - 6.2. GA shutdown
    - 6.3 EM Jettisons and Carries out De-Orbit maneuver
    - 6.4. Mission Accomplished - Break out the champagne

Appendix 1.2 Contingency Scenarios

Appendix 1.2.1. Mechanical failure of the 7/16” tool

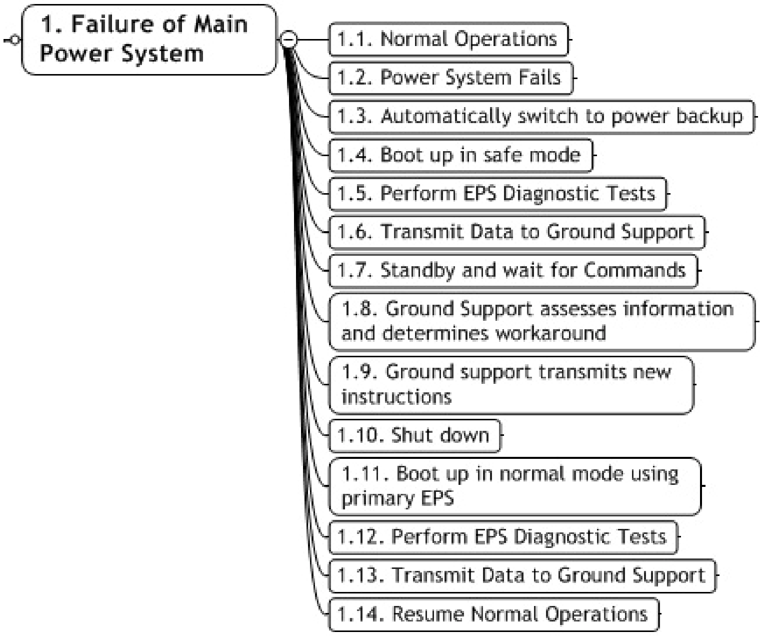
This following is a detailed description of the operations that will take place if a failure occurs while using the 7/16” tool. This process can be generalized to outline the scenario for any mechanical tool failure. Further more, eliminating steps 2.8 and 2.9 will provide a basic framework for any mechanical failure of the RSS.

Chronological sequence is in the downwards direction as indicated by the numbering of the blocks.



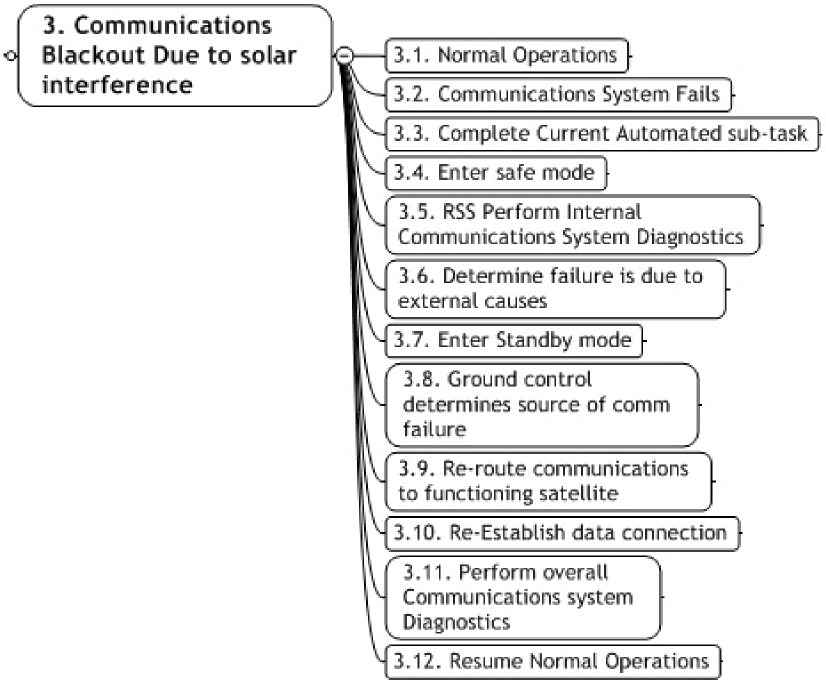
Appendix 1.2.2. Failure of the main power system

In the event of a power failure the following operations will be performed:



Appendix 1.2.3. Communications black out due to solar

The following scenario details the steps to be done in the event of a total communications failure. This is a worst-case scenario that can be taken as characteristic of any smaller communication problems.


3. Communications Blackout Due to solar interference
3.1. Normal Operations
3.2. Communications System Fails
3.3. Complete Current Automated sub-task
3.4. Enter safe mode
3.5. RSS Perform Internal Communications System Diagnostics
3.6. Determine failure is due to external causes
3.7. Enter Standby mode
3.8. Ground control determines source of comm failure
3.9. Re-route communications to functioning satellite
3.10. Re-Establish data connection
3.11. Perform overall Communications system Diagnostics
3.12. Resume Normal Operations

Appendix 2 System Requirements

Note to the reader: Numbering of the requirements is separate from that of the structure of this document, and is consistent with the original definition of requirements in our first systems assingnment.

4.2 Dexterous Robot derived functional requirements

4.2.1 The DR shall achieve the following performance requirements during its operations.*

4.2.1.1 The DR shall be capable of maneuvering anywhere in the workspace

4.2.1.1.1 The DR shall have a range of motion such that it can move anywhere in the workspace with a resolution of 2.4mm (translational) and 0.1° (rotational)

4.2.1.1.2 The DR shall have reach and maneuverability TBD.

4.2.1.2 The DR shall have accuracy of ± 1° relative to commanded position.

4.2.1.2.1 The DR shall have closed loop accuracy of 0.16”

4.2.1.2.2 The DR shall have angle resolvers with tolerance stack-up of less than 1°

4.2.1.2.3 The DR motor and gearbox tolerance stack-up shall be sufficiently small to satisfy the above

* These requirements will be affected by the accuracy of the GA.

4.2.2 The DR shall perform the power augmentation procedure.

4.2.2.1 The DR shall retrieve both DBA II connector interface plates (-V2 and +V2) from the conduit

4.2.2.1.1 The DR End Effector shall grapple the DBA II Connector Interface Plate

- This is the process of removing the DBA II connector interface plate from its storage location on the conduit
- The DBA II connector interface plate must meet the requirements for the DR tool arm End Effector Interface

4.2.2.1.2 The DR shall move the DBA II connector interface plate to its location on the Diode Box

- DBA II connector interface plate assumptions
    - Angle Aluminum, 6"x3"x3"x1/8"
    - mass of plate: 200g
    - mass of J8B and J6B connectors: 100g each
    - total mass: 500g

4.2.2.2 The DR shall attach the harness from the conduit to the HST handrails

4.2.2.2.1 The DR shall grapple the Harness Attachment Tool

- The Harness Attachment Tool shall meet the requirements for the DR End Effector Interface

4.2.2.2.2 The DR shall use the Harness Attachment Tool (the specially designed clip to harness the conduit in position.

4.2.2.3 The DR shall connect the HST 's SA3 power to the DM batteries via the new harness

4.2.2.3.1 The DR shall grapple the DBA Connector Tool

- The DBA Connector Tool shall meet the requirements for the DR Tool Interface

4.2.2.3.2 The DR shall move the DBA Connector Tool to the work site

- Harness Attachment Tool assumptions
    - mass: 5 kg

4.2.2.3.3 The DR shall use the DBA Connector Tool

- The tool shall grapple the connector
- The tool will remove the connector from the DBA II
- The tool will attach the connector to the DBA II Connector Interface Plate
- The tool will release the connector

4.2.3 The DR shall perform the following actions to complete the WFC3 change out

4.2.3.1 Remove ground strap and clamp it to handrail

4.2.3.2 Install WF/PC2 Interface Plate

4.2.3.2.1 Acquire and grapple WF/PCII interface plate
4.2.3.2.2 Position WF/PCII interface plate
4.2.3.2.3 Install interface plate by driving guide stud interfaces on it into the guide studs on the WF/PC2
4.2.3.2.4 use 7/16” hex tool to bolt interface plate in position

4.2.3.3 WF/PC2 Blind Mate Release

4.2.3.3.1 Identify and reach blind mate connector
4.2.3.3.2 Release blind mate connector (7/16" interface)

4.2.3.4 Release and Secure Ground Strap

4.2.3.4.1 Grapple ground strap
4.2.3.4.2 Release ground strap (7/16" hex interface)
4.2.3.4.3 Install ground strap on GS temporary stowage fixture (7/16" hex interface)

4.2.3.5 Release Latch-A

4.2.3.5.1 Locate released Latch A
4.2.3.5.2 Verify Latch A has been removed
4.2.3.5.3 Grapple it and bring it into position
4.2.3.5.4 Secure it into position (7/16" interface)

4.2.3.6 Remove and Stow WF/PC2

4.2.3.6.1 Grapple WF/PC2 grappling fixture on the interface plate.
4.2.3.6.2 Linearly retract WF/PC II 7.5' in the plane of WF/PC II

  - 4.2.3.6.3 Move WF/PC II to stowage location on EM
  - 4.2.3.6.4 Secure WF/PC II on EM to prevent it from floating away

- 4.2.3.7 Retrieve and Position WFC3
  - 4.2.3.7.1 Locate and reach WFC3 storage/housing bay on EM
  - 4.2.3.7.2 Remove/retract WFC3 thermal/contamination protection cover on EM
  - 4.2.3.7.3 Locate and release ground strap on EM
  - 4.2.3.7.4 Release Latch-A on EM
  - 4.2.3.7.5 Verify release of latch A.
  - 4.2.3.7.6 Grapple robotics interface on WFC3
  - 4.2.3.7.7 Pull WFC3 out of storage/housing bay
  - 4.2.3.7.8 Move it into position ready for installation

- 4.2.3.8 Install WFC3 into HST
  - 4.2.3.8.1 Stabilize WFC3
  - 4.2.3.8.2 Align WFC3 with is guide rails
  - 4.2.3.8.3 Verify proper alignment
    - o Shall be done with camera on DR gripper arm mini Cams
  - 4.2.3.8.4 Push WFC3 into WFC3 enclosure on along guide rails.
  - 4.2.3.8.5 Monitor force/moment on all axes to ensure that jamming does not occur

- 4.2.3.9 Replace Latch-A
  - 4.2.3.9.1 Locate released Latch A
  - 4.2.3.9.2 Grapple it and bring it into position
  - 4.2.3.9.3 Secure it into position (7/16" interface)

- 4.2.3.10 Replace Ground Strap
  - 4.2.3.10.1 Release ground strap from temporary clamp
  - 4.2.3.10.2 Bring GS back to position on WFC3
  - 4.2.3.10.3 Secure GS in position on WFC3

- 4.2.3.11 Replace Blind Mate if automatic function fails

4.2.4 The DR shall be able to perform the following functions to make the power and data connections for the gyros.

- 4.2.4.1 Release blind mate connector (same as 4.2.3.3)

- 4.2.4.2 Connect conduit harness to WFC3
  - 4.2.4.2.1 The DR End Effector shall have the ability to grapple the conduit harness that may (in the worst case) be loose cabling floating in space.
  - 4.2.4.2.2 The DR shall be capable of tracking the conduit harness and returning this information to the DC&H system.
  - 4.2.4.2.3 The DR shall have the ability to mate conduit harness to the WFC3, through the use of the circular connector interface on the WFC3. This will require positioning the circular connector correctly on the WFC3 prior to mating this may include a specialized tool or use of the DR End Effector.

4.2.4.2.4 The DR shall have the ability to disengage itself from the conduit harness without undue harm to the harness.

4.2.4.3 Open Bay 1 and make 1553 data bus connection through J9

4.2.4.3.1 The DR End Effector shall have the ability to open Bay 1

4.2.4.3.2 The DR shall have a tool to grapple the J9 connector

4.2.4.3.3 The DR shall have a tool to grapple the 1553 connector

4.2.4.3.4 The DR shall be capable of sensing its environment to such a degree, that it is able to work within the confined space of the WFC3 bay on the HST (see 4.3.5)

4.2.5 The DR's tool actuator shall be capable of applying 50 ft-lb of torque

4.2.5.1 The DR Tool Drive Motor and DR Tool Drive Gearbox ratios shall be sufficient to apply this torque

- Getting this kind of torque and a reasonable turn speed may influence DR power requirements

4.2.6 The DR will track the progression of its tool by monitoring the number of revolutions and the torque applied

4.2.6.1 The DR shall have a torque sensor in its tool drive mechanism capable of measuring up to 50*1.5=75ft-lb torques.

4.2.6.1.1 (1.5 is estimated F.O.S.)

4.2.6.1.2 50*1.5=75ft-lb = 101.6865 Nm

4.2.6.2 The DR's tool actuator shall use an optical encoder/tachometer/stepper motor ((Minimum resolution of O(360°)).

4.2.7 The DR shall be capable of stopping a 1000lb mass from maximum commanded tip velocity within 2” and 2°. i.e. it must have the strength, stiffness etc to stop operations any if commanded to do so.

4.2.7.1 The DR shall produce a minimum tip force of **4465*v^2 N** where **v** is the tip velocity.

4.2.7.2 The DR shall produce a minimum torque of **677*w^2 Nm** where **w** is the angular rate.

4.2.7.3 The DR shall be sufficiently stiff so that stopping distances / angles are satisfied.

4.2.7.3.1 Stiffness of the Arms and Joints gives how much the stopping distance is extended by elastic deformation.

4.2.7.3.2 need to find out how to model/budget linear and tortional deflections.

4.2.7.3.3 Overall stiffness is affected by DR/GA structural interface and Stiffness of GA i.e. how the strength of the DR stacks up on top of the GA.

Note: For details of above calculations see Appendix 5

4.2.8 DR shall be capable of limiting forces normal to constrained translational paths to no more than 10lbs and delivering up to 25lbs along those paths.

4.2.8.1 Shall have a six axis force and torque sensor near end effector

4.2.8.2 Resolution accuracy of Force/Moment at end effector shall be

4.2.8.2.1 at least ±2lbs and

4.2.8.2.2 at least ±2ft-lb

4.2.8.3 All actuator commands will be based on feedback from the 6 axis sensor to conform to the 10lb/25lb requirement

4.2.9 The DR shall have the following interfaces:

4.2.9.1 The required structural interface between DR and GA is the same as 4.1.3.1.1

4.2.9.2 The DR shall be able to interface with the HST in two following ways:

4.2.9.2.1 Directly grapple Different Components that include

- Harness from conduit to WFC3
- Power cables
- Data cables
- New Ground Strap Stow Fixture
- WF/PCII interface plate
- blind mate connector
- Ground Strap
- A-Latch
- Thermal/contamination cover for WFC3
- Robotic interface on WFC3
- Bay 1 covering
- Robotic Tools

4.2.9.2.2 Via tools to release/secure different parts that include (see Section 4.3.3)

4.2.10 The DR should not weigh more than 500 KG. Possible allocation scheme

4.2.11 The DR should not consume more than 250W at any time.

4.2.11.1 The DR should operate at a maximum of 160W during nominal operations or survival mode. Power consuming components will include

4.2.11.1.1 Sensors (touch, position, video camera/3D LCS)

4.2.11.1.2 Actuators (motors)

4.2.11.1.3 Thermal control (heating systems)
4.2.11.1.4 Computer CPU

4.2.11.2 The DR shall not consume more than 250W. Power consuming elements are the same as above.

4.2.11.3 The DR will draw its power from the interface between the GA and DR (refer to 4.1.3.3)

4.3 Miscellaneous requirements

4.3.1 The system will have a vision system capable of supporting both controlled and semi autonomous operations.

4.3.1.1 DR vision system requirements

4.3.1.1.1 DR vision system shall be capable of viewing most components of the DR arms body and workspace.

4.3.1.1.2 The DR vision system shall be capable of distinguishing between the GA, DR, HRV, and HST at all times using 3D model matching.

4.3.1.1.3 The DR vision system shall be capable of operating in both, night, day and high glare conditions while in space.

4.3.1.1.4 The range of each vision sensor will be partially covered by other sensor in the event of a single failure, such that the vision system is single fault tolerant.

4.3.1.1.5 Imaging system may include stereoscopic cameras or LIDAR

4.3.1.2.6 The vision system shall have stable supporting software/algorithm able to resolve the DR pose regardless of its configuration.

4.3.1.2.7 The vision system shall be capable of providing real-time feedback the CD&H system to facilitate closed loop positioning and semi autonomous operations.

4.3.2 The DR shall have the ability to perform operations directly under Earth Control:

4.3.2.1 The DR CPU shall be capable of receiving scripted ground commands through the EM to control DR operations

4.3.2.2 The DR CPU shall be able to send visual and position data feed back to ground control from data fed back to it from DR via the EM comm.

4.3.2.3 The DR shall feedback data (applied torque and force as felt at end effector, video and position) to GC to assist in Ground Control feed back

4.3.2.4 The DR actuators shall be able to follow ground commands with the accuracy as found in 4.2.1

4.3.2.5 The Vision System on DR shall be of sufficient resolution to provide enough details for efficient ground control

4.3.3 The tools shall be capable of properly interfacing with the DR as well as all the required interfaces on HST.

4.3.3.1 All tools will have two interfaces
  4.3.3.1.1 Interface with one of the DR end effector (ideally the same in all the tools)
  4.3.3.1.2 Interface with the appropriate part of the HST or the component it is supposed to install.
4.3.3.2 All tools shall be capable to tolerating the maximum force applied by the DR
4.3.3.3 The DR shall be capable of acquiring the required tool as necessary for each operation
4.3.3.4 The DR shall be capable of fastening the tool to its appropriate arm in a secure manner
4.3.3.5 The DR shall be capable of using its end effector to apply the required force/torque to operate the tools
4.3.3.6 The DR shall be able monitor torque/revolutions monitor the progression of the tool.
4.3.3.7 The DR shall ensure that all tools are safely stowed away after completion of use (not floating around as it might damage the HST or cause other unwanted complications)

4.3.4 The DR and GA will be able to perform self diagnostics to identify malfunctions.

4.3.4.1 The DR software shall have appropriate algorithms to communicate with the sensors to check status before or during operations
4.3.4.2 The DR sensors shall be capable of checking the internal circuits of the GA/DR
4.3.4.3 The HRV shall be capable of checking the on board processor functionality
4.3.4.4 The DR shall be able to verify whether all its actuators are functioning
4.3.4.5 The DR software shall be capable of checking the control software before the control commands are executed
4.3.4.6 The EM C&DH shall be able to verify that communication link is established with both GA and DR.
4.3.4.8 The DR/GA will communicate self check results to Ground Control

4.3.5 The DR shall have the appropriate software for performing all the function and have the following modes.

4.3.5.1 Earth Control Mode

The software will

- continuously check for feed from earth
- stop all operations if feed is lost
- try to reestablish feed if lost
- relay sensor signals (vision, torque, force, moment, position) to ground control if continuous feed present.
- relay commands from ground control to actuators and end effectors if continuous feed present

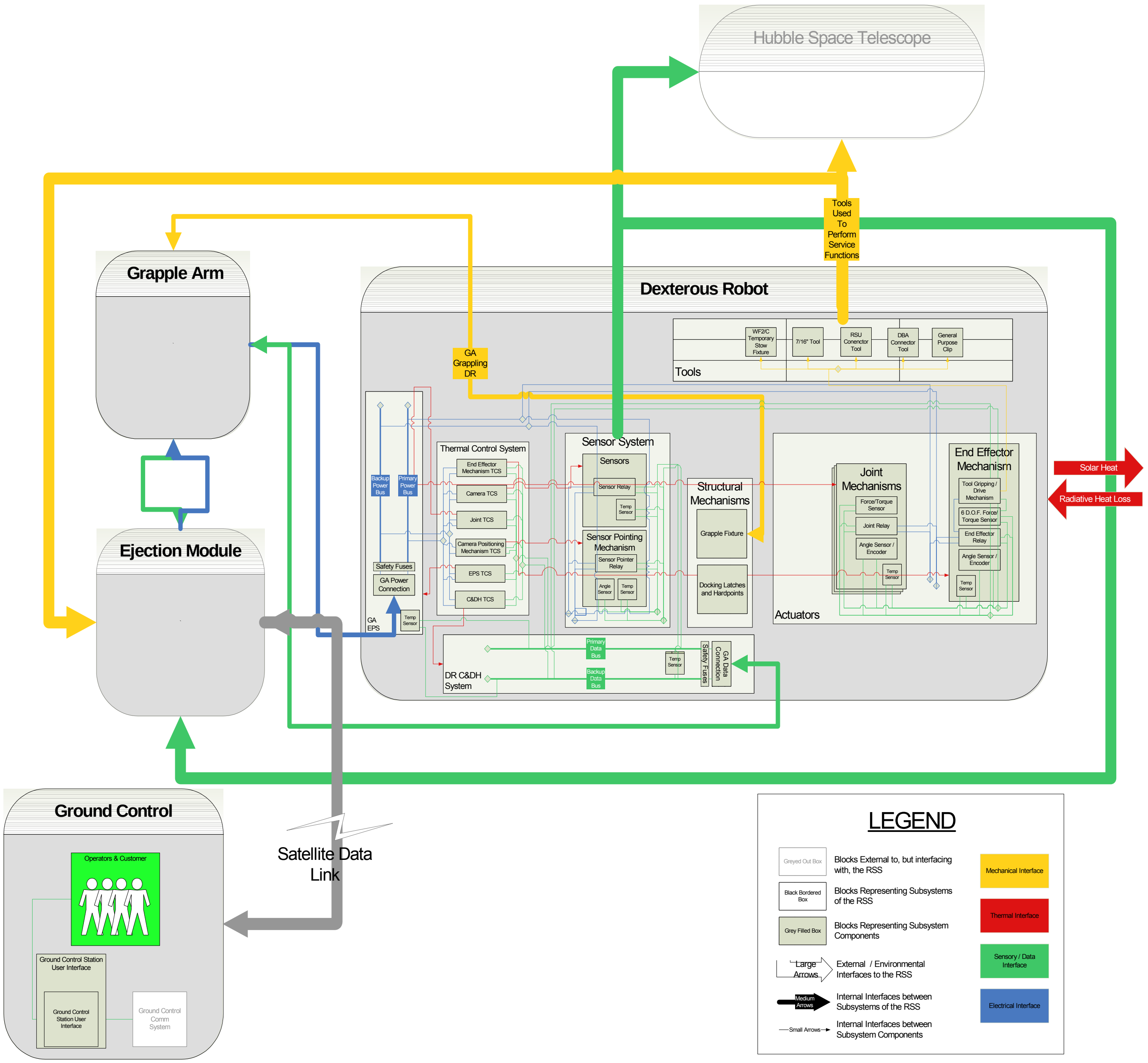
- Change to autonomous mode if feed cannot be established after a determined minimum number of attempts or if commanded to do so from Ground control

4.3.5.2 Semiautonomous mode

This mode is the same as the Earth control mode except that the commands are uploaded to the DR CPU in scripted from and the DR follows the commands while people at ground station observe.

Appendix 3 System Architecture

Appendix 3.1 System Block Diagram



Appendix 4 Failure Mode Effects Analysis

Action	FREQ	Key Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	Controls	CON	RISK	Notes
What is the Action Category?	How often?	What is the Key Input?	In what ways can the Key Input go wrong?	What is the impact on the customer requirements?	How severe?	What causes the Key Input to go wrong?	What are the control strategies that will prevent the cause or the failure mode?	What control?		
GA/DR movement w/o payload	2	Position of GA/DR wrt HST	GA/DR collides with HST	Damage to HST GA/DR	9	Structural failure - due to overload	Design GA and DR to withstand loads greater than the anticipated maximum	5	360	
DR manipulating payload at worksite	8	Grapple payload securely	DR fails, tool collides with HST	Damage to HST by payload	9	Electrical failure - unintentional power to actuators	implement a double positive system for activation. Power alone will not cause activation	5	360	
Note: The two process steps and failure modes and effects above have different frequency and severity indexes. However, they have been grouped together because all of the causes listed on the right apply to all three of the failures. In calculating the Risk Index, a frequency of 8 and a severity of 9 wree used, representing the highest combination in the set, and therefore the worst case scenario.						Electrical failure - no communication between GC and DR and GA	DR to enter safe mode when there is a comunication failure - ie movement ceases untill further instruction	10	720	Largest risk index
						Sensor failure - loss of feedback, incorrect picture of surroundings	DR to enter safe mode when there is a sensor failure	10	720	Largest risk index
						Command corruption - DR activated inadvertantly	implement a double positive system for activation.	5	360	
						Command corruption - GA or DR activated incorrectly	DR will sense location during ops. Warning given when proximity too close.	10	720	Largest risk index
						Power failure	joints not backdrivable, effectively have brakes enaged when not driven	5	360	
						Operator error - incorrect command	double check system - input command, confirm, then send	5	360	
						Operator error - accidental command	double positive system to send commands	5	360	
GA/DR movement w/ payload	8	Grapple payload securely	DR releases payload, payload collides with HST	Damage to HST by payload	9	Mechanical failure - wear on DR end effector, payload slips	DR wil have a double grapple system, 2 independent means of gripping	5	360	
						Structural failure - overloaded DR, end effector fails	Design DR to withstand loads greater than the anticipated maximum	5	360	
						Electrical failure - no communication between GC and DR and GA	DR to enter safe mode when there is a comunication failure - ie movement ceases untill further instruction	5	360	
						Sensor failure - loss of feedback	DR to enter safe mode when there is a sensor failure	10	720	Largest risk index
						Command corruption - DR incorrectly or inadvertantly signalled to release	implement a double positive system for release. A single corrupt command cannot have damaging effects	5	360	
						Power failure - end effector opens	End effector normal state is closed, reaqires electrical power to open.	5	360	
						Operator error - incorrect command to release	double check system - input command, confirm, then send	5	360	
						Operator error - accidental command to release	double positive system to send commands	5	360	

Table 2 - FMEA Detailed Analysis

Appendix 4.1 Frequency and Severity Ratings for FMEA

Number	Description
1	once in the mission
2	
3	
4	
5	
6	
7	
8	
9	
10	Continuously

Table 3 - Frequency Rating

Number	Description
1	no damage to HST
2	
3	
4	
5	
6	
7	
8	HRV trapped to HST
9	Payload collides with HST
10	HRV collides with HST

Table 4 - Severity Rating

Number	Description
1	Remove/control hazard through operational strategies
5	Remove/control hazard through design
10	Reduce consequence of hazard

Table 5 - Control Rating

Appendix 5 Autonomy

Appendix 5.1 Levels of Autonomy

In order to identify the required capabilities of each subsystem of the Dexterous robot we have adopted the following scale for varying levels of autonomy. These are based on the levels discussed in the SMAD [9].

Level 0	Non-Autonomous tasks or commands performed by ground controllers.
Level 1	The robot runs relatively simple and continuous on board closed loop processes
Level 2	The robot can execute planned events and respond to expected inputs based on a stored set of rules and timed commands
Level 3	The robot can interpret unplanned sensor inputs and react to unplanned events based on event-driven rules and algorithms.
Level 4	"At the fourth level of autonomy, spacecraft react to unplanned events not just by executing rules but by using forms of on board intelligence, inference engines, and planning agents." [9]

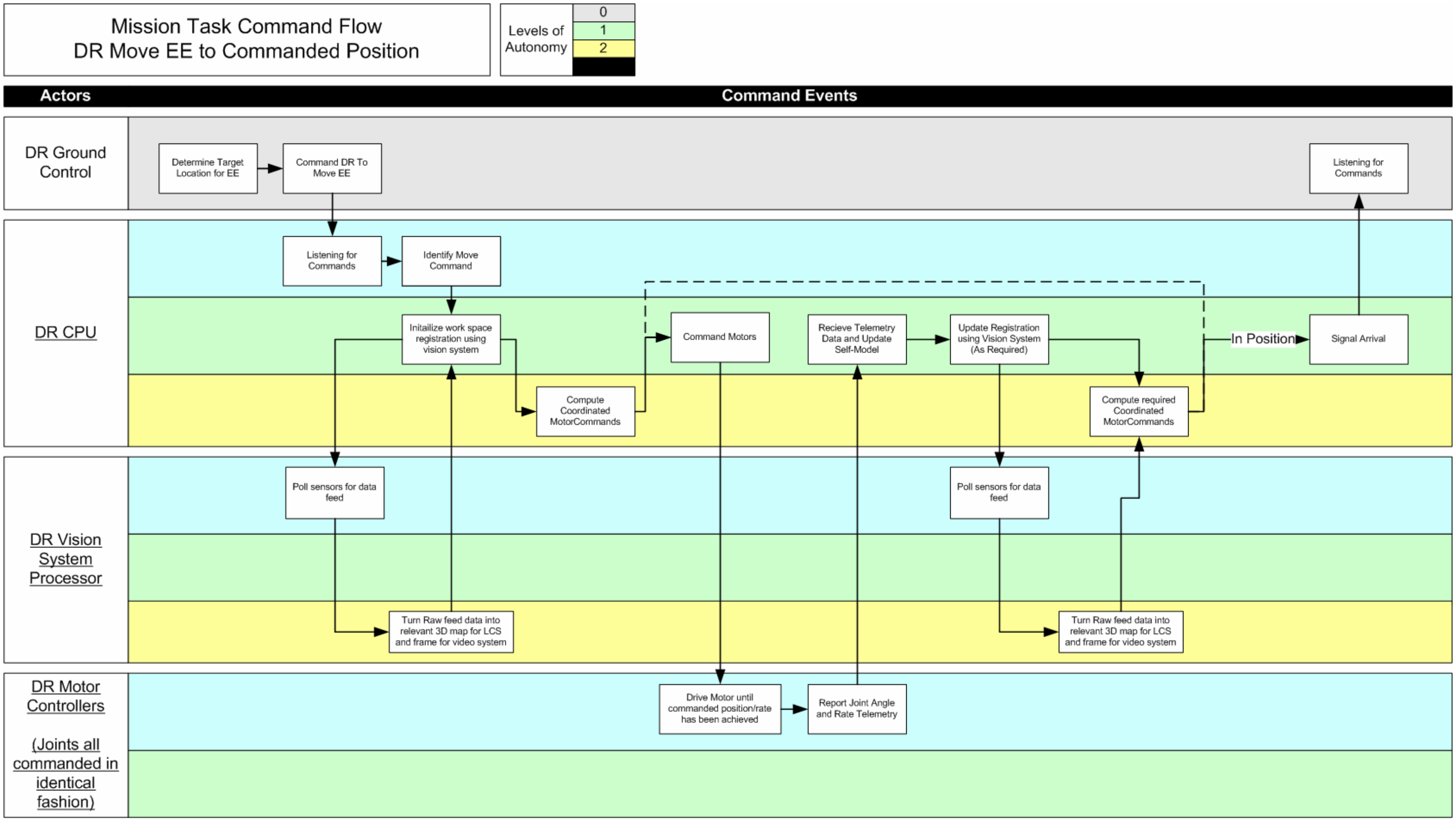
The design of the DR's control and command architecture is such that we generally minimize the level of autonomy required to perform a given task satisfactorily. That is, we consider a low number on this scale to be desirable, and trades on system autonomy are viewed with the aim of minimizing the number of actors that require level 3 autonomy.

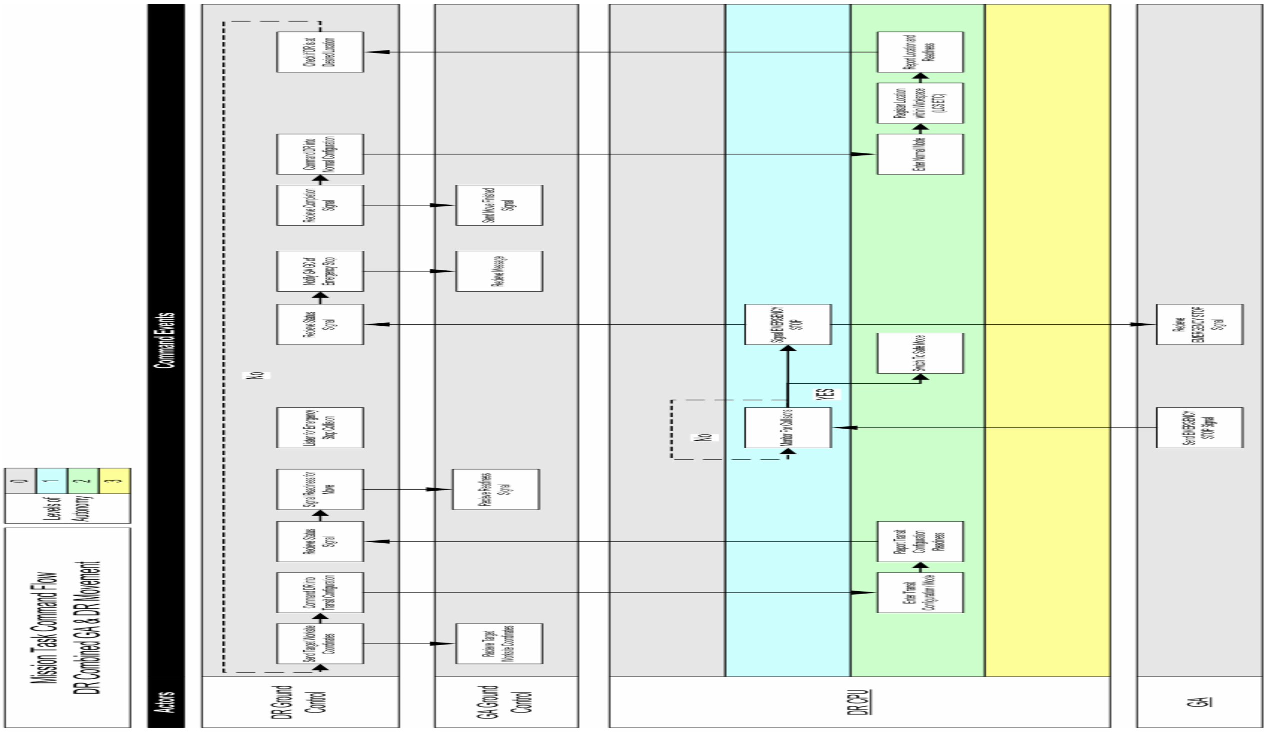
Appendix 5.2 Command and Control Flow Down

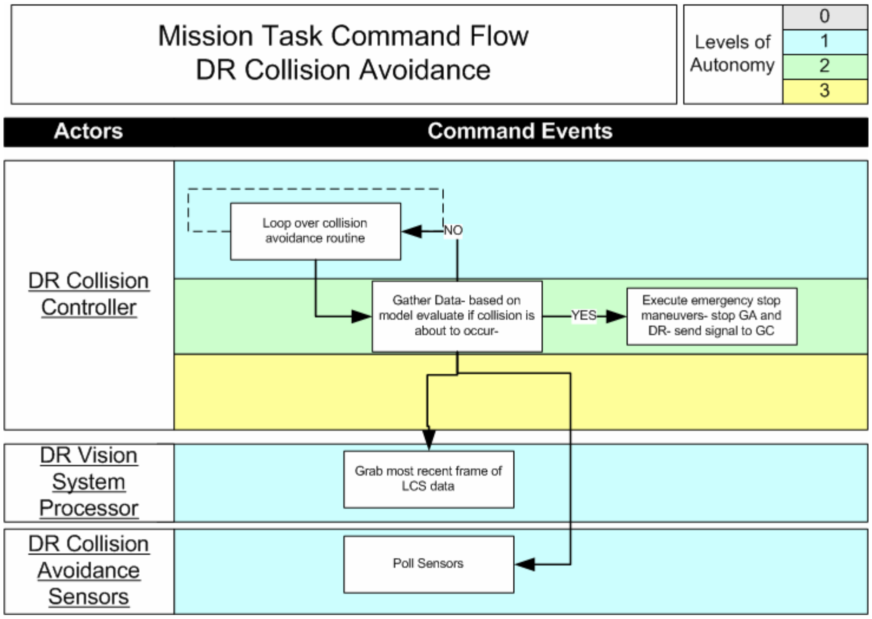
These diagrams are made to illustrate the level of autonomy involved in each operational process and mission task executed by the DR. For a definition of the various levels of autonomy, see Appendix 5.1 (above).

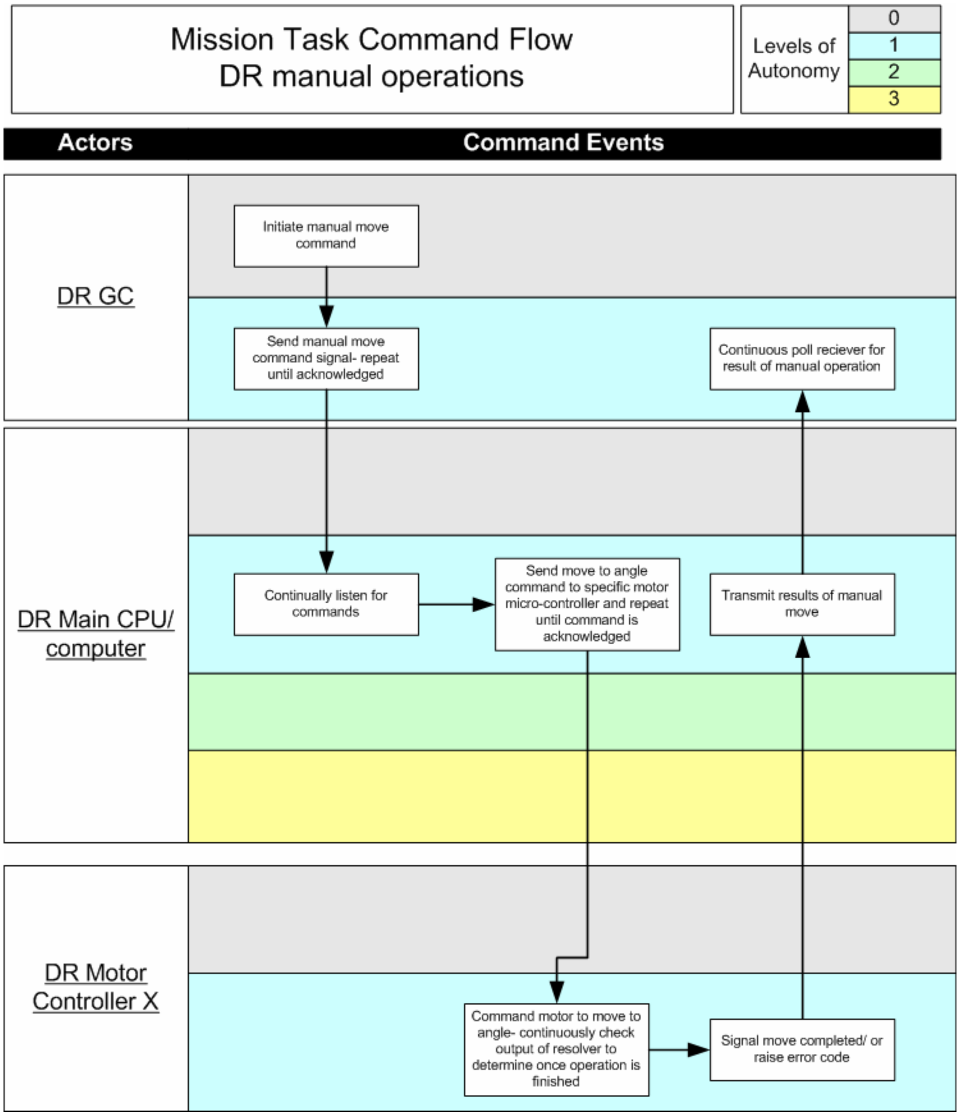
The reader should gain an understanding of which subsystems use low-level continuous loops or closed loop control, and which systems require a level of self-control that is compatible with the conventional definition of autonomy.

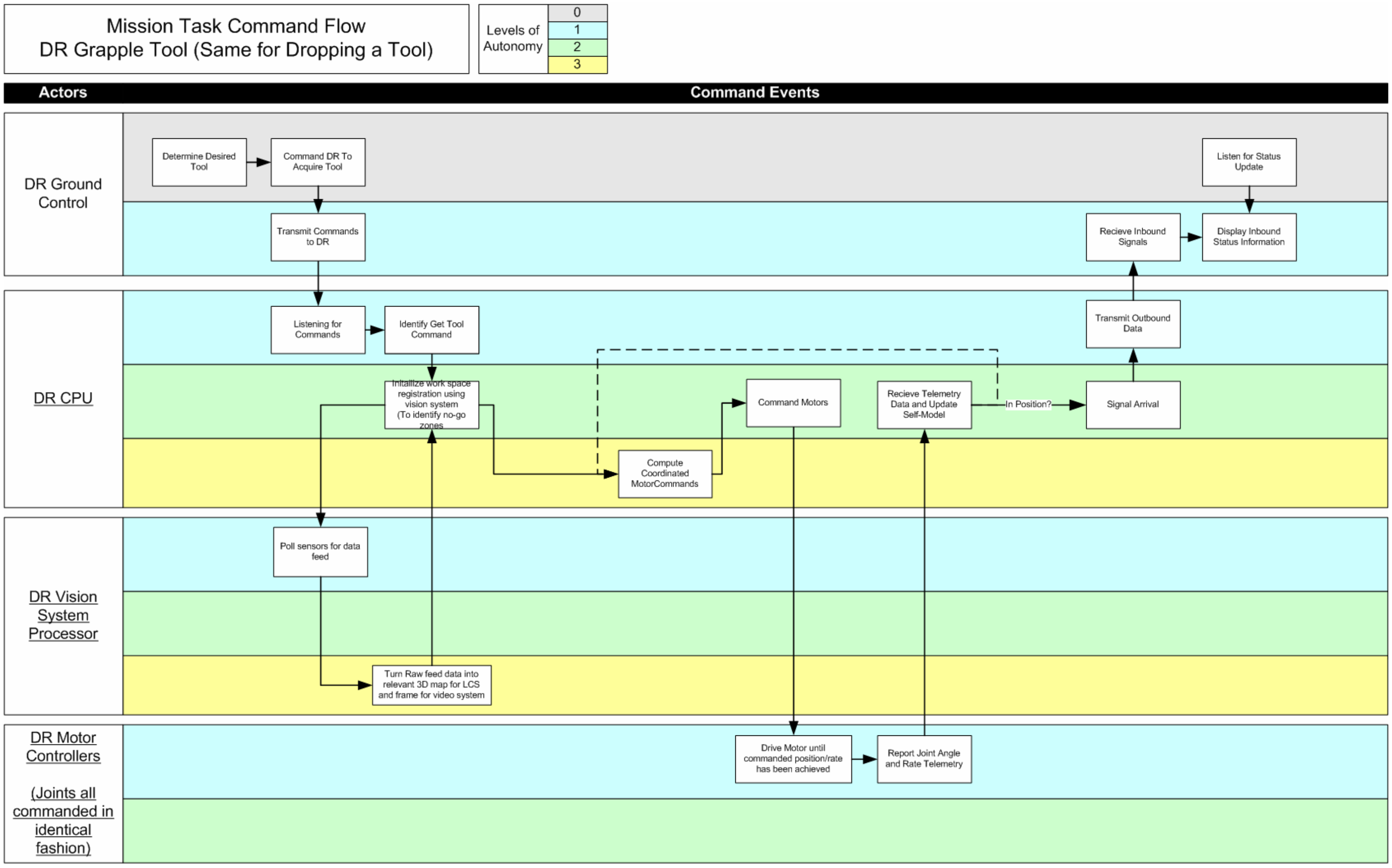
Additionally, these diagrams identify the initiators of each operation, and trance how commands and control of the DR passes through the system.

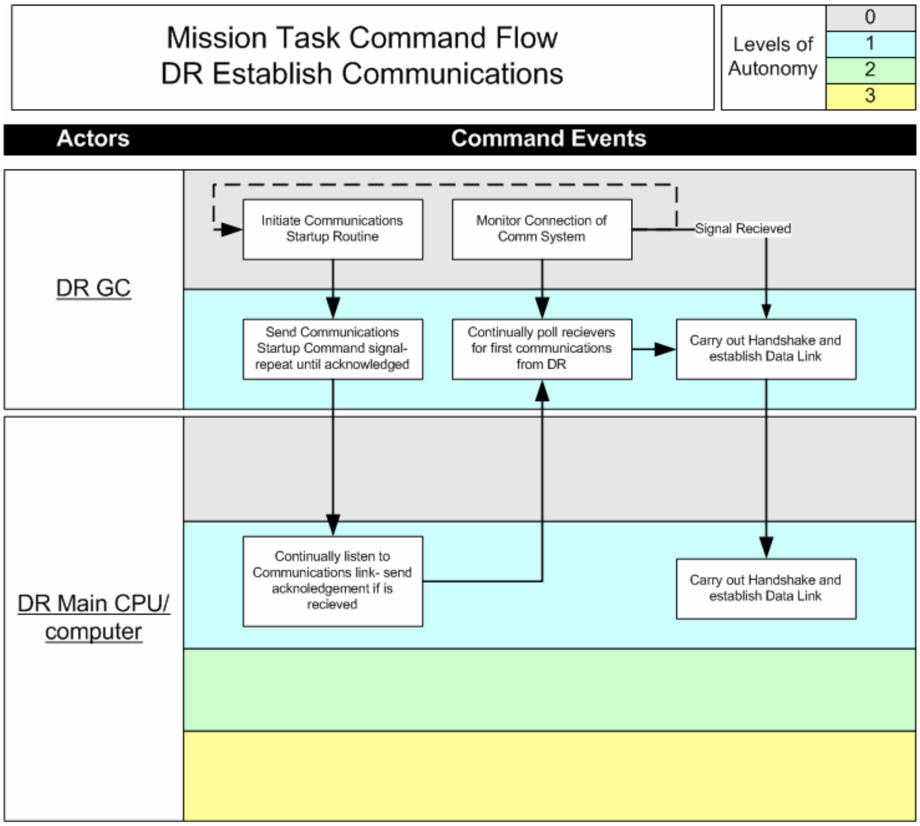

Mission Task Command Flow
DR Move EE to Commanded Position
Levels of Autonomy
0
1
2
Actors
Command Events
DR Ground Control
Determine Target Location for EE
Command DR To Move EE
Listening for Commands
DR CPU
Listening for Commands
Identify Move Command
Initailize work space registration using vision system
Compute Coordinated MotorCommands
Command Motors
Recieve Telemetry Data and Update Self-Model
Update Registration using Vision System (As Required)
Compute required Coordinated MotorCommands
In Position
Signal Arrival
DR Vision System Processor
Poll sensors for data feed
Turn Raw feed data into relevant 3D map for LCS and frame for video system
Poll sensors for data feed
Turn Raw feed data into relevant 3D map for LCS and frame for video system
DR Motor Controllers
(Joints all commanded in identical fashion)
Drive Motor until commanded position/rate has been achieved
Report Joint Angle and Rate Telemetry

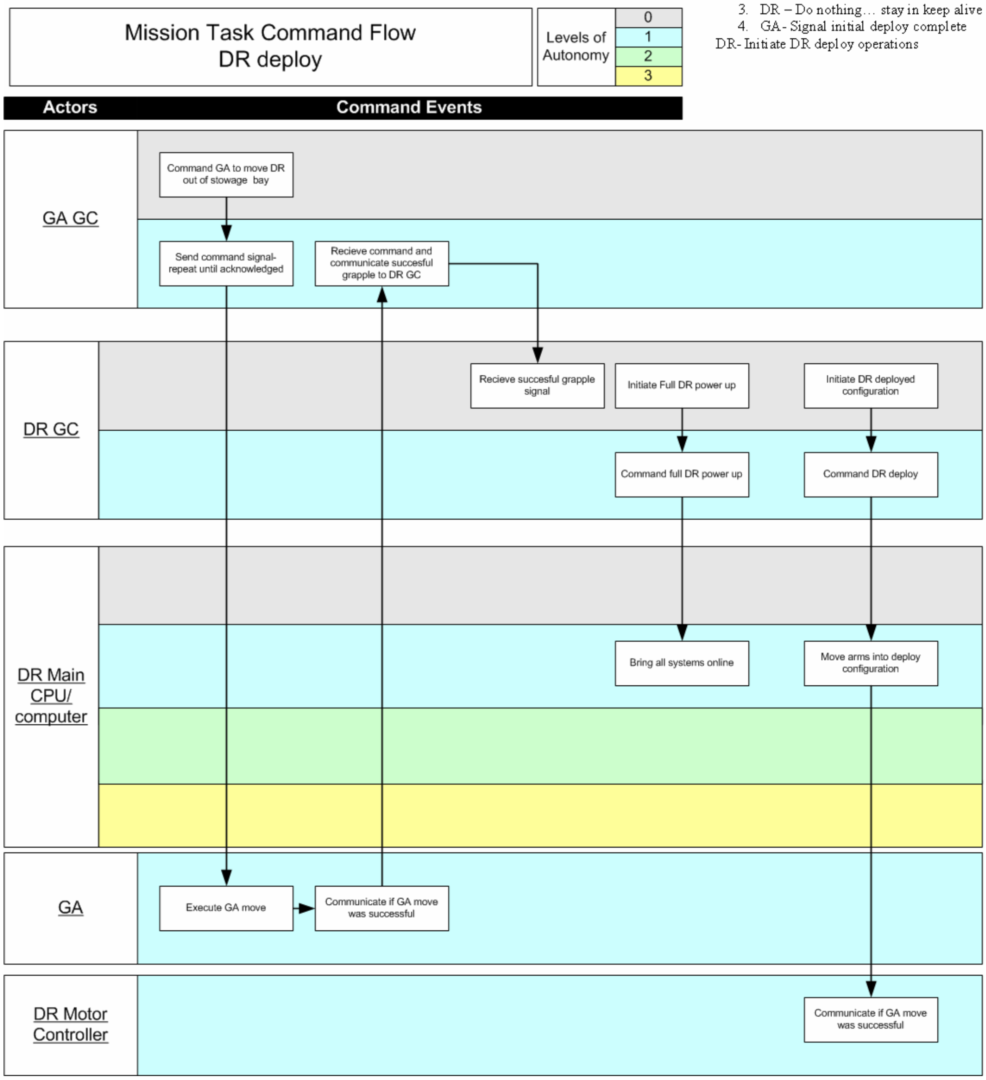

Mission Task Command Flow
DR Combined GA & DR Movement
Levels of Autonomy
0
1
2
3
Actors
Command Events
DR Ground Control
GA Ground Control
DR CPU
GA
Send Target Worksite Coordinates
Command DR into Transit Configuration
Recieve Status Signal
Signal Readiness for Move
Listen for Emergency Stop Collision
No
Recieve Status Signal
Notify GA GC of Emergency Stop
Recieve Completion Signal
Command DR into Normal Configuration
Check if DR is at Desired Location
Recieve Target Worksite Coordinates
Recieve Readiness Signal
Recieve Message
Send Move Finished Signal
Enter Transit Configuration Mode
Report Transit Configuration Readiness
No
Monitor For Collisions
YES
Signal EMERGENCY STOP
Switch To Safe Mode
Enter Normal Mode
Register Location within Workspace (LCS ETC)
Report Location and Readiness
Send EMERGENCY STOP Signal
Recieve EMERGENCY STOP Signal


Mission Task Command Flow
DR Collision Avoidance
Levels of Autonomy
0
1
2
3
Actors
Command Events
DR Collision Controller
DR Vision System Processor
DR Collision Avoidance Sensors
Loop over collision avoidance routine
NO
Gather Data- based on model evaluate if collision is about to occur-
YES
Execute emergency stop maneuvers- stop GA and DR- send signal to GC
Grab most recent frame of LCS data
Poll Sensors


Mission Task Command Flow
DR manual operations
Levels of Autonomy
0
1
2
3
Actors
Command Events
DR GC
Initiate manual move command
Send manual move command signal- repeat until acknowledged
Continuous poll reciever for result of manual operation
DR Main CPU/ computer
Continually listen for commands
Send move to angle command to specific motor micro-controller and repeat until command is acknowledged
Transmit results of manual move
DR Motor Controller X
Command motor to move to angle- continuously check output of resolver to determine once operation is finished
Signal move completed/ or raise error code


Mission Task Command Flow
DR Grapple Tool (Same for Dropping a Tool)
Levels of Autonomy
0
1
2
3
Actors
Command Events
DR Ground Control
DR CPU
DR Vision System Processor
DR Motor Controllers
(Joints all commanded in identical fashion)
Determine Desired Tool
Command DR To Acquire Tool
Transmit Commands to DR
Listening for Commands
Identify Get Tool Command
Initialize work space registration using vision system (To identify no-go zones
Poll sensors for data feed
Turn Raw feed data into relevant 3D map for LCS and frame for video system
Compute Coordinated MotorCommands
Command Motors
Drive Motor until commanded position/rate has been achieved
Report Joint Angle and Rate Telemetry
Recieve Telemetry Data and Update Self-Model
In Position?
Signal Arrival
Transmit Outbound Data
Recieve Inbound Signals
Listen for Status Update
Display Inbound Status Information


Mission Task Command Flow
DR Establish Communications
Levels of Autonomy
0
1
2
3
Actors
Command Events
DR GC
Initiate Communications Startup Routine
Monitor Connection of Comm System
Signal Recieved
Send Communications Startup Command signal- repeat until acknowledged
Continually poll recievers for first communications from DR
Carry out Handshake and establish Data Link
DR Main CPU/ computer
Continually listen to Communications link- send acknoledgement if is recieved
Carry out Handshake and establish Data Link

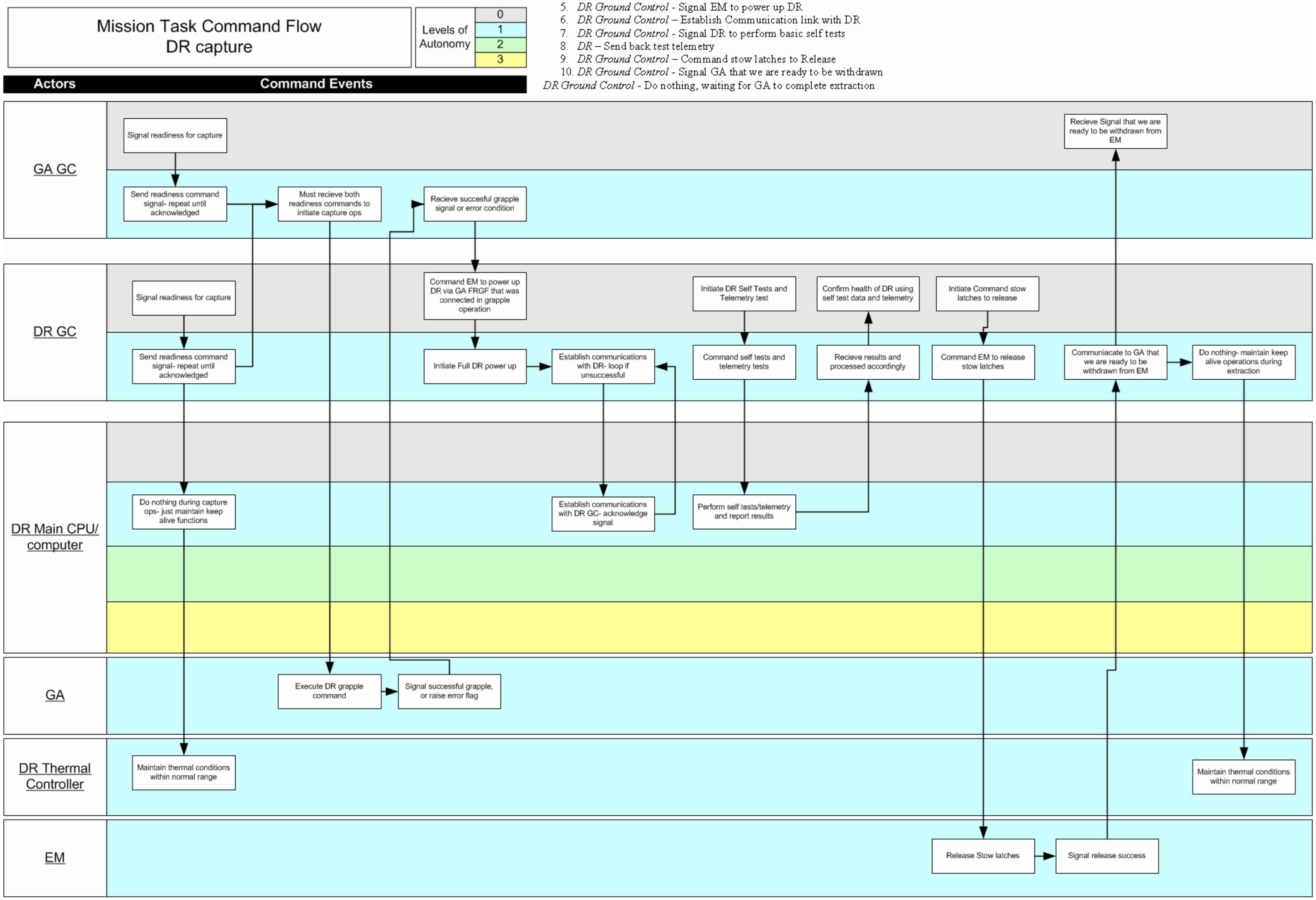


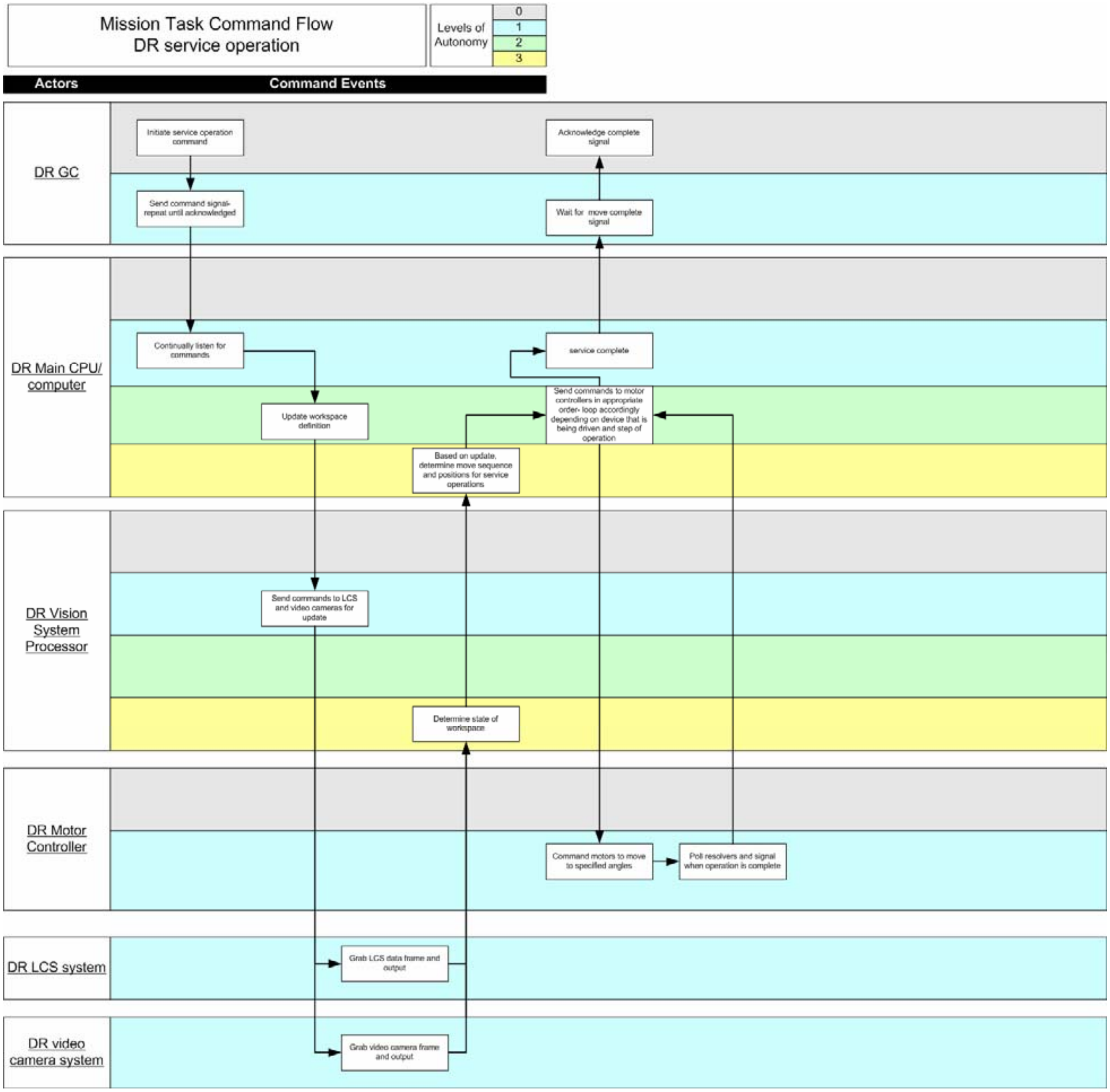
1. DR *Ground Control*- Command GA to move DR out of Bay
2. GA *Ground Control*- Command acknowledge
3. DR – Do nothing… stay in keep alive while GA moves DR out of stow position
4. GA- Signal initial deploy complete

DR- Initiate DR deploy operations

1. *DR Ground Control* - GA/DR indicate mission readiness
2. *DR Ground Control* - Initiate opening of EM bay door
3. *DR Ground Control* - Do nothing, waiting for GA to complete capture operation.
4. *DR Ground Control* - Receive signal from GA that capture is complete
5. *DR Ground Control* - Signal EM to power up DR
6. *DR Ground Control* – Establish Communication link with DR
7. *DR Ground Control* - Signal DR to perform basic self tests
8. *DR* – Send back test telemetry
9. *DR Ground Control* – Command stow latches to Release
10. *DR Ground Control* - Signal GA that we are ready to be withdrawn

DR Ground Control - Do nothing, waiting for GA to complete extraction

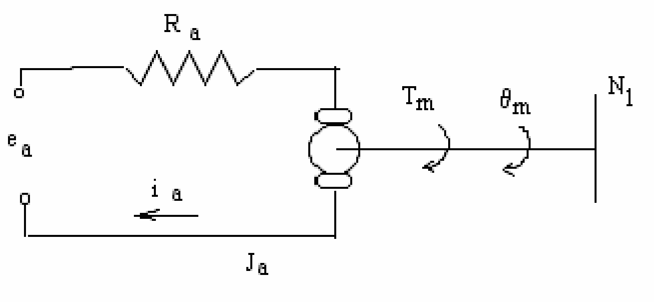



Mission Task Command Flow
DR service operation
Levels of Autonomy
0
1
2
3
Actors
Command Events
DR GC
Initiate service operation command
Send command signal- repeat until acknowledged
Acknowledge complete signal
Wait for move complete signal
DR Main CPU/ computer
Continually listen for commands
Update workspace definition
Based on update, determine move sequence and positions for service operations
service complete
Send commands to motor controllers in appropriate order- loop accordingly depending on device that is being driven and step of operation
DR Vision System Processor
Send commands to LCS and video cameras for update
Determine state of workspace
DR Motor Controller
Command motors to move to specified angles
Poll resolvers and signal when operation is complete
DR LCS system
Grab LCS data frame and output
DR video camera system
Grab video camera frame and output

Appendix 6 Controls

11.1 Dynamic Model

We model the DC motor armature to have resistance and negligible inductance. The speed of the motor generates a back emf voltage.



The equations governing the motor (with torque constant K) is:

$e_a - i_a R_a - V_b = 0$ where: e_a is the voltage supplied at the armature,

Ra is the armature resistance,

i_a is the armature current,

V_b is the back emf voltage due to the shaft rotation $K\dot{\theta}$

For the mechanical equation, we lump the motor inertia with the load inertia into the term I. The radial position of the shaft θ is related by:

$I\ddot{\theta} + C\dot{\theta} = Ki_a + T_l$ where C is a damping constant in the model, and T_l is some externally applied load.

After some algebraic manipulation, we get:

$$I\ddot{\theta} + \left(C + \frac{K^2}{R_a}\right)\dot{\theta} = \frac{KV_a}{R_a} + T_l$$

A simpler way to write it would be:

$$\tau\ddot{\theta} + \dot{\theta} = K_0(V_a + K_1 T_l)$$

where the new constant τ is $\tau = \dfrac{I}{(K^2/R_a) + C}$

And define K_0 to be $K_0 = \dfrac{K}{K^2 + CR_a}$, then $K_1 = \dfrac{R_a}{K}$

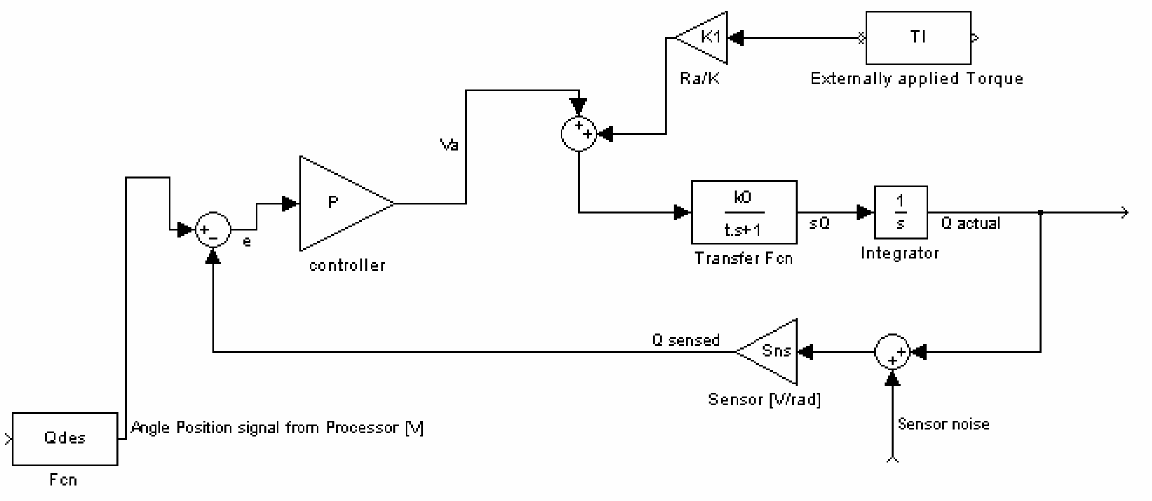
The final model relates the radial position derivatives in terms of the input voltage V_a.

$$\tau \ddot{\theta} + \dot{\theta} = K_0 (V_a + K_1 T_l)$$

The Laplace transform of the equation is:

$$s\theta(s) \times (\tau s + 1) = K_0 (V_a(s) + K_1 T_l(s))$$

11.2 Plant and Controller Block Diagram



Q represents θ, and t represents τ. Qdes(ired) is compared to Q sensed, and the error is sent to the PID controller that outputs the required armature voltage to the motor.

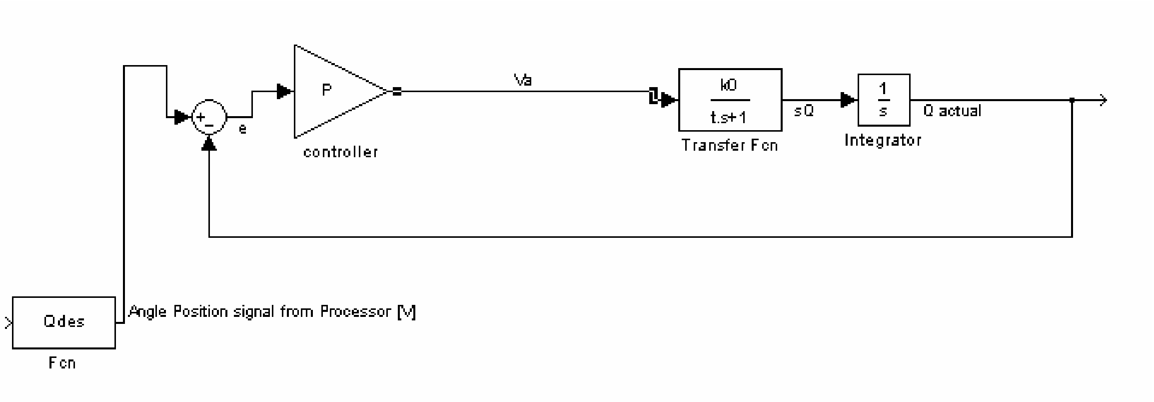
We selected a P controller because it satisfies all our transient and steady state need.
Using the data from the motor specification sheet we get:
Ra = 9 Ω
K = 0.043 Nm/amp

We require the rise time to be 2.5 seconds. Hence if we use the approximation that $t_r = \frac{1 - 0.4167\zeta + 2.917\zeta^2}{\omega_n}$, we can calculate that for t_r = 2.5 seconds and $\xi = 1$, we find that ω_n is at least 1.4 rad/sec. We should have a higher ω_n for a quicker rise time.

The settling time requirement to be no greater than 5 seconds imposes that:
$\omega_n = \frac{4.5\zeta}{t_s}$ = 0.9 rad/sec. Of course, ω_n will be greater to meet the initial requirement

I = mass of upper boom x (length /2)^2 + motor inertia = 2.58 kg – m^2.

For a simplified model with no noise or disturbances, we can assume the functional flow block diagram:



$$\frac{Ko}{\tau s+1}=\frac{0.00185}{s+0.387156(c+0.000205)}$$

The forward transfer function becomes:

$$G(s)=\frac{0.00185P}{s(s+0.387156(c+0.000205))}$$

For the stead state error requirement of 0.0046 degrees, we meet this because our forward transfer function has a zero pole, meaning this system is of type 1, and hence has a steady state error of zero for position control.

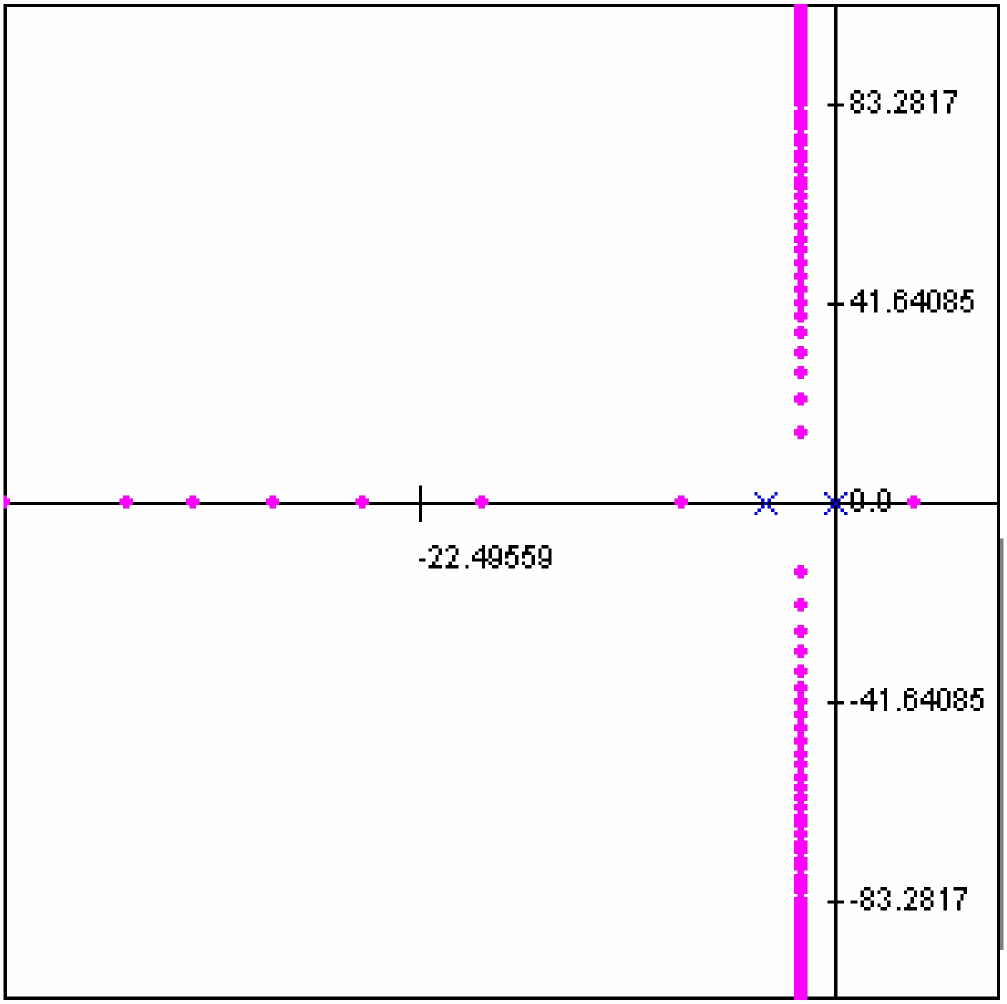
The final closed loop transfer function is:

$$\frac{\theta(s)}{\theta des(s)}=\frac{0.00185P}{s^2+0.387156(c+0.000205)s+0.00185P}$$

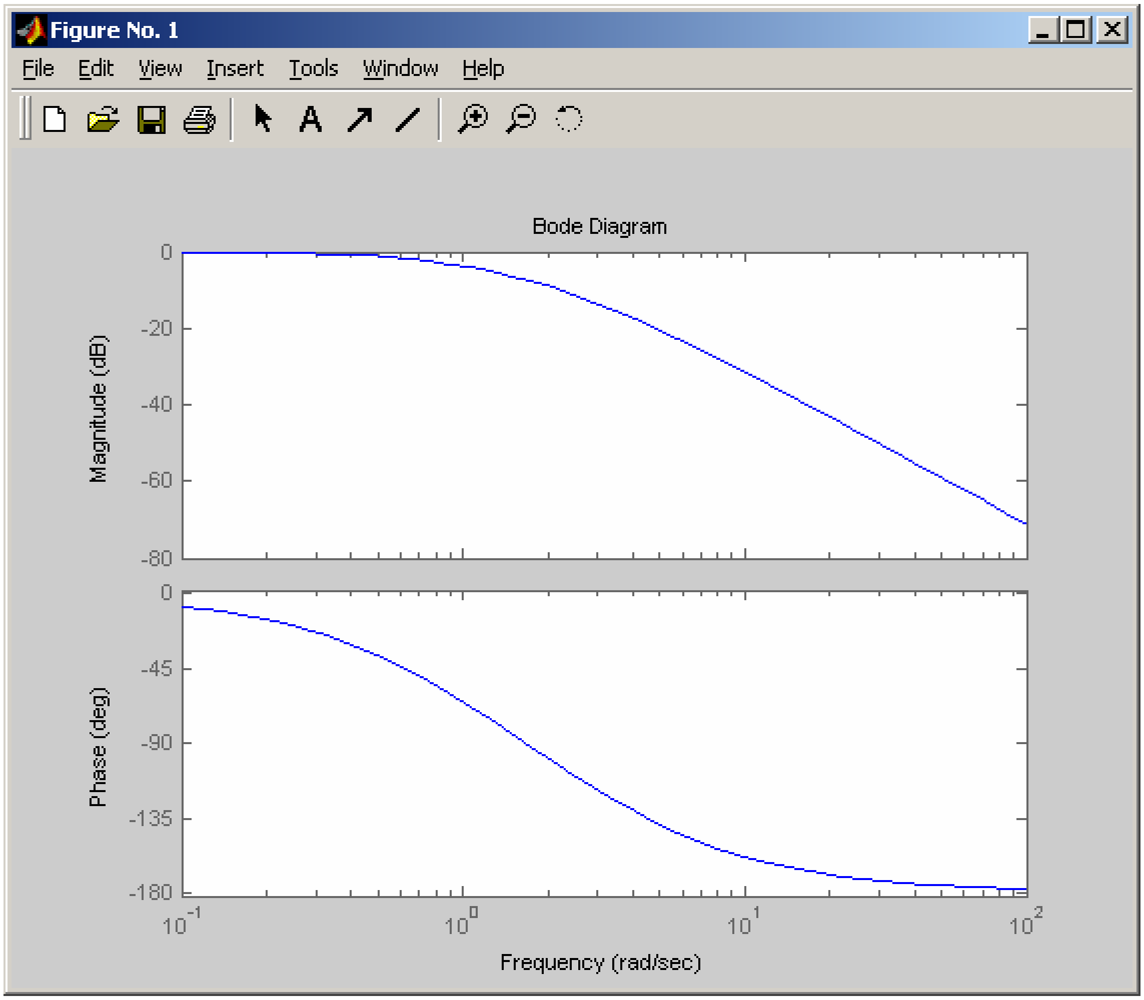
For 0.00185P =($\omega_n{}^2$ => 1.96), P >= 1059.
The damping ratio required is ξ =1, and hence
0.387156(c+0.000205)=2ξ ω_n , and so
c>= 7.232Ns/m
We take P to be 1500, and we take C = 10 to exceed the boundaries required.
The final transfer function is:

$$\frac{\theta(s)}{\theta des(s)}=\frac{2.775}{s^2+3.872s+2.775},\qquad \omega_n = 1.67 \text{ rad/sec, and } \xi = 1.16$$

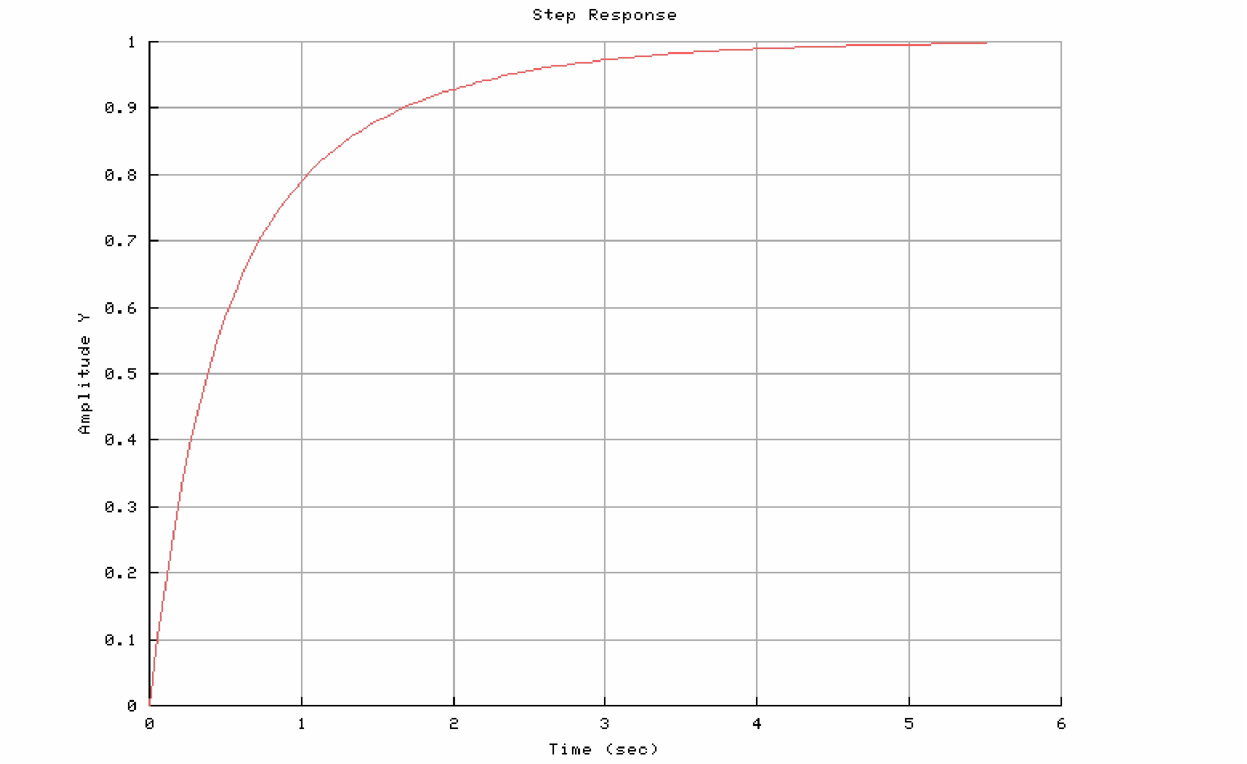
11.3 Root Locus Plot



11.4 Bode Plot



11.5 Step Input Response



11.6 Correspondence with Dr. Chad English PhD. NepTec,

Hello Dr. English,

Thanks for your reply, it really helped to clarify some misconceptions I had about the LCS, SVS and vision systems in general.

As my space systems course has been progressing, we have finally returned to vision systems as a final topic, and I think I perhaps know enough now to ask some better questions. Before doing that though, I thought I might give you a bit of background about our project so that you might understand what is motivating my interest in NepTec's LCS.

Our fourth-year space systems project is to design a robotic servicing system that will repair/replace hardware on the Hubble Space Telescope and provide it with a controlled de-orbit capability for it future disposal. All this of course, has to be done without any immediate human presence and requires the use of an advanced vision system (this is where your LCS sensor comes in!). My team is responsible (specifically) for designing a dexterous robot which will perfrom the close-range serviicing operations.

So here are some questions I've thought of,

1)I've selected the LCS because it can operate in any lighting condition... Immune to glare etc. To what extent does this assumption hold (can direct sunlight blind the LCS?) and is this the case for all surfaces? this leads me to my next one,

1) Since the LCS determines depth information by bouncing a laser off of an object.. how well does it perform on a highly specular surface such as the Hubble (the exterior is as shiny as a mirror)?

2) I know the LCS has two modes operation- scanning and tracking- could you elaborate on the advantages and limitations of either mode? Does tracking require pre-placed targets? or will well defined edges suffice?

3)How fast can the LCS update its scan..?. what resolutions are available? since there are no markers on the Hubble we'll have to match each scan to a 3D model.

4)How large (Mb) is each scan- are you aware of any rad-hard processors that can deal with that much information to provide useful feedback for a control loop (our robotic arms)?

5)Has NepTec used the LCS to provide visual feedback to a control system? how did you do this?

6)Lets say I had two LCS's operating at the same time, side by side... would they interfere with each other? (we're required to have single fault tolerance in our system etc- we wouldn't necessarily run them at the same time... but who knows!)

7)How do scientists in the machine vision field estimate the computational cost of 3d model matching or registration? (this is the one that we're really struggling with, since we need to select a processor that's up to the task)

well that about sums it up-

I really appreciate your help.

thanks,

Kristian

Dr English’s Response-

Kristian,

See my answers after each question below.

Regards,
Chad

This has been proven several times. We flew the LCS on shuttle flight STS-105 (August 2001) and performed scans during "day" and "night" (in orbital terms) passes. We showed that the scans were identical. (This was published.) Also, in July 2003 we did tests with NASA at Johnson Space Center where the shone a mini-sun lamp (simulates wavelengths and intensities of sunlight in space) during scans and found that there was no effect on the scan results.

The solar immunity comes from a few sources. First, the laser wavelength in LCS is 1500 nm which is a low point in the solar spectrum. The detector we use is only sensitive from about 900 nm to 1700 nm so any other solar light won't show up. Then we also put a narrow bandpass filter in front of the detector that only lets in 1500 nm +/- 10 nm.

Next, although LCS has a total field-of-view (FOV) of 30 deg by 30 deg, the instantaneous FOV is only about 3.5 degrees, meaning the detector can only see 3.5 degrees at a time and we move this small FOV around the big FOV as we scan. This small instantaneous FOV means that the detector can only pick up a small amount of solar light during each measurement compared to wider FOV sensors like normal cameras.

Combining these, there is very little intensity from the sun that reaches the detector that could possibly create any interference in the measurement. As I say, the immunity has been proven several times as well.

> 1) Since the LCS determines depth information by bouncing a laser off
> of an object.. how well does it perform on a highly specular surface
> such as the Hubble (the exterior is as shiny as a mirror)?

Excellent question. (Two questions #1?) As with any optical system, specular surfaces pose a difficulty. Keep in mind that surfaces might be specular at one wavelength of light but not another. I don't know the specular reflectivity of Hubble for near-IR like 1500 nm. (Of course, I don't know it for visible light either.)

The net effect of specular surfaces is that we can only "see" parts where the surface normal is generally pointing back towards the camera, plus or minus some angle. We've scanned many specular surfaces successfully, including in space, but in areas where the normal is steep relative to the camera we don't get any measurement. Again, that's true of any optical system.

> 2) I know the LCS has two modes operation- scanning and tracking-
> could you elaborate on the advantages and limitations of either mode?
> Does tracking require pre-placed targets? or will well defined edges
> suffice?

Things have changed a little. In the original software these were the only modes. Scanning could be done on anything. It entailed moving the laser spot in a raster pattern and making a range image where each "pixel" of the scan would have an (X,Y,Z) and intensity value. Tracking was the original intent of the scanner and it worked on circular targets, either normal SVS targets or retro-reflectors. I'm not sure what I'd say about advantages of either, they did what they were designed to do.

Since then, we've developed algorithms for tracking generic objects without targets. All it needs is some 3D detail like curvature. Flat surfaces are harder to track, although we can get most of their degrees-of-freedom, just not the roll.

We also have modes of scanning in various scanning patterns. Since LCS uses scanning mirrors, we don't have to scan in raster patterns. We can scan in essentially arbitrary patterns at gather 3D data at each point. This has big benefits over other approaches because raster scanning (like most 3D scanners) gathers *all* data in FOV of the scanner (or some section of the FOV). If we only want to scan certain objects or features on an object then everyone ends up throwing away most of the data and only keeping the relevant data. Arbitrary scan patterns allow the scanner to only scan the points of interest, especially given the ability to track where the object and features are.

> 3)How fast can the LCS update its scan..?. what resolutions are
> available? since there are no markers on the Hubble we'll have to
> match each scan to a 3D model.

The update rate depends on a number of factors. The length of time to take a single point measurement depends on the integration time of the detector, which we control. If the object is close we only have to integrate the reflected light for a very short time (e.g., 20 microseconds). If it's far away it might take hundreds up to thousand of microseconds per point. (Light intensity falls with the square of distance, so the integration time correspondingly increases with the square of object distance.)

That covers the time for a single point measurement. How long the entire scan takes depends on how many points are in the defined scan. We typically use up to 1024 points in a non-raster scanning pattern (such as Lissajous patterns). At that rate we can repeat the pattern generally about 2-10 times per second depending on the integration time (range to object). It scales linearly for fewer points (e.g., with 256 points per scan pattern we could get 4 times as many - 8-40 scans per second).

For raster scans it just scales up linearly. If we do 1024 x 1024, and we do 2-10 lines per second (as above for 1024 points), then it takes about 100 (1.5 min) - 500 seconds (8 min) for the total scan. (We rarely take more than about 3 minutes for a 1024x1024.) Lower resolutions scale with the square, e.g., a 256x256 takes 1/16th the time since there is 1/16th the number of points.

The resolutions available for raster scans are 2x2 up to 1024x1024 and don't have to be square (e.g., 2x1024). For other scan patterns the resolution is anywhere from 2 to 1024 points in the scan pattern. The FOV that the raster images or scan patterns is completely adjustable, so you can make 1024x1024 points cover 30deg x 30deg or as low as 0deg x 0deg (measuring the same point a million times). So there is a wide range of possible scanning configurations.

As far as a 3D model, we have software that tracks objects and updates the pose estimation with a 3D model of the object. Autonomous rendezvous and docking is one of the applications we are looking at using this for, but there are a number of other applications. We tend to use non-raster patterns for this since we don't need all of that data to get the pose estimation.

> 4)How large (Mb) is each scan- are you aware of any rad-hard
> processors that can deal with that much information to provide useful
> feedback for a control loop (our robotic arms)?

Yes, we are working on some of that already with our current NASA contract. As far as the processor I don't have the exact answer. We have ones that are rad-hard but I don't know the models. I can find out later but it will be tomorrow. I think the VR7 board is one possibility. (I can't remember the manufacturer.)

The scans are about 10 bytes per voxel measurement. (About 10 MB for a 1024x1024.) But that's before compression.

> 5)Has NepTec used the LCS to provide visual feedback to a control
> system? how did you do this?

For an external control system, no. We are working with several groups to do this for autonomous vehicle operations (rovers, mining vehicles, etc.) as well as robotic arms for manufacturing environments. But these are preliminary efforts right now.

Internally, we use data from scan patterns to plan the next scan pattern within the scanner. In other words, the object pose estimation from one scan pattern will change the size, shape, and position of the next scan pattern. This approach could generally be applied to a pan-tilt unit or even a robotic arm, though the computations would be different and more complicated. (2 DOFs for scanning mirrors or pan-tilt is easier than multi-DOF for robotic arms.)

> 6)Lets say I had two LCS's operating at the same time, side by side...
> would they interfere with each other? (we're required to have single
> fault tolerance in our system etc- we wouldn't necessarily run them at
> the same time... but who knows!)

Generally, no. We've never had a reason to have two running at the same time or interfacing with each other. That being said, our current control software can control more than one scanner at a time and use the data however you want, e.g., have the data from one scanner affect the commanded scan pattern for the other scanner. We haven't done this, but there's no reason you couldn't.

> 7)How do scientists in the machine vision field estimate the
> computational cost of 3d model matching or registration? (this is the
> one that we're really struggling with, since we need to select a
> processor that's up to the task)

Ooh, tough question. We tend not to calculate it. We just do it and see how long it takes. Currently, our 3D model pose estimation calculations / registration is on the order of a few milliseconds on a 3 GHz PC. But we're using some proprietary algos. Other algos can take many seconds to minutes to register data. It really depends on the algos.

> well that about sums it up-
>
> I really appreciate your help.

OK. Hope this all helps.

11.7 DataDictionary

Device	Data	Description	To	From	Units	Range	Precision	Accuracy
LCS	3D map	The three dimentional map of the workspace and surrounding	LCS CPU	LCS	N/A	30	16777216 bits per image	4096x 4096 resolution
	Distance		LCS CPU	LCS	m	30 m	13 bits	0.1mm @ 1m 2mm @ 5m 10mm @ 10m 80mm @ 30m
Minicams(4)		Video	Earth control	Minicams	N/A	0 to infinite		659 (H) x 494 (V) @
Camera Lighting System	on/off state	whether the lights have to be on or off			N/A	0,1	1 bit	1
IR Sensors	on/off	indicates whether they are too close to the Hubble for collision	DR CPU	IR Sensors	N/A	0,1	1 bit	1
Resolvers (16)	motor position	motor shaft angle relaive to initial position	DR CPU	Resolvers (16)	arc sec	0 to 135	20 bits	+/- 4 arc mins
T/F Sensors (2)	Torque	Torque at motor shaft of EE			N/m			
	Force	Force at motor shaft of EE			N			

Thermocouple	Voltage	voltage drop proportional to temperature relative to normal temperature			degrees Celcius	-120 to 120	8 bits	1
Touch Sensors					N/A	0 and 1	1 bit	1
Limit Switches (28)	on/off state	To indicate whether a motor has reached the end of its range of motion			N/A	0 and 1	1 bit	1
DR CPU	Position Data	To position DR into the required workspace in terms of (x,y,z) coordinates			m	0 to 15	14 bit	0.001
	Emmergency Stop				N/A	0 and 1	1 bit	1
Motor Microcontrollers								
Heater switches		Switch control to turn heaters on and off as necessary			N/A	0 and 1	1 bit	1
Ground/EM Comm	Command data and engineering data		-	-	-	-	-	-

11.8 Mini Specification for motor control Level 2

```
Function: Motor/Shaft position monitor 1.1.1
Inputs:   data input:pulse count, direction
          Time input:from CPU
Outputs:  position and velocity
Psuedocode:
     Loop
          When motor are in motion and when requested
```

```
          Read pulses for resolver
          Read time from central computer;
          Calculate position from pulses;
          Calculate velocity from position and time data;
          Provide these data to requesting module;
     End loop
```

```
Function: Monitor Force and Torque 1.1.2
Inputs:   data inputfrom sensor:Torque and force data from T/F sensors
          Outputs:  torque and force at each joint
Psuedocode:
          Loop
               Read torque/force data from t/F sensors;
               Apply 6D jacobian (1) to calculate force and torque at each joint;
               Output data to motor command calculator(1.1.4);
               Report data to Overload monitor module (1.1.6);
          end loop
```

(1) See appendix 8 for the 6D jacobian

```
Function: Command interpreter 1.1.3
Inputs:   Data input: scripted motor control data
          Data input: Earth Control command for motors
          Data input: Emmergency commands
Outputs:  destination position and velocity
Psuedocode:
          Loop
               Check for emmergency halt commands;
               Check for command from Earth control;
               Get required motor position data from script;
               If
                    Emmergency halt command exists forward to command control module;
               Else if
                    Earth command exists, it overrides scripted command;
               Else
                    Pass on scripted command to motor command calculator;
          End loop
```

```
Function: Motor command calculator 1.1.4
Inputs:   Data input: Command from interpreter
```

Data input: motor/shaft position from encoder
Data input: force/torque on each joint
Data input: Power availability
State data: overload status
State data: motor health
Outputs: PWM values for each motor

Psuedocode:

```
Loop
    Acquire overload status;
        If overload
            Shutdown motor;
        Else
            Acquire command from interpreter (1.1.3);
            Acquire motor position and velocity (1.1.1);
            Acquire force torque at each joint(1.1.2);
            Acquire motor health;
            Calculate force and torqure required at each joint using 6D jacobian;
            Translate it into pwm for mosfets controlling current to motor;
            Output PWM values to moto microcontrollers;
End loop
```

Function: power availability command signal unit 1.1.5
Inputs: data input: motor power requirements
Data input: power availability
Outputs: power available for motors
Psuedocode:

```
Loop
    Acqure power required;
    Aquire power available;
    Deficit = power availabe – power required
    if deficit < 0
            Report to motor command calculator (1.1.4);
        Else
            return zero to motor command calculator (1.1.4);
End loop
```

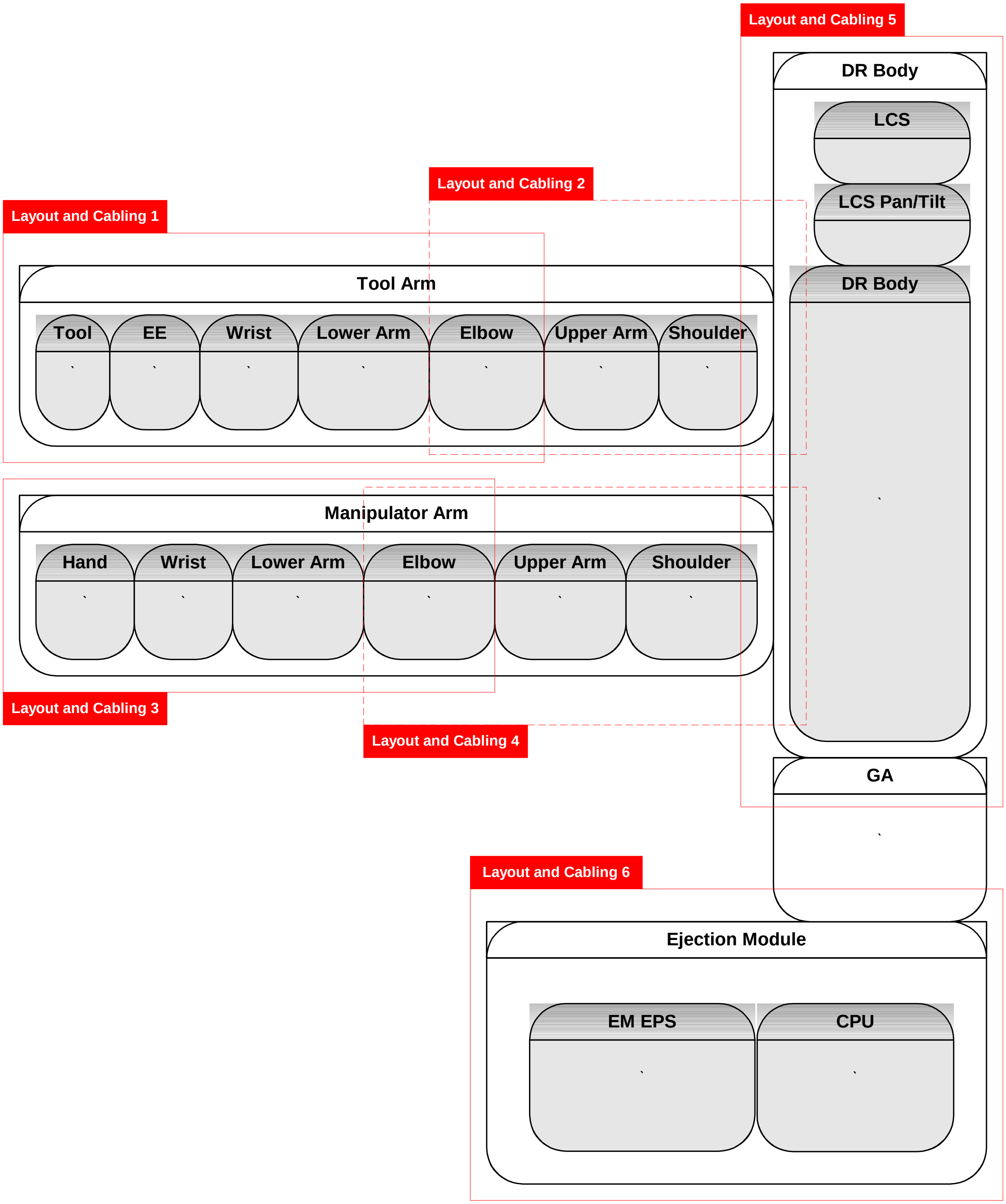
Function: Overload monitor 1.1.6
Inputs: data input:force/torque at each joint
Outputs: emmergency stop command
Psuedocode:

```
Loop
    Acqure force/Torque at each joint;
    For each joint{
        Difference = max load – current load
        If differnece < 0
            Issue emmergency stop command to motor command calculator;
        Else
            Return everythin normal to motor command calculator;
    }
End loop
```

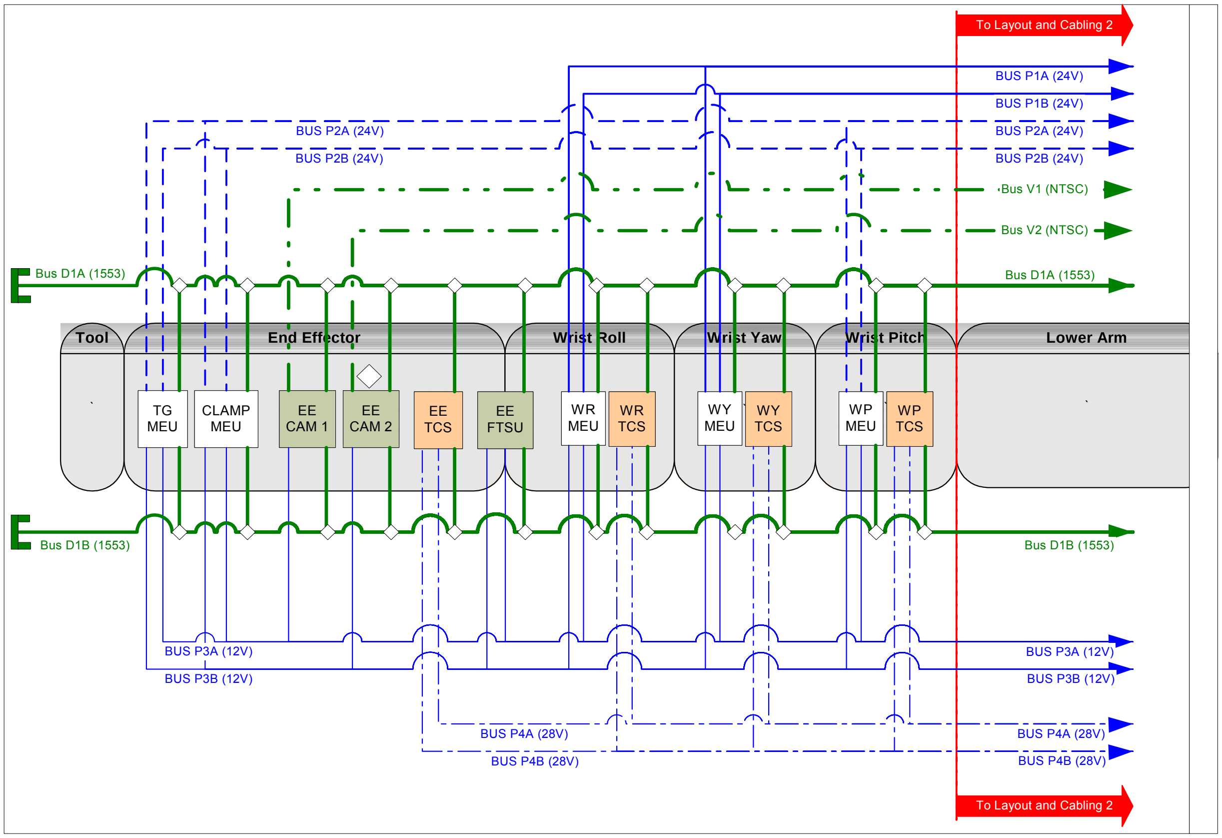
Appendix 7 Electrical

Appendix 7.1 Cable Layout

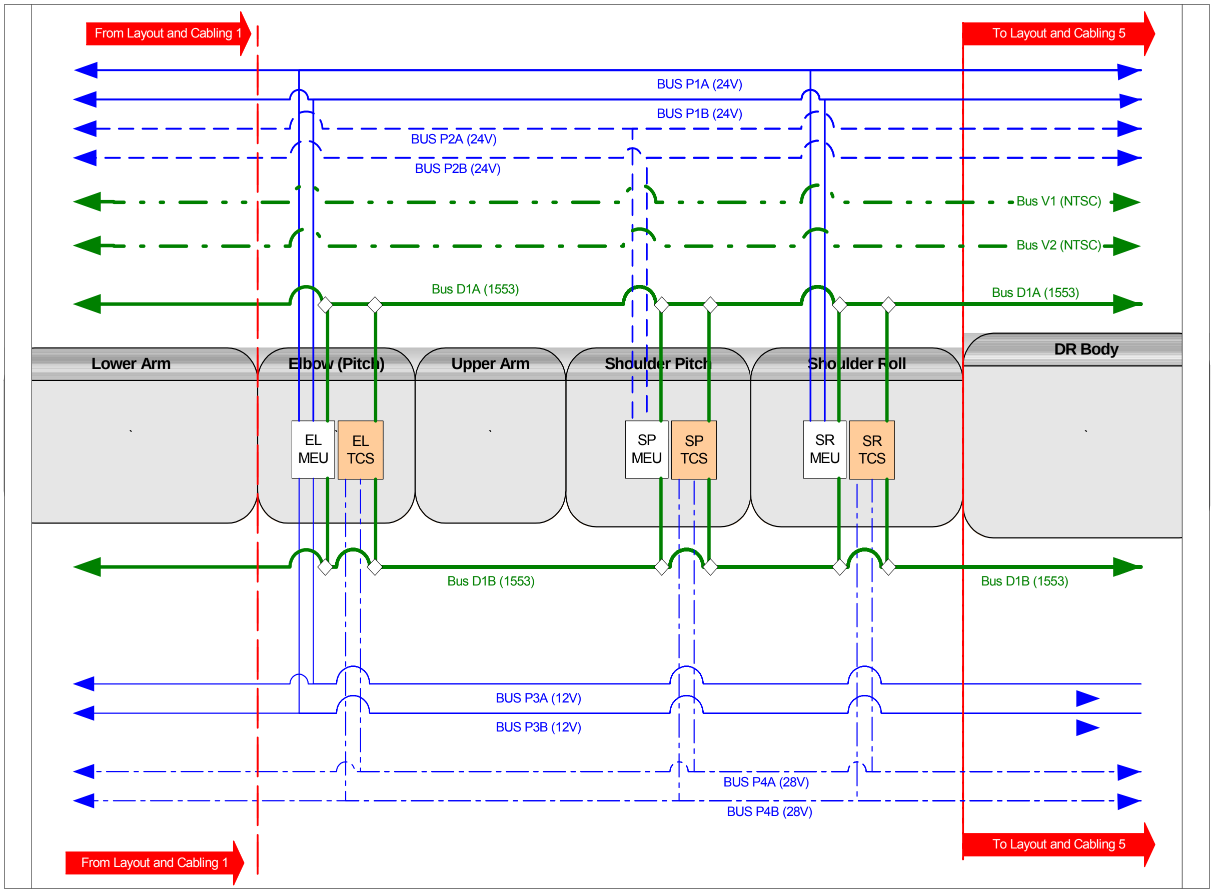
Appendix 7.1.1. Cable Layout Map



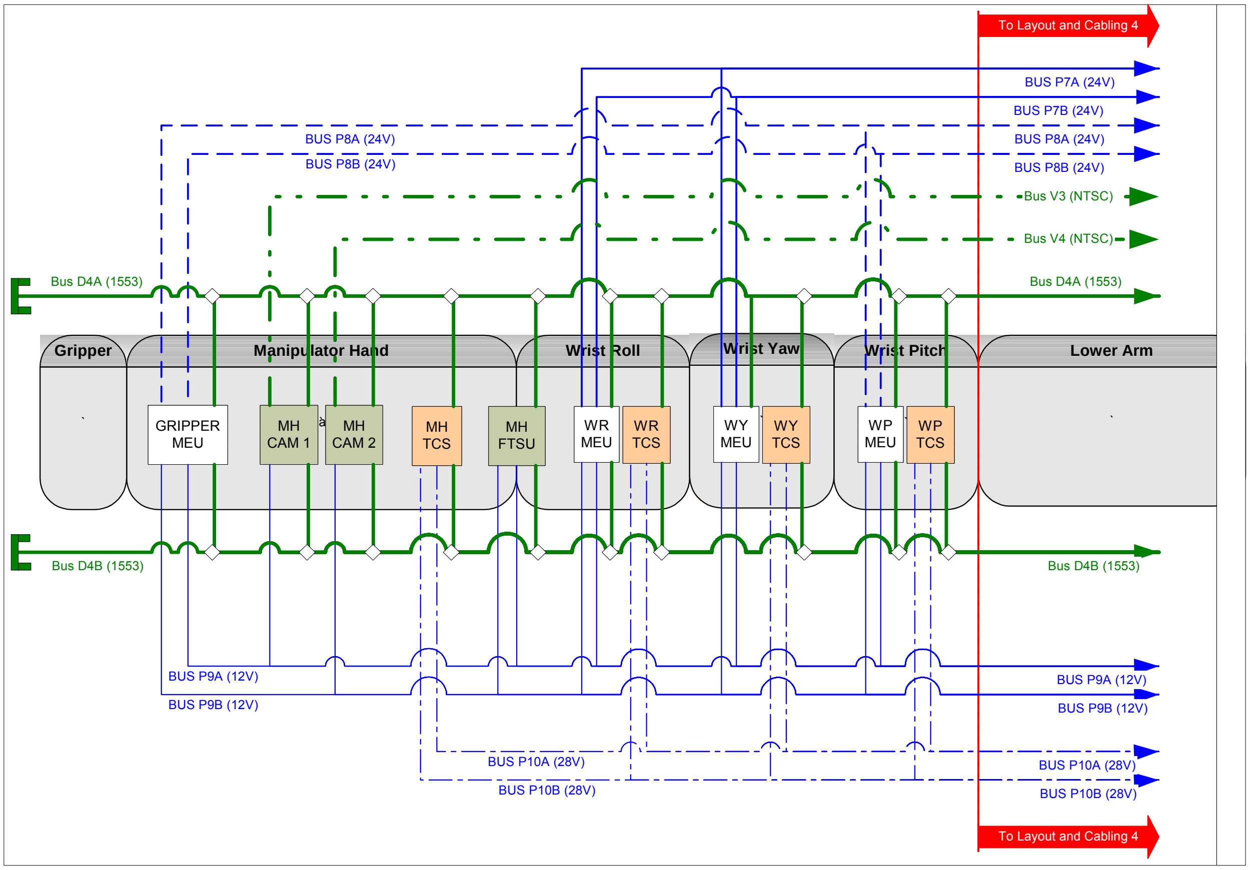
Appendix 7.1.2. Layout and Cabling 1 – Lower Tool Arm



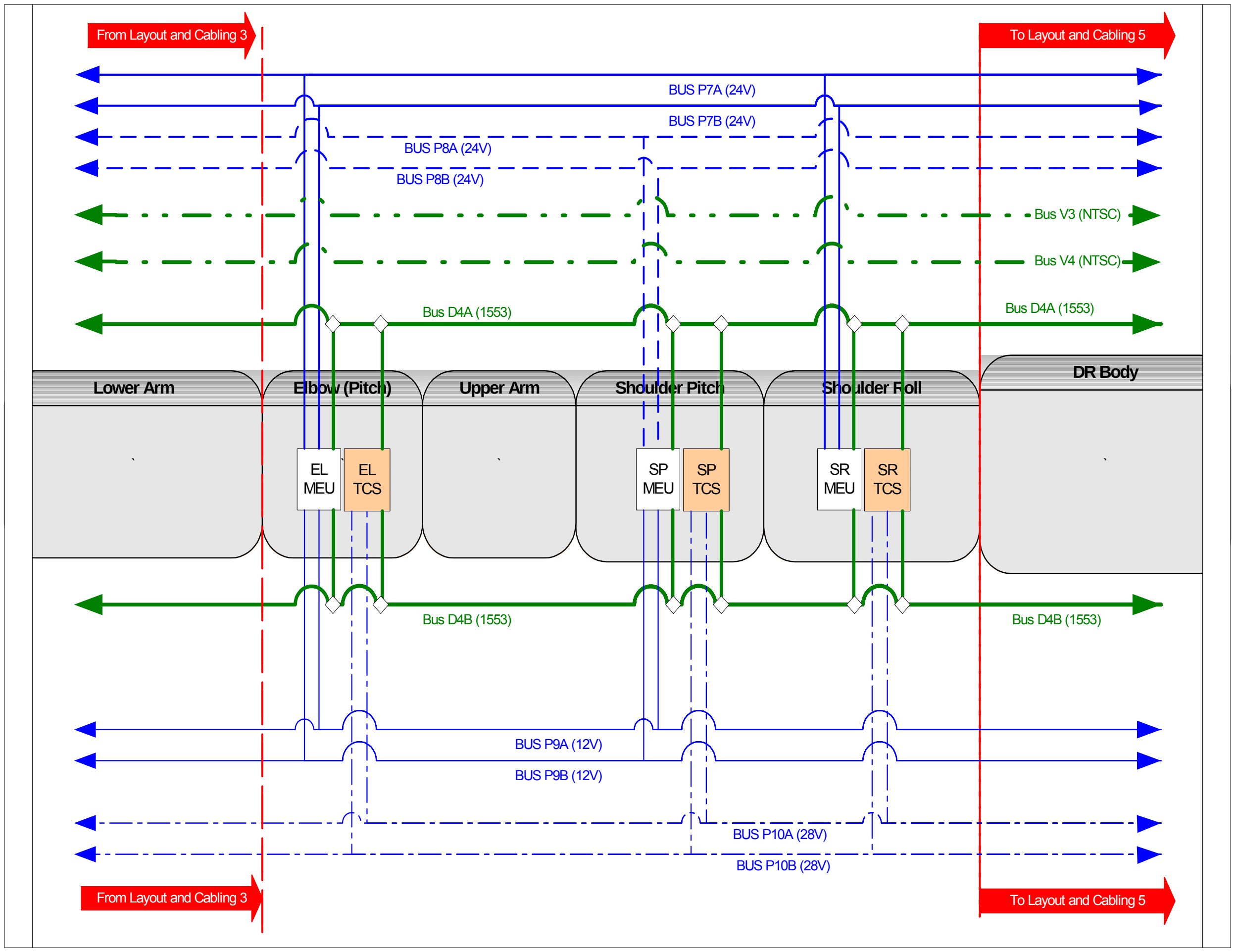
Appendix 7.1.3. Layout and Cabling 2 – Upper Tool Arm



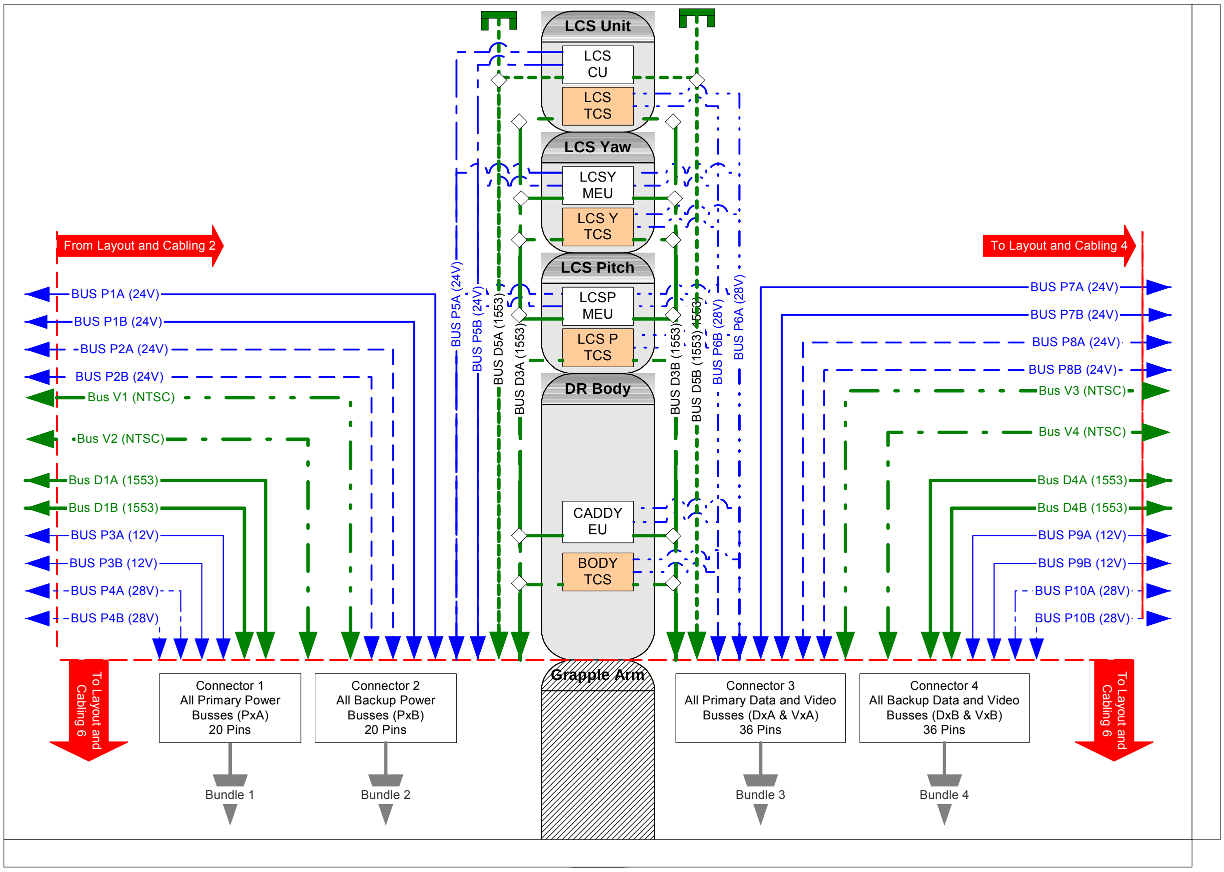
Appendix 7.1.4. Layout and Cabling 3 – Lower Manipulator Arm



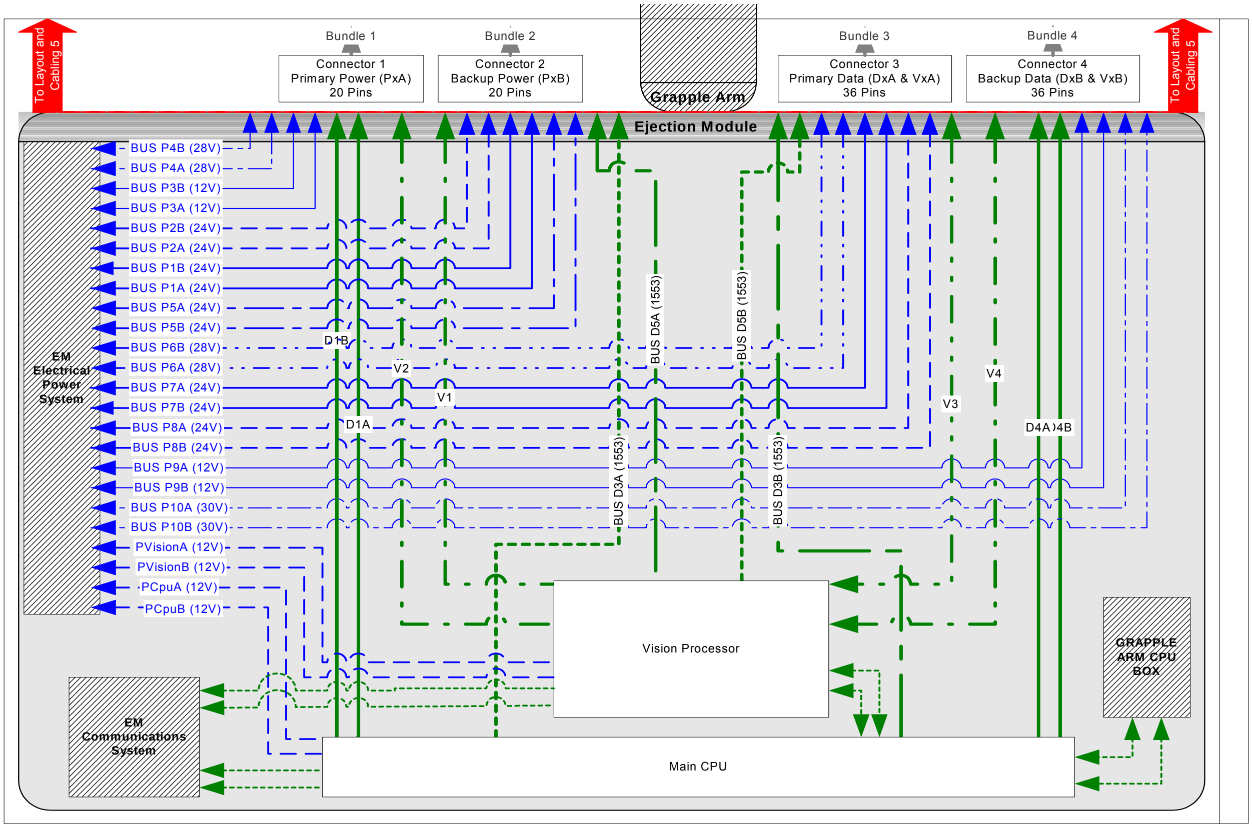
Appendix 7.1.5. Layout and Cabling 4 – Upper Manipulator Arm



Appendix 7.1.6. Layout and Cabling 5 – DR Body

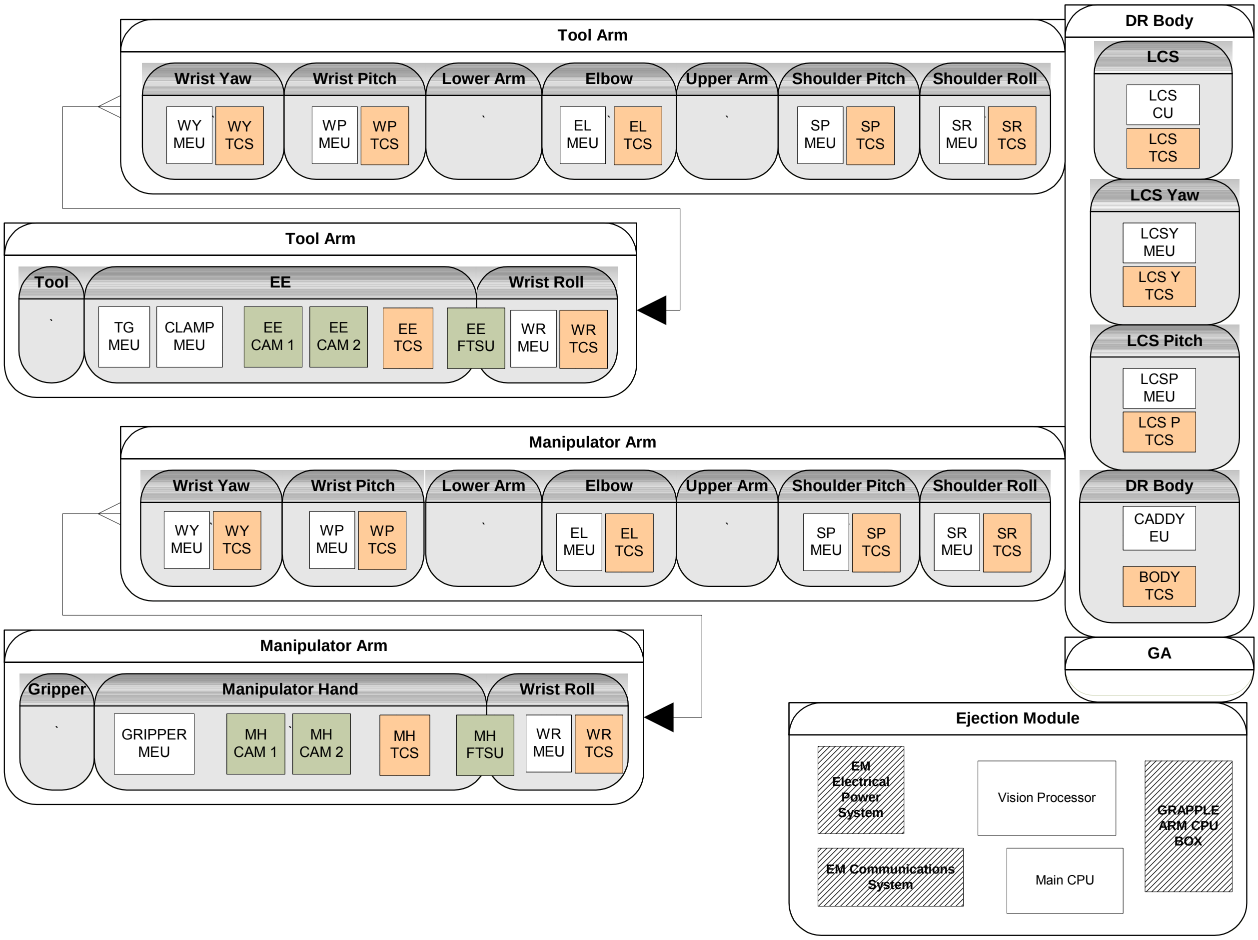


Appendix 7.1.7. Layout and Cabling 6 – EM

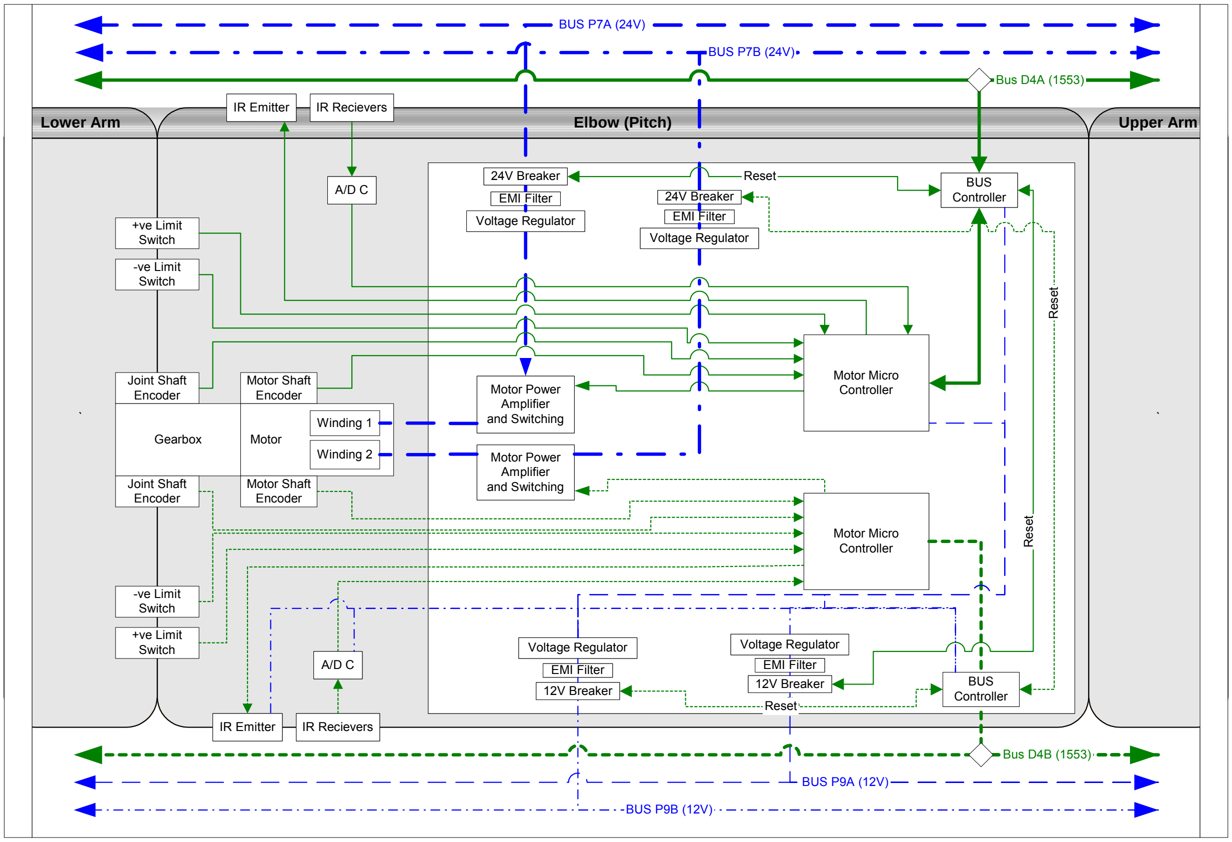


Appendix 7.2 Electrical Functional Block Diagram

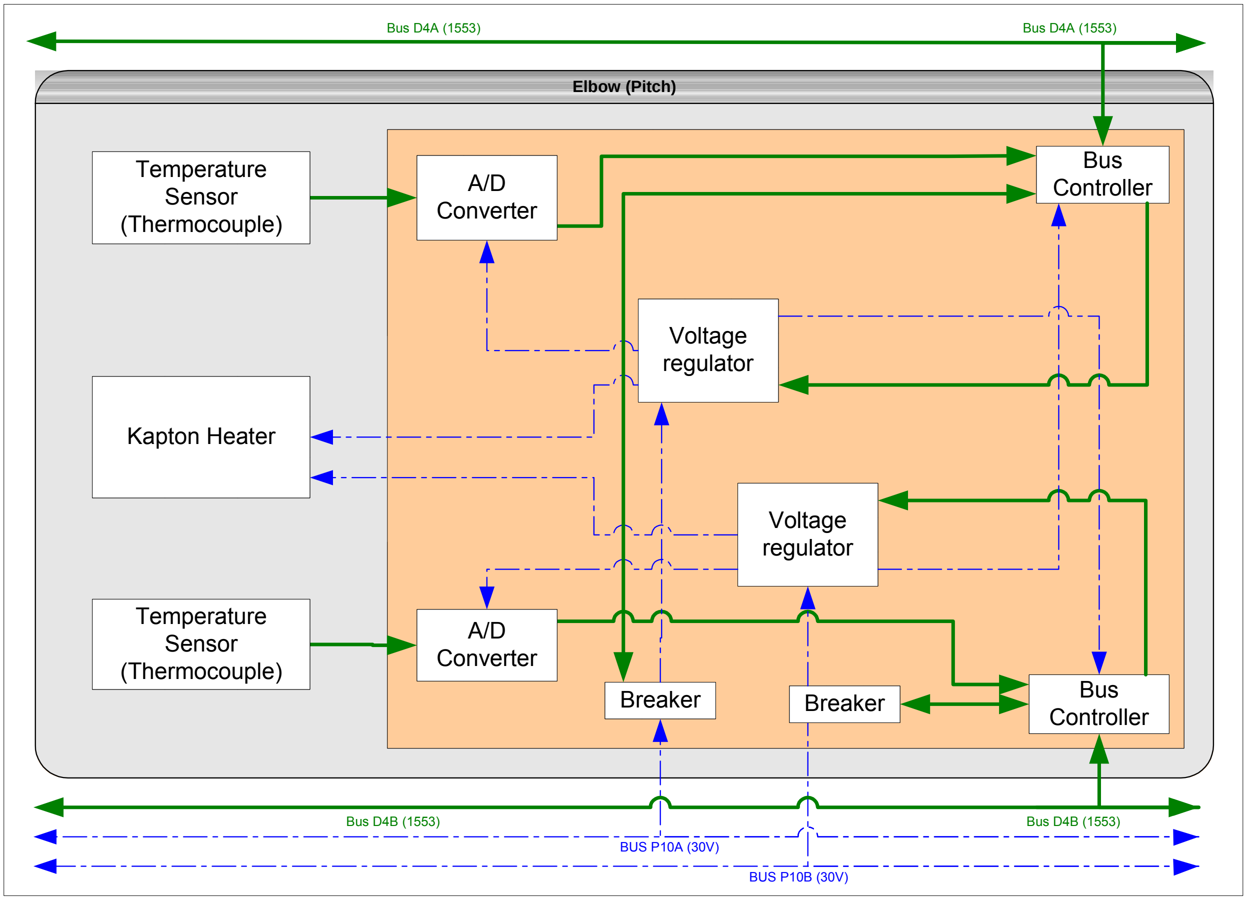
Appendix 7.2.1. High Level EFBD



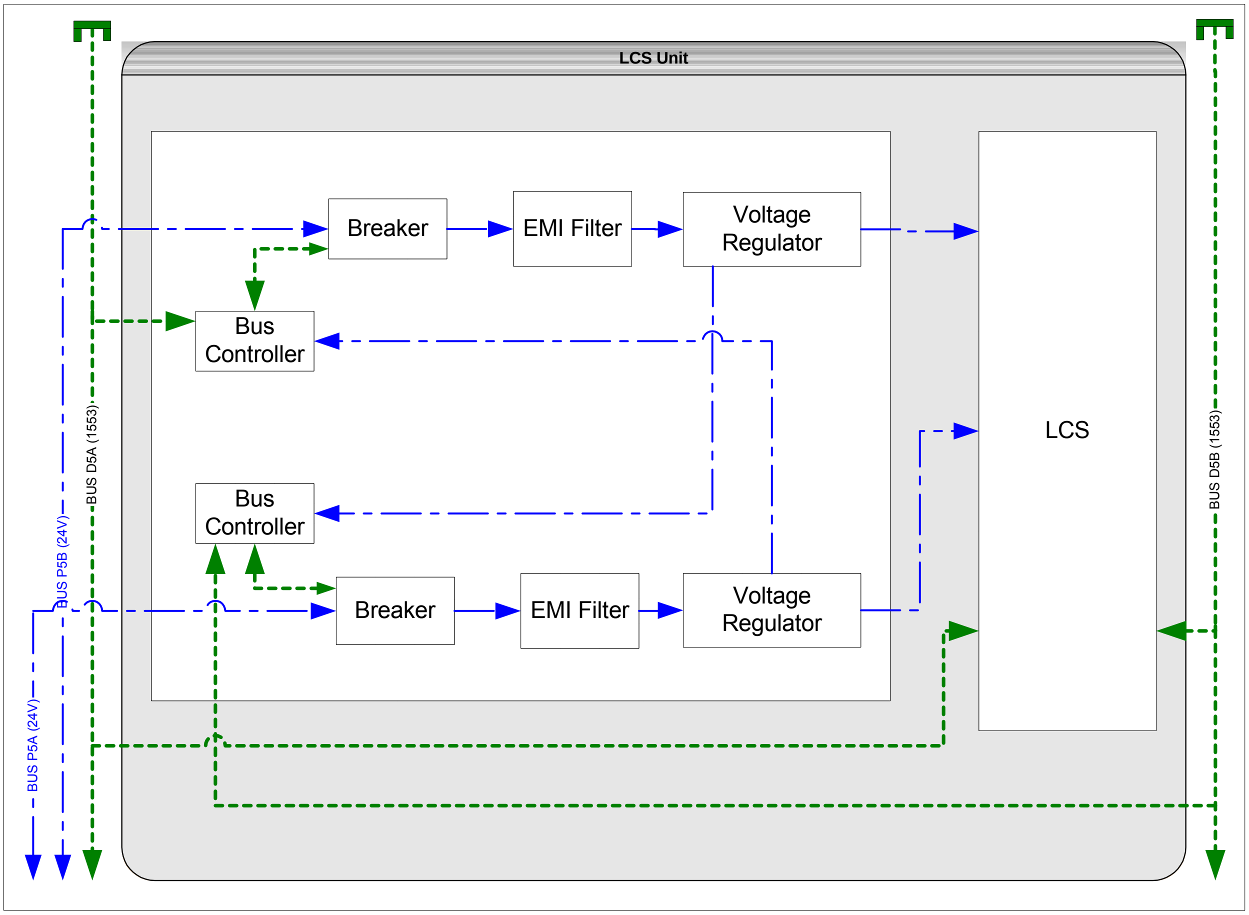
Appendix 7.2.2. EFBD 1 - Motor EU



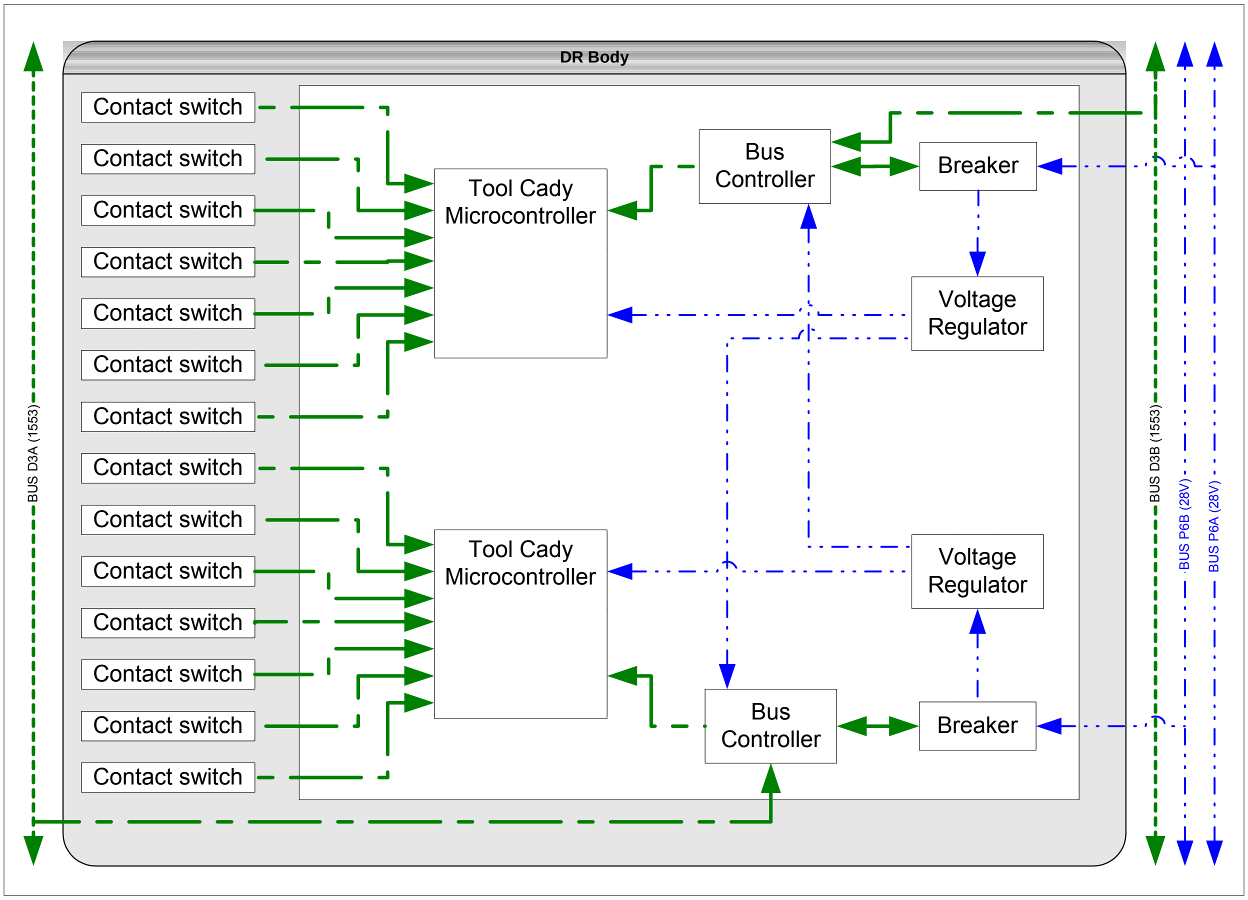
Appendix 7.2.3. EFBD 2 - Thermal Control System



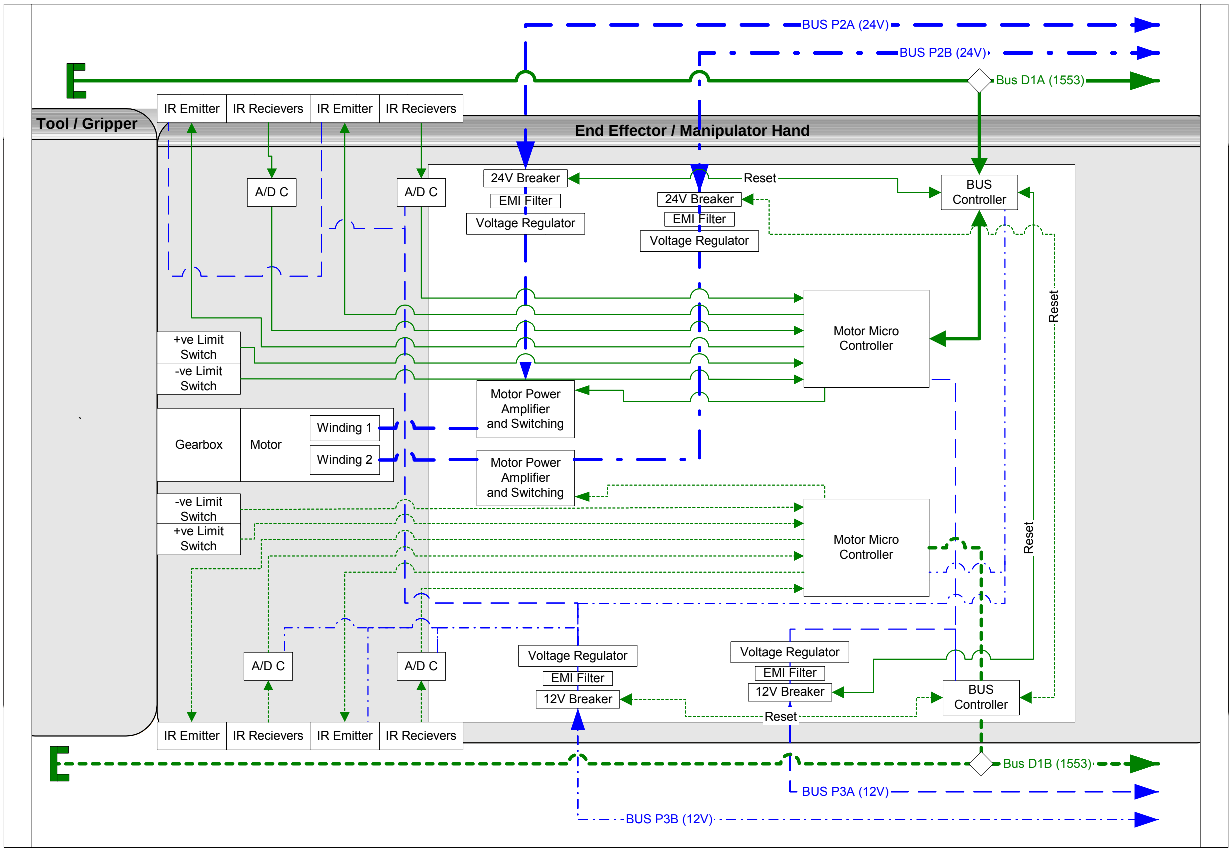
Appendix 7.2.4. EFBD 3 - LCS EU (Control Unit)



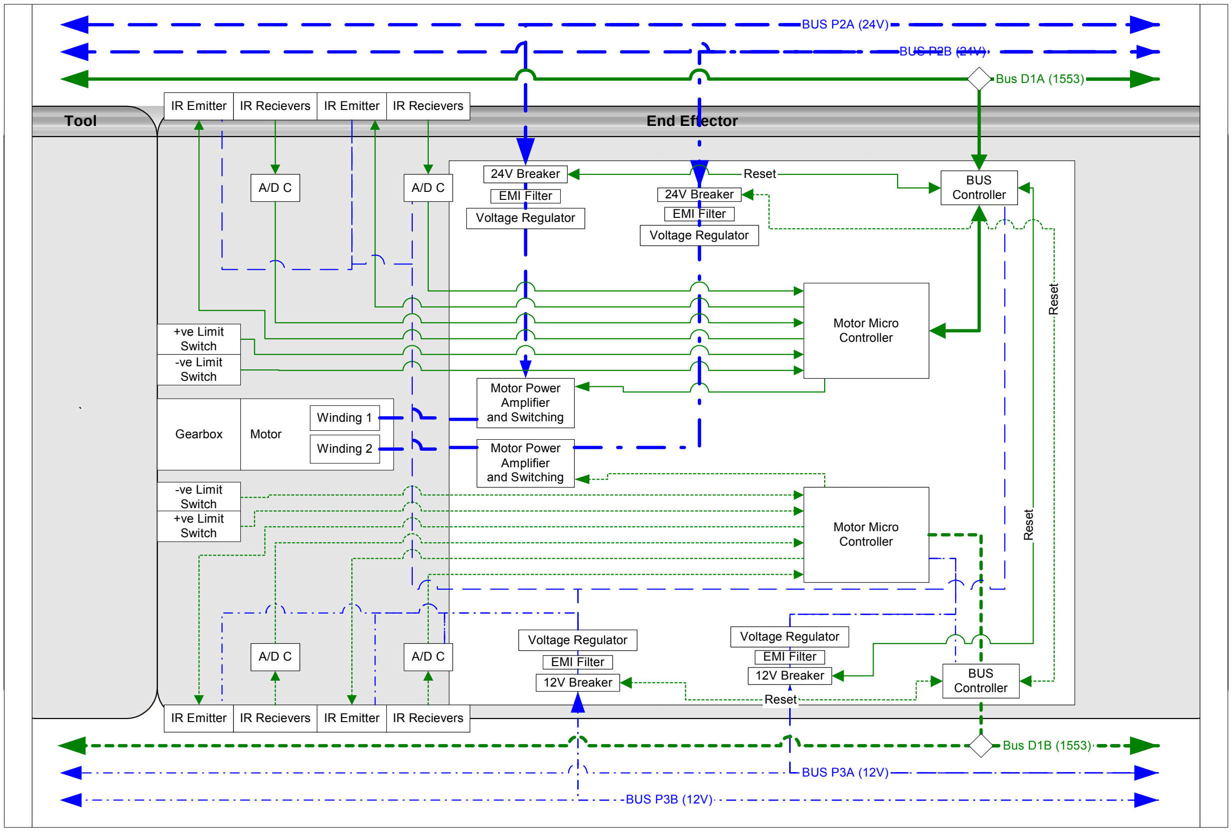
Appendix 7.2.5. EFBD 4 - Tool Caddy EU



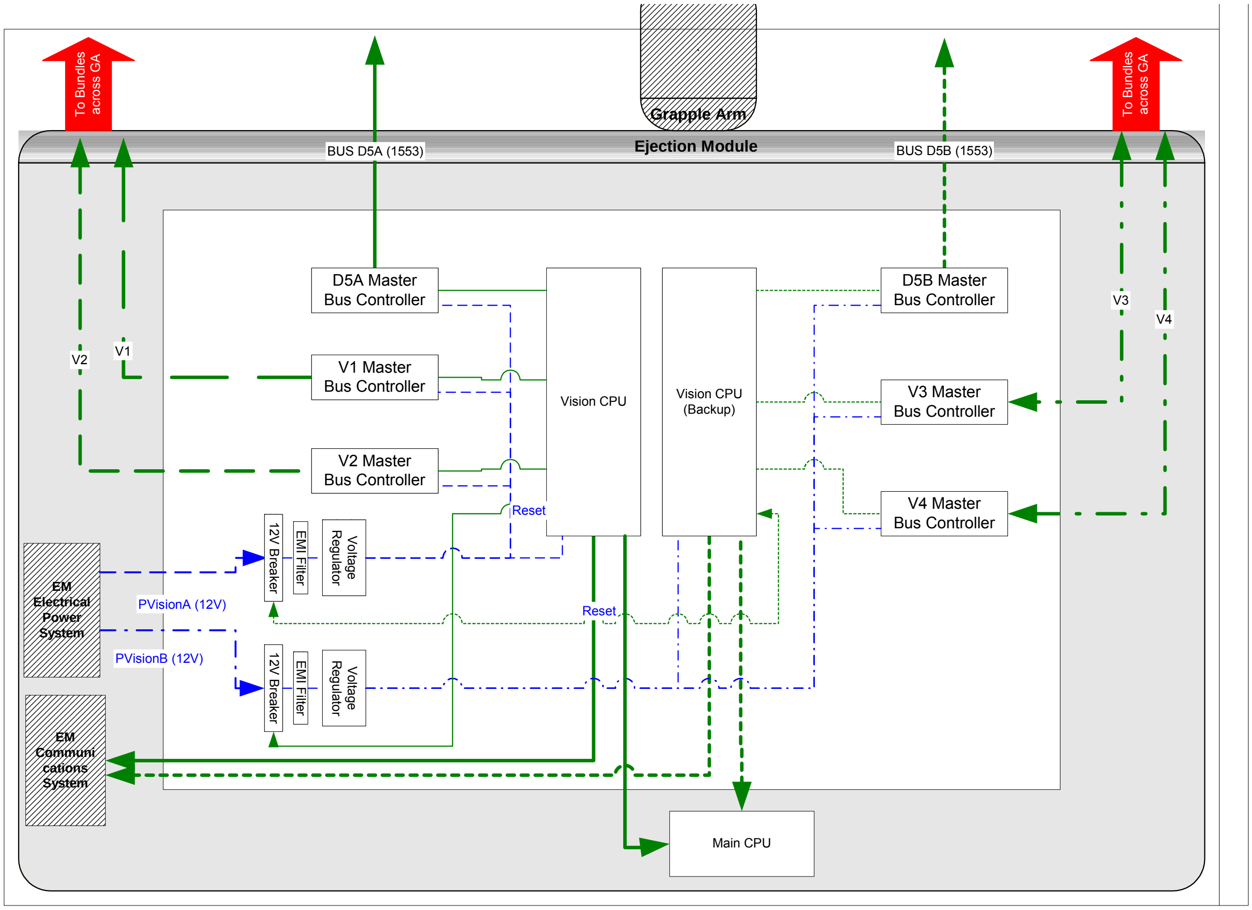
Appendix 7.2.6. EFBD 5 - Tool Gripper MEU



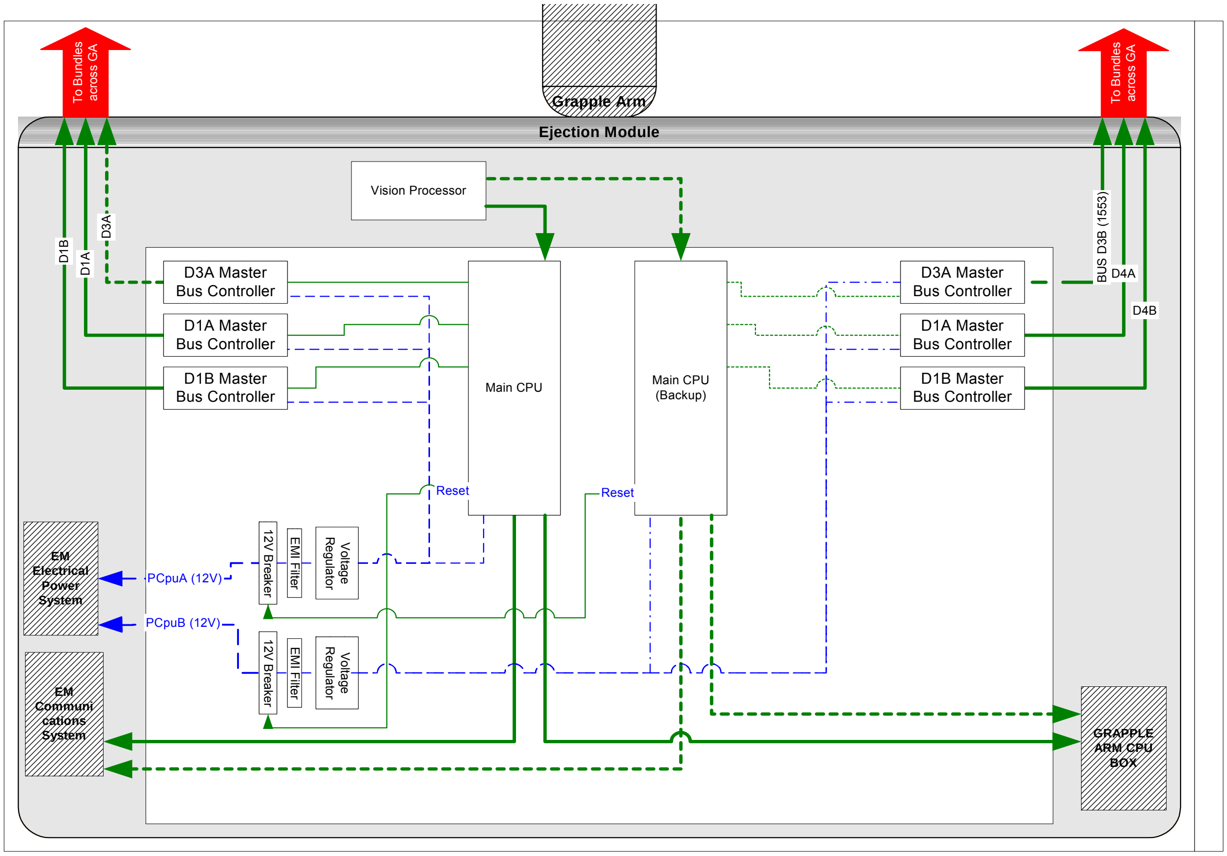
Appendix 7.2.7. EFBD 6 - Clamp EU



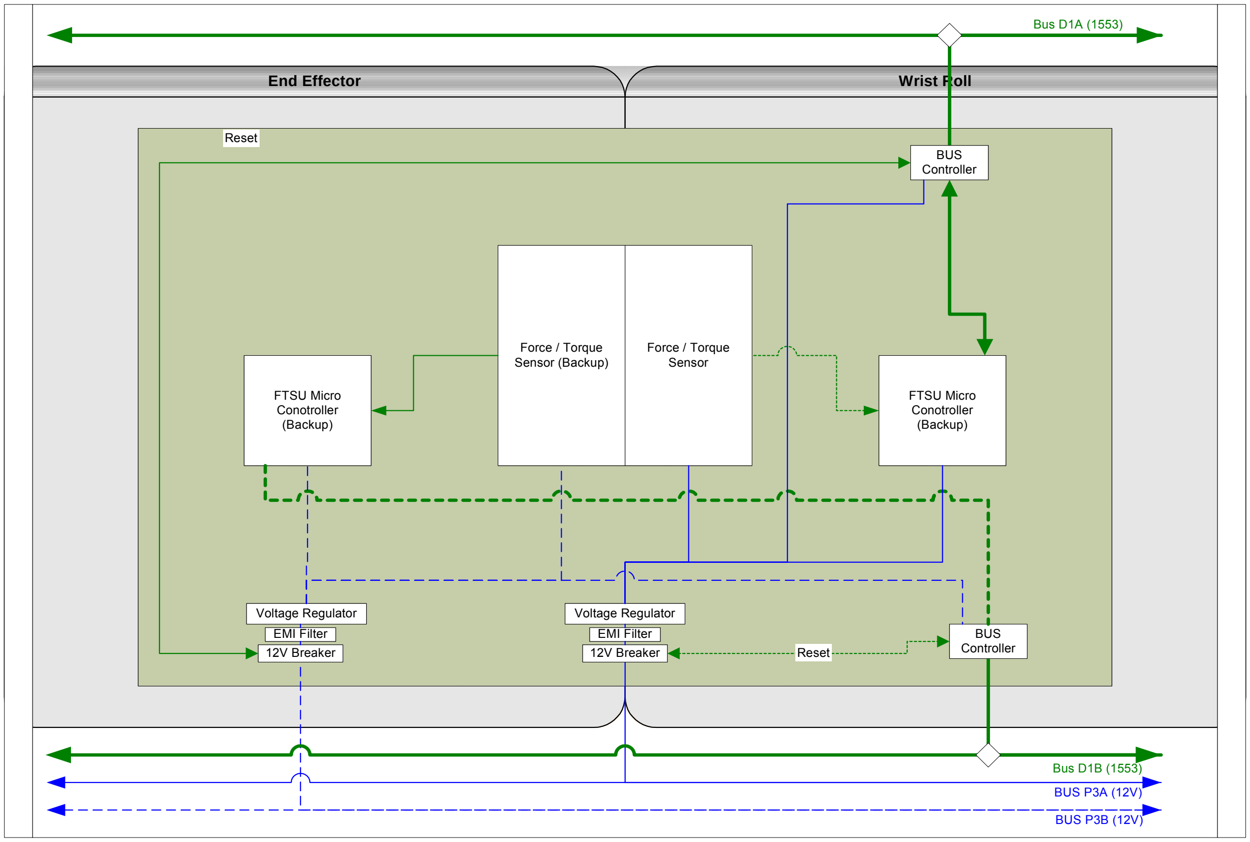
Appendix 7.2.8. EFBD 7 - Vision Processor



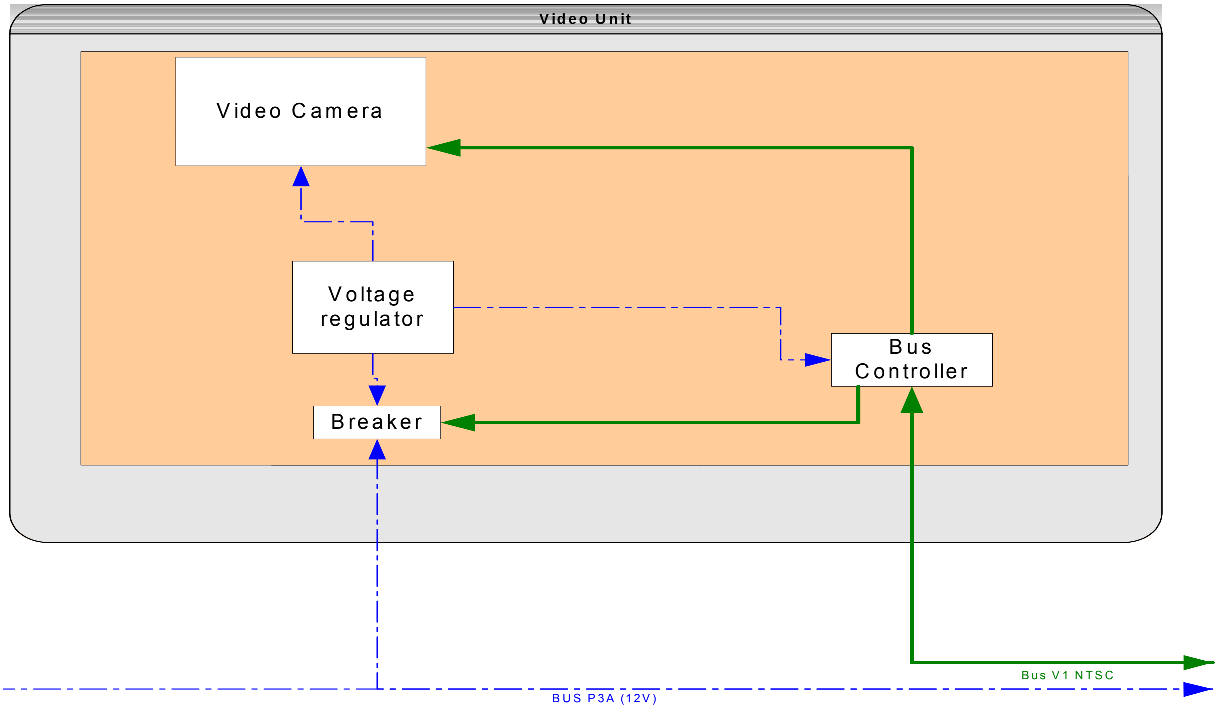
Appendix 7.2.9. EFBD 8 - CPU



Appendix 7.2.10. EFBD 9 - Force/Torque Sensor Unit



Appendix 7.2.11. EFBD 10 - Mini Camera



Appendix 7.3 Power Demand

Component	**Power Required (W)**
LCS	35
Tool Arm Shoulder Roll Motor	20
Tool Arm Shoulder Pitch Motor	20
Gripper Arm Shoulder Roll Motor	17
Gripper Arm Shoulder Pitch Motor	17
Gripper Arm Elbow Motor	17
Gripper Arm Wrist Pitch Motor	17
Gripper Arm Wrist Yaw Motor	17
Gripper Arm Wrist Roll Motor	17
LCS Motor 1	17
LCS Motor 2	17
Tool Arm Elbow Motor	17
Tool Arm Wrist Pitch Motor	17
Tool Arm Wrist Yaw Motor	17
Tool Arm Wrist Roll Motor	17
Gripper Control Motor	17
Tool Arm Gripper Control Motor1	17
Tool Arm Gripper Control Motor2	17
MicCTRL	13

Appendix 7.4 DR Cable Mass

Appendix 7.4.1. Power Cables

	Wires											
	# of wires			current required at interface	circuit length (m)	wire gage	wire current	bundle current	wire diameter (mm)	Insulation thickness (mm)	bundle diameter (mm)	bundle mass (kg)
	there	return	total									
Tool Arm Bundle												
Bus P1	2	2	4	2.63	4.72	20	6.5	3.25	0.813	0.50		0.23
Bus P2	2	2	4	2.63	4.97	20	6.5	3.25	0.813	0.50		0.24
Bus P3	2	2	4	3.91	7.10	18	9.2	4.6	1.024	0.50		0.46
Bus P4	2	2	4	0.58	5.88	30	1.3	0.65	0.254	0.50		0.09
			16		7.10						7.2	**1.03**
Total mass	**3.99**	**kg**										
Body Bundle												
Bus P5	2	2	4	2.50	2.51	22	4.5	3.38	0.643	0.500		0.09
Bus P6	2	2	4	1.07	3.63	28	1.8	1.35	0.320	0.500		0.07
			8		3.63						3.9	**0.16**
Total mass	**1.16**	**kg**										
Tool Arm Bundle												
Bus P7	2	2	4	2.58	4.72	20	6.5	3.25	0.813	0.500		0.23
Bus P8	2	2	4	1.94	4.66	22	4.5	2.25	0.643	0.500		0.17
Bus P9	2	2	4	3.11	6.49	20	6.5	3.25	0.813	0.500		0.32
Bus P10	2	2	4	0.58	5.88	30	1.3	0.65	0.254	0.500		0.09
			16		6.49						8.4	**0.81**
Total mass	**3.50**	**kg**										

Total mass	**8.66**	**kg**

	Shielding			Bus Drops		
	thickness (mm)	surface area (m^2)	mass (kg)	number of bus drops	mass per bus drop (kg)	mass (kg)
Tool Arm Bundle						
Bus P1				8		
Bus P2				8		
Bus P3				22		
Bus P4				14		
	0.3	0.161	**0.37**	52	0.05	**2.6**
Body Bundle						
Bus P5				6		
Bus P6				12		
	0.3	0.044	**0.10**	18	0.05	**0.9**
Tool Arm Bundle						
Bus P7				8		
Bus P8				6		
Bus P9				18		
Bus P10				14		
	0.3	0.171	**0.39**	46	0.05	**2.3**

Appendix 7.4.2. Power Sample Calculations

Derating Considerations

N = number of wires in bundle
I_req = current required
I_wire = individual wire current
I_bundle = current in wires after derating

If N >15
I_bundle = I_wire/2
Else
I_bundle = I_wire*(29-N)/28

Adjust wire gage until I_bundle > I_req

Mass

R = radius of the wire plus insulation
L = circuit length
Rho = density of copper = 8960 kg/m^3
t = shielding thickness
R_bundle = bundle radius
N_drops = number of bus drops
M_drop = mass per drop

M_bus = pi*R^2*L*rho*N

M_bundle = sum(M_bus)
M_shielding = t*2*pi*R_bundle*L*rho
M_bus drops = n_drops*m_drop

M_total = M_bundle + M_shielding + M_bus drops

Appendix 7.4.3. Data Cables

	Wires						
	# of wires	circuit length (m)	wire gage	wire diameter (mm)	Insulation thickness (mm)	bundle diameter (mm)	bundle mass (kg)
Tool Arm Bundle							
Bus D1 - 1553	4	4.72	26	0.404	0.50		0.11
Bus V1 - Video	4	4.05	26	0.404	0.50		0.09
Bus V2 - Video	4	4.05	26	0.404	0.50		0.09
	12	4.72				2.1	**0.30**
Total mass	**2.37**	**kg**					
Body Bundle							
Bus D3 - 1553	4	2.51	26	0.404	0.500		0.06
Bus D5 - 1553	4	2.10	26	0.404	0.500		0.05
	8	2.51				1.6	**0.06**
Total mass	**0.69**	**kg**					
Tool Arm Bundle							
Bus D4 -1553	4	4.72	26	0.404	0.500		0.11
Bus V3 - Video	4	4.05	26	0.404	0.500		0.09
Bus V4 - Video	4	1.00	26	0.404	0.500		0.02
	12	4.72				2.1	**0.22**
Total mass	**2.10 kg**						

Total mass	**5.15 kg**

	Shielding			Bus Drops		
	thickness (mm)	surface area (m^2)	mass (kg)	number of bus drops	mass per bus drop (kg)	mass (kg)
Tool Arm Bundle						
Bus D1 - 1553				36		
Bus V1 - Video				2		
Bus V2 - Video				2		
	0.3	0.031	**0.07**	40	0.05	**2**
Body Bundle						
Bus D3 - 1553				12		
Bus D5 - 1553				2		
	0.3	0.013	**0.03**	12	0.05	**0.6**
Tool Arm Bundle						
Bus D4 -1553				34		
Bus V3 - Video				0		
Bus V4 - Video				2		
	0.3	0.031	**0.07**	36	0.05	**1.8**

Appendix 7.4.4. Data Sample Calculations

Mass

R = radius of the wire plus insulation
L = circuit length
Rho = density of copper = 8960 kg/m^3
t = shielding thickness
R_bundle = bundle radius
N_drops = number of bus drops
M_drop = mass per drop

M_bus = pi*R^2*L*rho*n_wires
M_bundle = sum(M_bus)
M_shielding = t*2*pi*R_bundle*L*rho
M_bus drops = n_drops*m_drop

M_total = M_bundle + M_shielding + M_bus drops

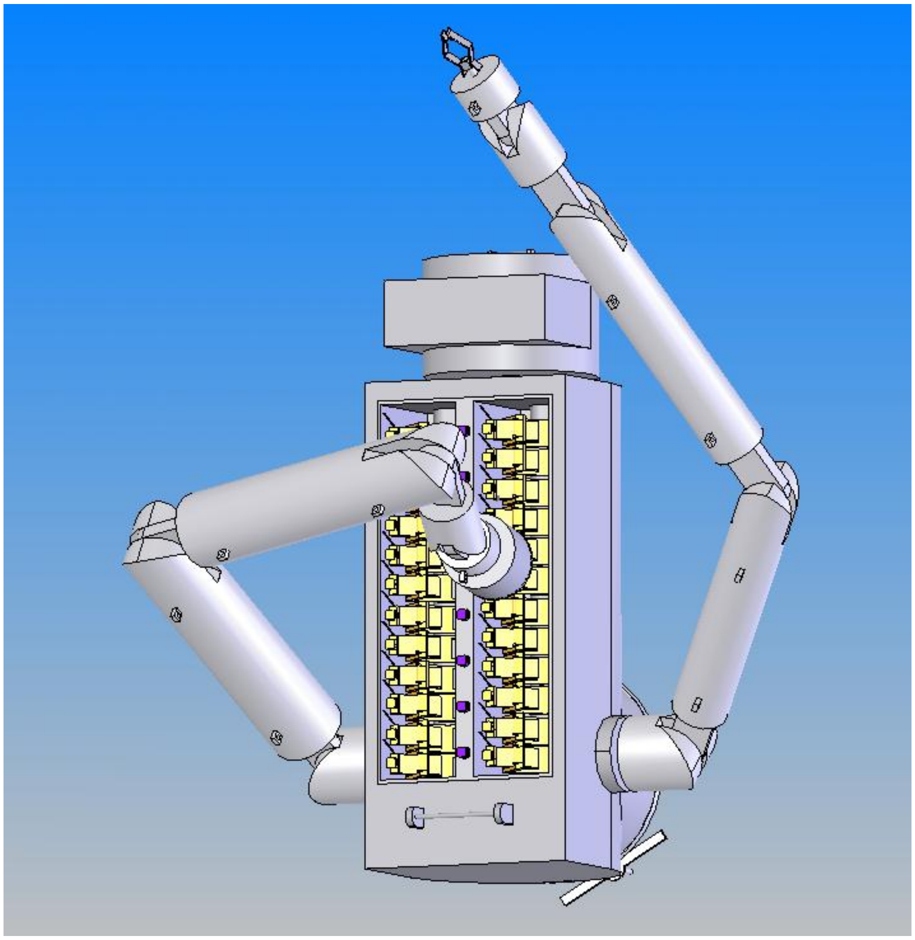
Appendix 7.5 GA Cable Mass

	Wires									
	# of wires	current required at interface	circuit length (m)	wire gage	wire diameter (mm)	Insulation thickness (mm)	wire current	bundle current	bundle diameter (mm)	bundle mass (kg)
Bundle 1										
power	20	3.91	10	18	1.024	0.5	9.2	4.6	7.9	**1.47**
Total mass	**2.04 kg**									
Bundle 2										
power	20	3.91	10	18	1.024	0.5	9.2	4.6	7.9	**1.47**
Total mass	**2.04 kg**									
Bundle 3										
data 1553	8	-								
video	8	-								
	16	-	10	26	0.404	0.5	-	-	4.1	**0.18**
Total mass	**0.05 kg**									
Bundle 4										
data 1553	8	-								
video	8	-								
	16	-	10	26	0.404	0.5	-	-	4.1	**0.18**
Total mass	**0.05 kg**									
Total mass	**4.19 kg**									

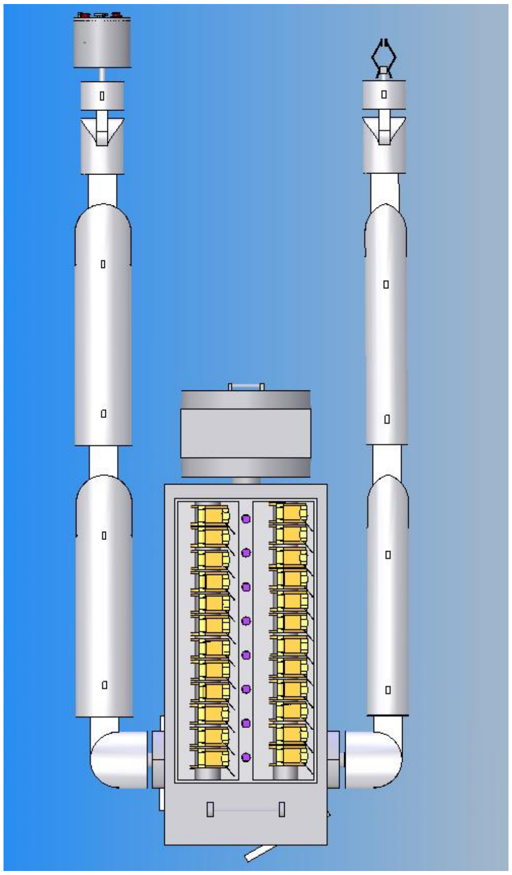
	Shielding			Connectors
	thickness (mm)	surface area (m^2)	mass (kg)	Number of pins
Bundle 1				
power	0.3	0.2	**0.56**	20
Bundle 2				
power	0.3	0.2	**0.56**	20
Bundle 3				
data 1553				16
video				16
	0.3	0.1	**0.29**	32
Bundle 4				
data 1553				16
video				16
	0.3	0.1	**0.29**	32

Appendix 8 Mechanical

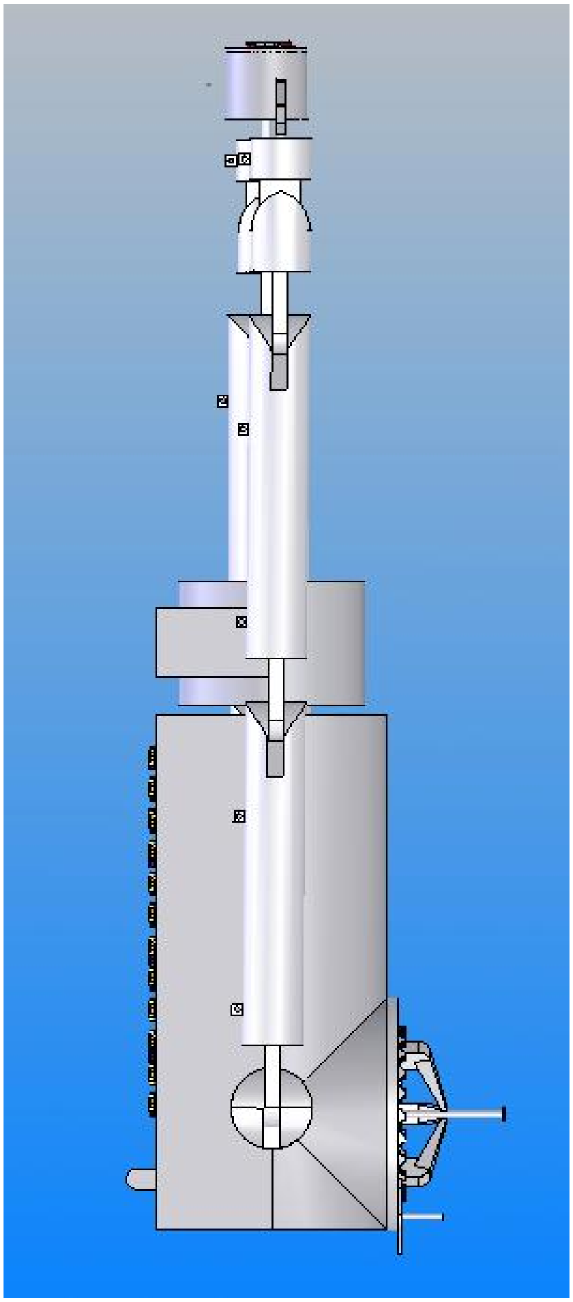
Appendix 8.1 CAD Models



DR Front View illustrating tool acquisition opearation



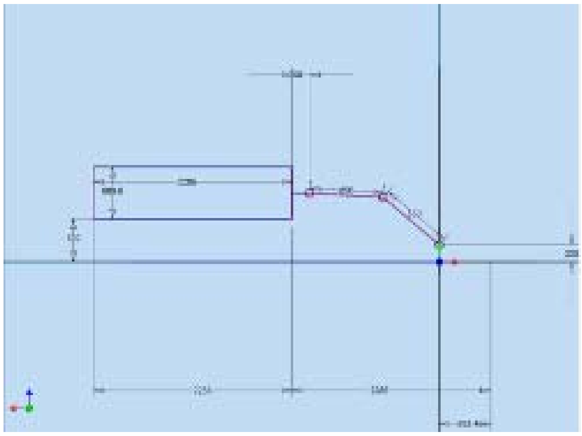
DR front view, Caddy contains 2 columns of clip tools, and one column of all the other tools.

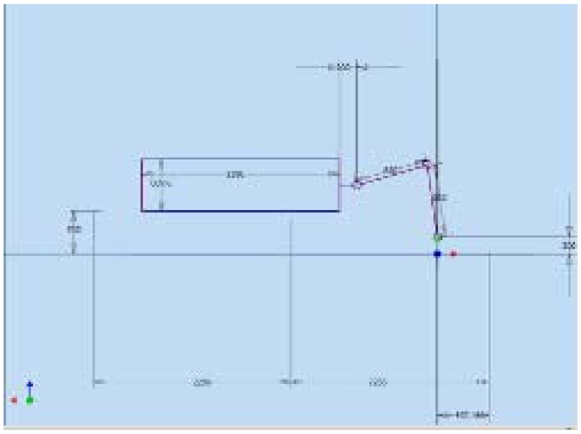


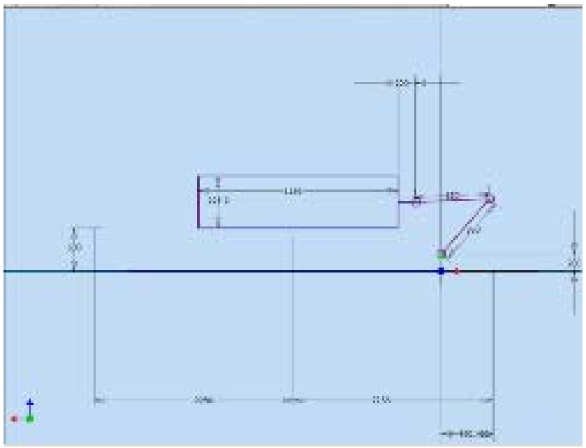
DR Side View

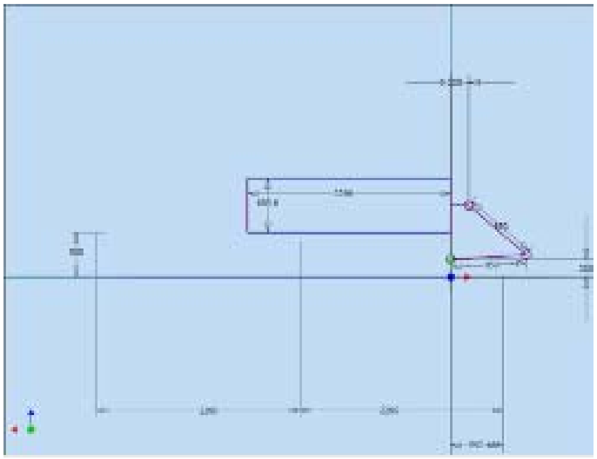
Appendix 8.2 Range of Motion Simulation

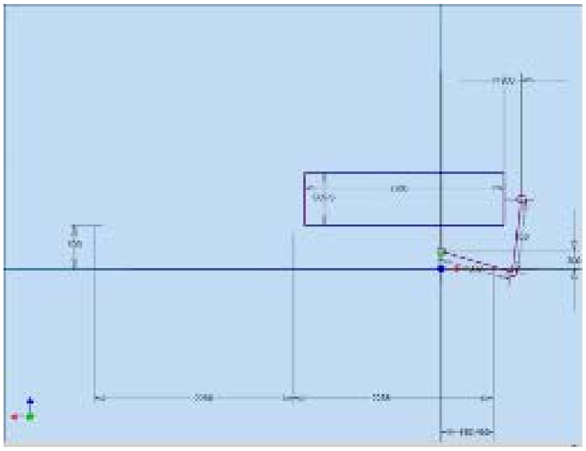
Major arm boom lengths (shoulder to elbow and elbow to wrist) of 85cm allow clearance of WFC and arm booms, and sufficient range of motion for 7.5 ‘ of linear translation at tip. This arm geometry will be sufficient for all other tasks.











Appendix 8.3 Calculations

Appendix 8.3.1. Tool Manipulator Arm Calculations:

Basic Parameters		
Main Boom Lengths	0.85	m
Arm Diameter	0.15	m
Arm Offset	0.45	m
Appprox Arm Length	2.6	m
Tip Speed with 1000lb mass	0.04	m/s
Tip Rotation	2	°/s

Factors of Safety	
Static Margin	2
Kinetic Margin	1

Assumptions: Inertial (self weight) Forces on Arm are neglected / Assumed small compared to end effector loads
Tip Speeds adjusted to make Power draw reasonable

Stop 1000lb Case

TA Self Mass			105.8044 kg	From Mass Budget
EE Payload	1000	lb	453.5924 kg	
Effective Payload Mass			506.4946237 kg	Payload plus half of self mass

Payload Moment of Inertia	210.9845		Assumes mass is the size of WfC3 which is approximated by a 82" x 90" x 32" rectangle torqued about the Ixx axis.
Payload Kinetic Energy	0.405196	J	
Payload Rotational Energy	0.128539	J	
Stopping Distance	0.008	m	
Stopping Angle	0.007	rad	

Tip Force F=KE/distance*StaticMargin*KineticMargin
= 99.31267 N

Tip Torque T=RE/angle*StaticMargin*KineticMargin
= 37.76795 Nm

This load case is less than the 50Nm requirement, therefore is not dominating.

Shoulder Torque - Normal Tip Load
Required Torque T=Length*TipForce
Required Torque 258 Nm
Required Power 9 W

Elbow Torque - Normal Tip Load
Required Torque T=Length/2*TipForce
Required Torque 129 Nm
Required Power 5 W

Wrist Torque - Normal Tip Load
Required Torque T=WristLength*TipForce
Required Torque 89.3814 Nm
Required Power 3 W

Apply 50 ftlb Torque Case
EE Torque 50 ft-lb 67.7909 Nm
Required Joint Torque T=EETorque*StaticMargin*DynamicMargin
Required Joint Torque 136 Nm
Required Power 5 W

move 1000lb
tip acceleration 0.02 m/s^2
EE Payload 1000 lb 453.5924 kg

Assumes mass is the size of WfC3 which is approximated by a 82" x 90" x 32" rectangle torqued about the Ixx axis.

Tip Force F=ma
= 9.071848 N

Appendix 8.3.2. Tool Manipulator Joints Calculations

TOOL ARM JOINTS

Dominant Load Cases:

Joint	Torque	Power
Shoulder	258 Nm	9 W
Elbow	136 Nm	5 W
Wrist	136 Nm	5 W

Mass Budget mass~=4+(0.03*Torque) -SMAD

Joint	Estimated Motor Mass	Qty	Total
Shoulder	11.7 kg	4	47.0 kg
Elbow	8.1 kg	2	16.1 kg
Wrist	8.1 kg	6	48.4 kg
		Total Mass of Joints	**111.5 kg**

Structure	Estimated Boom Mass	Qty	Total
Shoulder (Same I as upper boom)	3.4 kg	3	10.3 kg
Upper Boom	15.8 kg	1	15.8 kg
Lower Boom	8.6 kg	1	8.6 kg
Wrist	0.9 kg	3	2.7 kg
		Total Mass of Arm Structure	**27.1 kg**

Appendix 8.3.3. Tool Manipulator Material Selection

Material Properties:

Name	BendingStress/1.75		E		Density	
Composite	114285714.3	Pa	1.90E+11	Pa	1570	kg/m^3
Titanium	433714285.7	Pa	1.1E+11	Pa	4700	kg/m^3
Aluminium	55142857.14	Pa	7.10E+10	Pa	2700	kg/m^3

Minimum strength for Bending:

I minimum = Bending Moment * Radius / Bending stress capability

Segment	I carbon	I Titanium	I Aluminium	Radius	t carbon	t Titanium	t Aluminum
Upper Boom	1.69E-07	4.47E-08	3.51E-07	0.075	0.0001	3.4E-05	0.0003
Lower Boom	8.90E-08	2.34E-08	1.84E-07	0.075	0.0001	1.8E-05	0.0001
Wrist	8.90E-08	2.34E-08	1.84E-07	0.075	0.0001	1.8E-05	0.0001

Minimum Strength for Allowed Deflection (BENDING)

MaxNetDeflection= 0.002 m

I= M*L^2/(2*E*MaxDeflection)

Segment	Max Deflection	I carbon	I Titanium	I Aluminium	Radius	t carbon	t Titanium	t Aluminum
Shoulder	0.0002	3.28E-05	5.67E-05	8.78E-05	0.075	0.0248	0.0428	0.0663
Upper Boom	0.0007	1.16E-05	2.00E-05	3.10E-05	0.075	0.0087	0.0151	0.0234
Lower Boom	0.0007	6.08E-06	1.05E-05	2.82E-05	0.075	0.0046	0.0079	0.0213
Wrist	0.0004	1.15E-05	1.98E-05	2.82E-05	0.075	0.0087	0.0150	0.0213

Note: All these materials can easily handle the required loads. However, it is desireable to produce beams with higher moments of inertia than the calculated minimums to produce a stiffer arm. The stopping distance budget allows for a net displacement of 2mm due to mechanical deflection of the arm.

Appendix 8.3.4. General Manipulator Arm Calculations

Basic Parameters		
Main Boom Lengths	0.85	m
Arm Diameter	0.15	m
Arm Offset	0.45	m
Appprox Arm Length	2.2	m
Tip Speed	0.1	m/s
Tip Rotation	3	°/s

Factors of Safety	
Static Margin	2
Kinetic Margin	1

Assumptions:

Inertial (self weight) Forces on Arm are neglected / Assumed small compared to end effector loads

Tip Speeds adjusted to make Power draw reasonable

Stop 200lb Case

MA Self Mass			99.50545	kg	Mass Budget
EE Payload	200	lb	90.71848	kg	
Effective EE Payload			140.4712054	kg	Payload plus half of se

Payload Moment of Inertia	58.51445	
Payload Kinetic Energy	0.453592	J
Payload Rotational Energy	0.08021	J
Stopping Distance	0.008	m
Stopping Angle	0.007	rad

Tip Force F=KE/distance*StaticMargin*KineticMargin

= 111.1746 N

Tip Torque T=RE/angle*StaticMargin*KineticMargin

= 23.56776 Nm This load case is less than the 50Nm requirement, th

Shoulder Torque - Normal Tip Load

Required Torque T=Length*TipForce

Required Torque 245 Nm

Required Power 13 W

Elbow Torque - Normal Tip Load

Required Torque T=Length/2*TipForce

Required Torque 122 Nm

Required Power 6 W

Wrist Torque - Normal Tip Load

Required Torque T=WristLength*TipForce

Required Torque 55.5873 Nm

Required Power 3 W

Apply 50 ftlb Torque Case

EE Torque 20 ft-lb 27.11636 Nm

Required Joint Torque T=EETorque*StaticMargin*DynamicMargin

Required Joint Torque 54 Nm

Required Power 3 W

move 1000lb

tip acceleration 0.05 m/s^2

EE Payload 200 lb 90.71848

Tip Force F=ma

= 4.535924 N

Appendix 8.3.5. General Manipulator Joints Calculations

MANIPULATOR ARM JOINTS

Dominant Load Cases:

Joint	Torque	Power
Shoulder	245 Nm	13 W
Elbow	122 Nm	6 W
Wrist	56 Nm	3 W

Mass Budget mass~=4+(0.03*Torque) -SMAD

Joint	Estimated Motor Mass	Qty	Total
Shoulder	11.3 kg	4	45.4 kg
Elbow	7.7 kg	2	15.3 kg
Wrist	5.7 kg	6	34.0 kg
	Total Mass of Joints		**94.7 kg**

Structure	Estimated Boom Mass	Qty	Total
Shoulder	3.3 kg	3	9.9 kg
Upper Boom	15.0 kg	1	15.0 kg
Lower Boom	7.7 kg	1	7.7 kg
Wrist	0.4 kg	3	1.2 kg
	Total Mass of Arm Structure		**23.9 kg**

Appendix 8.3.6. General Manipulator Material Selection Calculations

Material Properties:

Name	BendingStress/1.75	E	Density
Composite	114285714.3 Pa	1.90E+11 Pa	1570 kg/m^3
Titanium	433714285.7 Pa	1.1E+11 Pa	4700 kg/m^3
Aluminium	55142857.14 Pa	7.10E+10 Pa	2700 kg/m^3

Minimum strength for Bending:

I minimum = Bending Moment * Radius / Bending stress capability

Segment	I carbon	I Titanium	I Aluminium	Radius	t carbon	t Titanium	t Aluminum
Upper Boom	1.61E-07	4.23E-08	3.33E-07	0.075	0.0001	3.2E-05	0.0003
Lower Boom	8.03E-08	2.11E-08	1.66E-07	0.075	0.0001	1.6E-05	0.0001
Wrist	3.65E-08	9.61E-09	7.56E-08	0.075	0.0000	7.3E-06	0.0001

Minimum Strength for Allowed Deflection (BENDING)

MaxNetDeflection= 0.002 m

I= M*L^2/(2*E*MaxDeflection)

Segment	Max Deflection	I carbon	I Titanium	I Aluminium	Radius	t carbon	t Titanium	t Aluminum
Shoulder	0.0002	3.11E-05	5.37E-05	8.32E-05	0.075	0.0235	0.0405	0.0628
Upper Boom	0.0007	1.10E-05	1.90E-05	2.94E-05	0.075	0.0083	0.0143	0.0222
Lower Boom	0.0007	5.49E-06	9.48E-06	2.55E-05	0.075	0.0041	0.0072	0.0192
Wrist	0.0004	4.71E-06	8.14E-06	1.16E-05	0.075	0.0036	0.0061	0.0087

Note: All these materials can easily handle the required loads. However, it is desireable to produce beams with higher moments of inertia than the calculated minimums to produce a stiffer arm. The stopping distance budget allows for a net displacement of

Appendix 8.3.7. Motor and Gearbox Calculations

	Joint Driving Torque (Nm)	Stopping Torques (Nm)	Joint Turn Rate (deg/s)	Gearbox Output Power (W)	Gear Ratio	Worm Gear Efficiency	Main Gear Efficiency	Motor Ouput Torque (mNm)	motor turn rate (deg/s)
Tool Arm									
Shoulder Roll	222.0	676	1.00	3.9	15000	0.6	0.6	44.8	15000
Shoulder Pitch	222.0	676	1.00	3.9	15000	0.6	0.6	44.8	15000
Elbow Pitch	135.6	400	1.50	3.5	9000	0.6	0.6	41.9	13500
Wrist Pitch	135.6	124	1.50	3.5	9000	0.6	0.6	41.9	13500
Wrist Yaw	135.6	124	1.50	3.5	9000	0.6	0.6	41.9	13500
Wrist Roll	135.6	124	1.50	3.5	9000	0.6	0.6	41.9	13500
Tool Gripper					9000				
Clamp Gripper					9000				
LCS									
Pitch					2500				
Yaw					2500				
Manipulator Arm									
Shoulder Roll	40.0	542	5.0	3.5	2500	0.6	0.6	44.4	12500
Shoulder Pitch	40.0	542	5.0	3.5	2500	0.6	0.6	44.4	12500
Elbow Pitch	40.0	322	5.0	3.5	2500	0.6	0.6	44.4	12500
Wrist Pitch	40.0	100	5.0	3.5	2500	0.6	0.6	44.4	12500
Wrist Yaw	40.0	100	5.0	3.5	2500	0.6	0.6	44.4	12500
Wrist Roll	40.0	100	5.0	3.5	2500	0.6	0.6	44.4	12500
Gripper					2500				

	Motor RPM	Motor Output Power (W)	Selected Motor	Motor Torque Constant (mNm/A)	Motor Resistance (ohms)	Motor Input Power (W)		Selcted Worm Gear	Worm Gear Ratio	Main Gear Ratio	Selcted Main Gear
Tool Arm											
Shoulder Roll	2500	11.7	3564 024 B	20.1	1.2	17.7		G2.6	36	417	30/1
Shoulder Pitch	2500	11.7	3565 024 B	20.1	1.2	17.7		G2.6	36	417	30/1
Elbow Pitch	2250	9.9	3566 024 B	20.1	1.2	15.0		G2.6	36	250	30/1
Wrist Pitch	2250	9.9	3567 024 B	20.1	1.2	15.0		G2.6	36	250	30/1
Wrist Yaw	2250	9.9	3568 024 B	20.1	1.2	15.0		G2.6	36	250	30/1
Wrist Roll	2250	9.9	3569 024 B	20.1	1.2	15.0		G2.6	36	250	30/1
Tool Gripper			3570 024 B			15.0		G2.7	37	250	30/1
Clamp Gripper			3571 024 B			15.0		G2.8	38	250	30/1
LCS											
Pitch			3572 024 B			15.0		G2.6	36	69	30/1
Yaw			3573 024 B			15.0		G2.6	36	69	30/1
Manipulator Arm											
Shoulder Roll	2083	9.7	3572 024 B	20.1	1.2	15.5		G2.6	36	69	30/1
Shoulder Pitch	2083	9.7	3573 024 B	20.1	1.2	15.5		G2.6	36	69	30/1
Elbow Pitch	2083	9.7	3574 024 B	20.1	1.2	15.5		G2.6	36	69	30/1
Wrist Pitch	2083	9.7	3575 024 B	20.1	1.2	15.5		G2.6	36	69	30/1
Wrist Yaw	2083	9.7	3576 024 B	20.1	1.2	15.5		G2.6	36	69	30/1
Wrist Roll	2083	9.7	3577 024 B	20.1	1.2	15.5		G2.6	36	69	30/1
Gripper			3578 024 B			15.5		G2.6	36	69	30/1

Appendix 8.3.8. Motor Sample Calculations

GA Interface

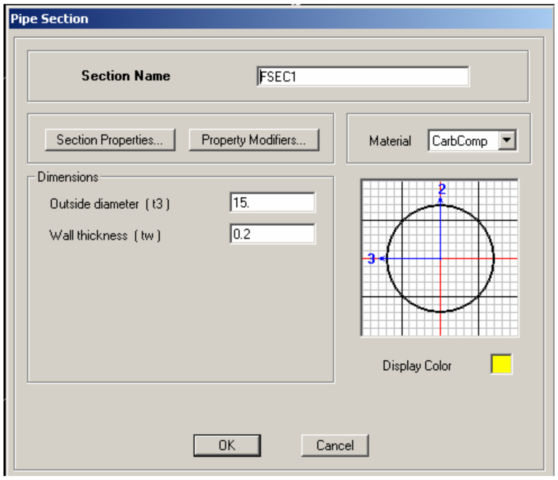
Loads on the GA/DR fixture during extreme cases

Stopping 1000lb	w/ FOS		**Equivalent Load on fixt**		
Linear Force case:	99.3			w/ FOS	
Distance from force to centre of fixture			Force	99.3	N
			Torque	**288.0**	**Nm**
Torque case:	37.8				
Distance from torque centre to centre fixture			Force	125.9	N
			Torque	37.8	Nm
Applying a 50-ftlb Torque					
Torque	67.8		Force	**226.0**	**N**
Distance from torque centre to centre fixture			Torque	67.8	Nm

Appendix 8.4 Modal Analysis

Modal Analysis was performed with SAP 2000, a structural analysis tool available on the Engineering Computing facility at the University of Toronto. It performs eigenvalue analysis based on the stiffness and mass matrices associated with the structure.

- A low fidelity model was created, where each Joint was assumed to have 15kg Mass, and boom characteristics were entered as follows:


Pipe Section

Section Name: FSEC1

Material: CarbComp

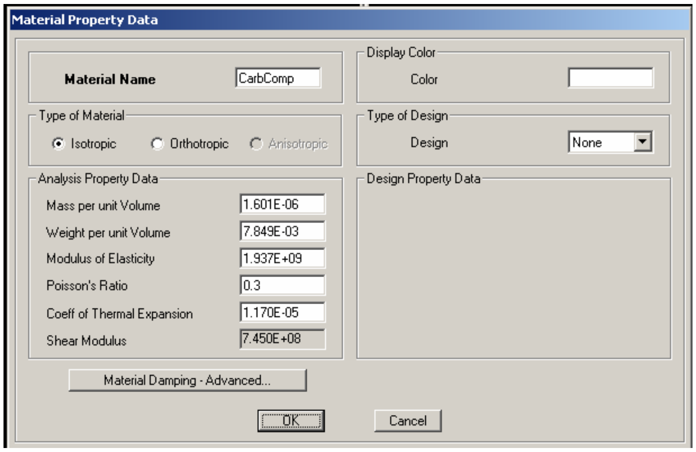
Dimensions

Outside diameter (t3): 15.

Wall thickness (tw): 0.2

Figure 11-1

- (Units are Kg/cm/°C)

- 

Material Property Data

Material Name CarbComp

Display Color

Color

Type of Material

● Isotropic ○ Orthotropic ○ Anisotropic

Type of Design

Design None

Analysis Property Data

Mass per unit Volume 1.601E-06

Weight per unit Volume 7.849E-03

Modulus of Elasticity 1.937E+09

Poisson's Ratio 0.3

Coeff of Thermal Expansion 1.170E-05

Shear Modulus 7.450E+08

Design Property Data

Figure 11-2

- (Units are Kg/cm/°C)

Case 1 - Arm with 1000lb Payload on EE

Payload Mass = 1000lb =453.6kg

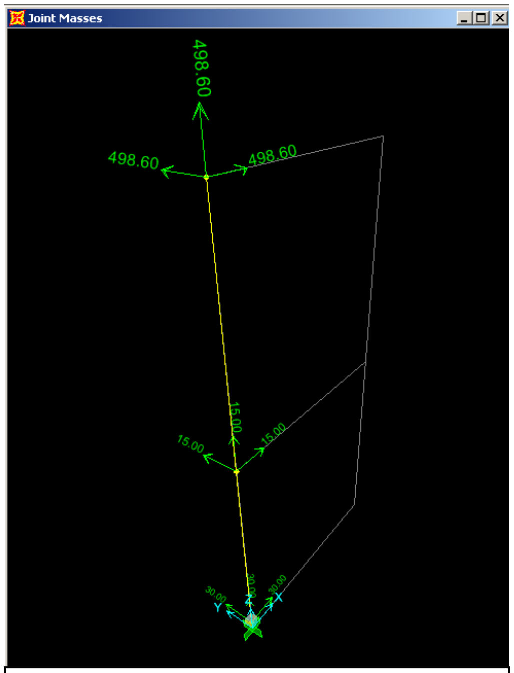
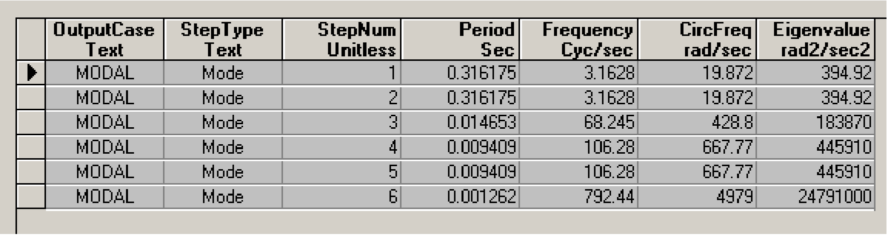


Figure 11-3

Model with Masses indicated.



OutputCase Text	StepType Text	StepNum Unitless	Period Sec	Frequency Cyc/sec	CircFreq rad/sec	Eigenvalue rad2/sec2
MODAL	Mode	1	0.316175	3.1628	19.872	394.92
MODAL	Mode	2	0.316175	3.1628	19.872	394.92
MODAL	Mode	3	0.014653	68.245	428.8	183870
MODAL	Mode	4	0.009409	106.28	667.77	445910
MODAL	Mode	5	0.009409	106.28	667.77	445910
MODAL	Mode	6	0.001262	792.44	4979	24791000

Frequency Analysis Output

- Modes 1&2 are 1st transverse, Mode 3 is 1st axial, Modes 4&5 are 2nd transverse, and Mode 6 is 2nd axial.
- For control, the important natural frequencies are the transverse ones:
  - 3.1628 Hz
  - 106.28 Hz

Case 2 - Arm with no Payload on EE

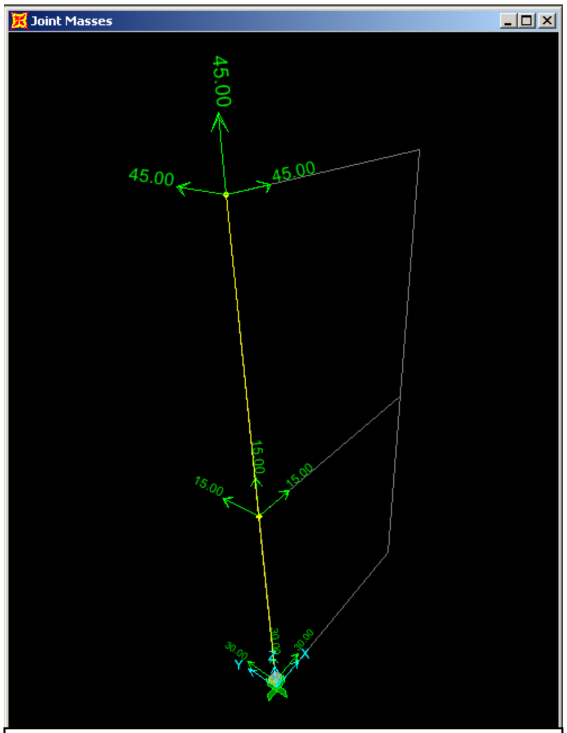
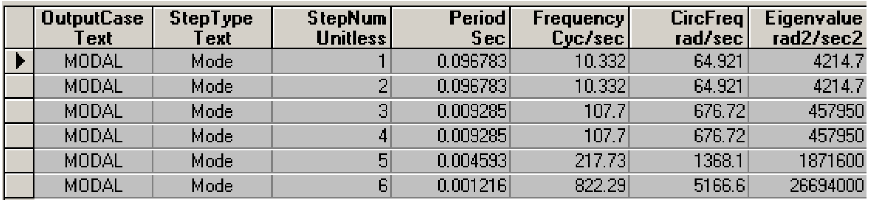


Figure 11-4

Model with Masses indicated.



	OutputCase Text	StepType Text	StepNum Unitless	Period Sec	Frequency Cyc/sec	CircFreq rad/sec	Eigenvalue rad2/sec2
▶	MODAL	Mode	1	0.096783	10.332	64.921	4214.7
	MODAL	Mode	2	0.096783	10.332	64.921	4214.7
	MODAL	Mode	3	0.009285	107.7	676.72	457950
	MODAL	Mode	4	0.009285	107.7	676.72	457950
	MODAL	Mode	5	0.004593	217.73	1368.1	1871600
	MODAL	Mode	6	0.001216	822.29	5166.6	26694000

Frequency Analysis Output

- Modes 1&2 are 1st transverse, Modes 3&4 are 2nd transverse, Mode 5 is 1st axial, and Mode 6 is 2nd axial.
- For control, the important natural frequencies are the transverse ones:
  - 10.332 Hz
  - 107.7 Hz

Appendix 8.5 Thermal Control Subsystem

Table A8-1 Temperature limits of DR

	Operational mode	Survival mode
Power/Fuses	-10 to 20	-15 to 35
C&DH	-20 to 70	-40 to 85
Electronic components	-20 to 65	-50 to 70
Joint actuators	-20 to 70	-65 to 80
End effector actuators	-20 to 70	-65 to 80
Camera/sensors	-20 to 65	-50 to 70
Structure	-15 to 65	-45 to 65

Temperatures are in ºC

Internal heat generation:

$q_{internal-\min} = 0$ (All electronics off)

With our 50 W power consumption requirement for actuators, we can assume the robot has 40 % efficiency, hence the heat dissipated would be

$q_{internal-\max} = 0.6 \times 50 = 30$ **[W]**

We can add to this active heating depending on our analysis and thermal control requirements

Solar flux extremes:

Assumptions:

Dexterous robot, when fully extended, is assumed to be a cylinder with a 4.72 m length and a diameter of 0.2 meters. This is used for the worst-case steady state analysis for the energy balance

$\alpha =$ Solar absorptivity.

Full sun: $q_{s-\max} = \alpha \times 1353 \times 4.72 \times 0.2 = 1277\alpha$ [W]

Full shadow: $q_{s-\min} = 0$ [W]

Albedo Extremes:

Distance to DR from earth makes DR view factor similar to a flat plate projected area of the DR cylinder onto the DR orbit.

Albedo factor is taken as 0.3 for hot case and 0.23 for cold case

$F_{Earth \to DR} \approx 0.85$ for hot case (as assumed for flat plate) and $F_{Earth \to DR} \approx 0.5$ for cold case (incase of HST/cloud in the way or other geometric variation)

Surface area of DR $A_{DR} = \Pi \times 0.2 \times 4.72 + 2\Pi \times 0.1^2 = 3.03$ [m^2]

Hot case: $q_{a\max} = \alpha \times A_{DR} \times 1353 \times 0.3 \times F_{Earth \to DR}$

$F_{Earth \to DR} \approx 0.85$

Hence $q_{a\max} = \alpha \times 3.03 \times 1353 \times 0.3 \times 0.85 = 1045.4\alpha$ **[W]**

Cold case: $q_{a\min} = \alpha \times A_{DR} \times 1353 \times 0.23 \times F_{Earth \to DR}$

$F_{Earth \to DR} \approx 0.5$ **hence** $q_{a\min} = 471.5\alpha$ **[W]**

Earth-Emitted IR:
Additional Assumption: Earth average surface temperature is 260K.
$\varepsilon_{surface}$ = IR surface emissivity of DR

Hot case**:** $q_{IR\max} = \varepsilon_{surface} \times A_{DR} \times F_{Earth \to DR} \times 5.67021 \times 10^{-8} \times 260^4$

Where $F_{Earth \to DR} = 0.85$, **Hence** $q_{IR\max} = 667.35 \ \varepsilon_{DR}$ **[W]**

Cold case: $q_{IR\min} = \varepsilon_{surface} \times A_{DR} \times F_{Earth \to DR} \times 5.67021 \times 10^{-8} \times 260^4$

Where $F_{Earth \to DR} = 0.5$, **Hence** $q_{IR\min} = 392.6\varepsilon_{DR}$ **[W]**

Radiated heat from DR surface area to space sink

$$q_{emitted} = \varepsilon_{surface} \times 5.67021 \times 10^{-8} \times A_{DR} \times T_{DR}{}^4 = 1.7181 \times 10^{-7} \times \varepsilon_{surface} \times T_{DR}{}^4$$

Energy balance for hot case:
a) Using an MLI blanket to reduce radiation loss, we can do the energy balance for the MLI as shown in the equation below

$$q_{s-\max} + q_{a-\max} + q_{IR-\max} + q_{DR-MLI} = q_{emitted}$$

$$1277\,\alpha + 1045.4\alpha + 667.35\varepsilon_{surface} + \varepsilon_{DR}\varepsilon_{MLI}(T_{DR}{}^4 - T_{MLI}{}^4) \times 1.7181 \times 10^{-7} = 1.7181 \times 10^{-7} \times \varepsilon_{surface} \times T_{MLI}{}^4$$

Or

$$2322.4\alpha + 667.35\varepsilon_{surface} + \varepsilon_{DR}\varepsilon_{MLI}(T_{DR}{}^4 - T_{MLI}{}^4) \times 1.7181 \times 10^{-7} = 1.7181 \times 10^{-7} \times \varepsilon_{surface} \times T_{MLI}{}^4$$

If we paint the MLI outer surface white to reduce the solar absorption of sunlight, we can simplify the equation further using $\varepsilon_{MLI} = 0.04$, $\varepsilon_{surface} = 0.92$ and $\alpha_s = 0.2$. Requiring that T_{DR} = 330K, we can get an expression for T_{MLI} in terms of ε_{DR}.

$$T_{MLI}{}^4 = \frac{1.18592 \times 10^{10}(\varepsilon_{DR} + 13.232)}{\varepsilon_{DR} + 23}$$

b) Energy Balance for DR during the hot case:

$q_{internal-\max} + q_{heating} = q_{DR-MLI}$ or

$$30 + q_{heating} = \varepsilon_{DR}\varepsilon_{MLI}(330^4 - T_{MLI}{}^4) \times 1.7181 \times 10^{-7}$$

using equation a) for T_{MLI}, we can get an expression for $q_{heating}$ in terms of ε_{DR} :

$$q_{heating} = \frac{796.086\varepsilon_{DR}}{\varepsilon_{DR} + 23} - 30$$

for 0< ε_{DR} <1, $q_{heatingmax}$ = 3.17 [W] for ε_{DR} =1
$q_{heatingmin}$ = -30 [W] for ε_{DR} =0 (i.e. need to cool off 30 W)

Energy balance for cold case:

a) Requiring that T_{DRmin}=273K, we have the energy balance for the MLI blanket to be

$$q_{s-\min} + q_{a-\min} + q_{IR-\min} + q_{DR-MLI} = q_{emitted}$$

$$475.1\alpha + 392.6\varepsilon_{surface} + \varepsilon_{DR}\varepsilon_{MLI}(273^4 - T_{MLI}{}^4) \times 1.7181\times10^{-7} = 1.7181\times10^{-7} \times \varepsilon_{surface} \times T_{DR}{}^4$$

which becomes

$$T_{MLI}{}^4 = \frac{273^4(\varepsilon_{DR} + 11.9511)}{\varepsilon_{DR} + 23}$$

b) Cold case energy balance for DR:

$$q_{heating} = \varepsilon_{DR}\varepsilon_{MLI}(273^4 - T_{MLI}{}^4) \times 1.7181\times10^{-7}$$

Using a) for cold case, we get

$$q_{heating} = \frac{421.773\varepsilon_{DR}}{\varepsilon_{DR} + 23}$$

for 0< ε_{DR} <1, $q_{heatingmax}$ = 17.57 [W] for ε_{DR} =1
$q_{heatingmin}$ = 0 [W] for ε_{DR} =0

To sum up, we have the following heating requirement range based on our equations:

	Hot case $q_{heating}$ needed	Cold case $q_{heating}$ needed
ε_{DR} =1	3.17 [W]	17.57 [W]
ε_{DR} =0	-30 [W]	0 [W]

Picking a high emissivity for DR, we can design it such that we do not get –30 W, i.e. we do not use a cooling system. If DR was also painted white such that ε_{DR} =0.92, then $q_{heating}$ for the cold case will be 16.22 [W] and 0.62 [W] for the hot case. Hence we require a 20 W heating capacity.

It is favorable to have a duty ratio to supply the designed 20 W need. A 30 W heater with a 67 % duty ratio should be sufficient.

Appendix 8.6 End Effector Performance

Stopping Distances

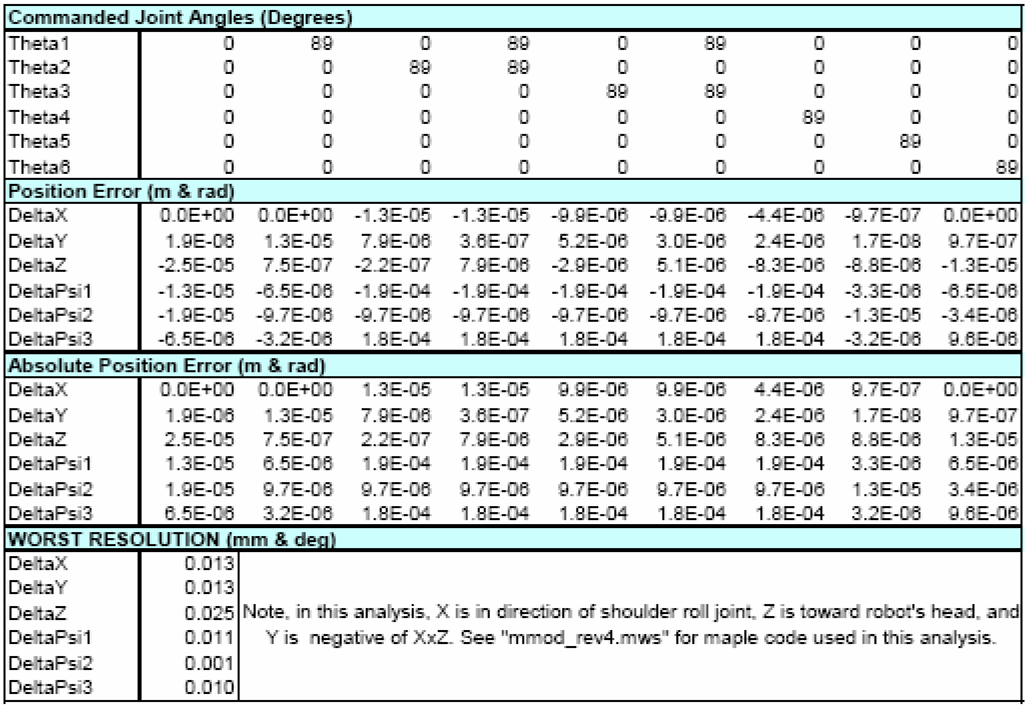
Global	Stopping Distance	2	"	0.0508	m		
	Stopping Angle	2	°	0.034907	rad		

DR	Total Stopping Distance	0.4	"	0.01016	m	Portion:	0.2
	Bending Portion	2	mm	0.002	m		
	Effective Stopping Distance			0.00816	m		
	Total Stopping Angle	0.4	°	0.006981	rad	Portion:	0.2
	Torsion Portion	0.01	°	0.000175	rad		
	Effective Stopping Angle			0.006807	rad		

Resolution:

Configurations were chosen to be somewhat representative of arm configurations during operation, as well as to explore the extremities of the operating envelope. While, this analysis is not exhaustive, it is representative of the overall performance of the arm.

- Joint Angle Error: +-4 Minutes = -4/(360*60)*PI()/180 radians = 0.0000032321 radians
- 89 degrees was chosen instead of 90 to avoid singularities in inverse kinematics calculations.
- The Maple code can be found on the following page.
- “Worst Resolution” is the maximum of the absolute values of the various computed position errors.



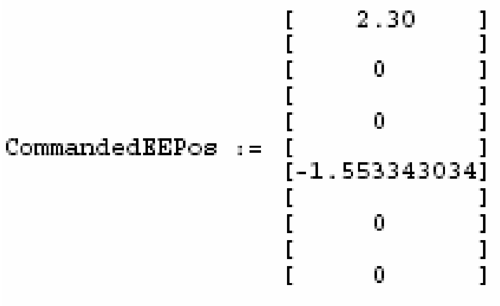
Commanded Joint Angles (Degrees)									
Theta1	0	89	0	89	0	89	0	0	0
Theta2	0	0	89	89	0	0	0	0	0
Theta3	0	0	0	0	89	89	0	0	0
Theta4	0	0	0	0	0	0	89	0	0
Theta5	0	0	0	0	0	0	0	89	0
Theta6	0	0	0	0	0	0	0	0	89
Position Error (m & rad)									
DeltaX	0.0E+00	0.0E+00	-1.3E-05	-1.3E-05	-9.9E-06	-9.9E-06	-4.4E-06	-9.7E-07	0.0E+00
DeltaY	1.9E-06	1.3E-05	7.9E-06	3.6E-07	5.2E-06	3.0E-06	2.4E-06	1.7E-08	9.7E-07
DeltaZ	-2.5E-05	7.5E-07	-2.2E-07	7.9E-06	-2.9E-06	5.1E-06	-8.3E-06	-8.8E-06	-1.3E-05
DeltaPsi1	-1.3E-05	-6.5E-06	-1.9E-04	-1.9E-04	-1.9E-04	-1.9E-04	-1.9E-04	-3.3E-06	-6.5E-06
DeltaPsi2	-1.9E-05	-9.7E-06	-9.7E-06	-9.7E-06	-9.7E-06	-9.7E-06	-9.7E-06	-1.3E-05	-3.4E-06
DeltaPsi3	-6.5E-06	-3.2E-06	1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.8E-04	-3.2E-06	9.6E-06
Absolute Position Error (m & rad)									
DeltaX	0.0E+00	0.0E+00	1.3E-05	1.3E-05	9.9E-06	9.9E-06	4.4E-06	9.7E-07	0.0E+00
DeltaY	1.9E-06	1.3E-05	7.9E-06	3.6E-07	5.2E-06	3.0E-06	2.4E-06	1.7E-08	9.7E-07
DeltaZ	2.5E-05	7.5E-07	2.2E-07	7.9E-06	2.9E-06	5.1E-06	8.3E-06	8.8E-06	1.3E-05
DeltaPsi1	1.3E-05	6.5E-06	1.9E-04	1.9E-04	1.9E-04	1.9E-04	1.9E-04	3.3E-06	6.5E-06
DeltaPsi2	1.9E-05	9.7E-06	9.7E-06	9.7E-06	9.7E-06	9.7E-06	9.7E-06	1.3E-05	3.4E-06
DeltaPsi3	6.5E-06	3.2E-06	1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.8E-04	3.2E-06	9.6E-06
WORST RESOLUTION (mm & deg)									
DeltaX	0.013	Note, in this analysis, X is in direction of shoulder roll joint, Z is toward robot's head, and Y is negative of XxZ. See "mmod_rev4.mws" for maple code used in this analysis.							
DeltaY	0.013								
DeltaZ	0.025								
DeltaPsi1	0.011								
DeltaPsi2	0.001								
DeltaPsi3	0.010								

Maple Code:

```
> restart;
> with(linalg):
> #The three principal rotation matrices
> C1 := x->matrix(3,3,[1,0,0,0,cos(x),sin(x),0,-sin(x),cos(x)]):
```

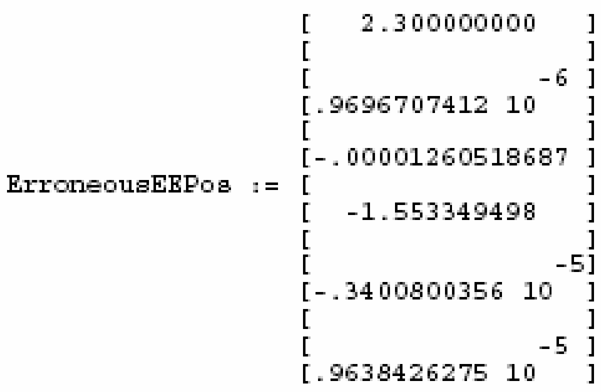
```
> C2 := x->matrix(3,3,[cos(x),0,-sin(x),0,1,0,sin(x),0,cos(x)]):
> C3 := x->matrix(3,3,[cos(x),sin(x),0,-sin(x),cos(x),0,0,0,1]):
>
> C1t := x->matrix(3,3,[1,0,0,0,cos(x),-sin(x),0,sin(x),cos(x)]):
> C2t := x->matrix(3,3,[cos(x),0,sin(x),0,1,0,-sin(x),0,cos(x)]):
> C3t := x->matrix(3,3,[cos(x),-sin(x),0,sin(x),cos(x),0,0,0,1]):
>
> C1 := x->matrix(3,3,[1,0,0,0,cos(x),sin(x),0,-sin(x),cos(x)]):
> C2 := x->matrix(3,3,[cos(x),0,-sin(x),0,1,0,sin(x),0,cos(x)]):
> C3 := x->matrix(3,3,[cos(x),sin(x),0,-sin(x),cos(x),0,0,0,1]):
>
> C1t := x->matrix(3,3,[1,0,0,0,cos(x),-sin(x),0,sin(x),cos(x)]):
> C2t := x->matrix(3,3,[cos(x),0,sin(x),0,1,0,-sin(x),0,cos(x)]):
> C3t := x->matrix(3,3,[cos(x),-sin(x),0,sin(x),cos(x),0,0,0,1]):
>
>
> #arm length segments
> l1:=matrix(3,1,[0.15,0,0]):
> l2:=matrix(3,1,[0.85,0,0]):
> l3:=matrix(3,1,[0.85,0,0]):
> l4:=matrix(3,1,[0.15,0,0]):
> l5:=matrix(3,1,[0.15,0,0]):
> l6:=matrix(3,1,[0.15,0,0]):
>
> #finding xyz in terms of the joint angles...
> x6:=evalm(l6):
> x5:=evalm(multiply(C1t(theta6),x6)+l5):
> x4:=evalm(multiply(C3t(theta5),x5)+l4):
> x3:=evalm(multiply(C2t(theta4),x4)+l3):
> x2:=evalm(multiply(C2t(theta3),x3)+l2):
> x1:=evalm(multiply(C2t(theta2),x2)+l1):
> xsol:=evalm(multiply(C1t(theta1),x1)):
>
>
> X1:= xsol[1,1]:
> X2:= xsol[2,1]:
> X3:= xsol[3,1]:
>
>
Cbig:=multiply(C1(theta6),C3(theta5),C2(theta4),C2(theta3),C2(theta2),C1(theta
1)):
>
> #A general rotation matrix used in order to find orientation of EE wrt base
> Cgeneral:=multiply(C3t(beta3),C2t(beta2),C1t(beta1)):
>
> sols[2]:= solve( -sin(beta2)=Cbig[3,1],beta2):
>
>
> S3:= solve(cos(sols[2])*sc=Cbig[2,1],sc):
> S1:= solve(sa*cos(sols[2])=Cbig[3,2],sa):
> C1:= solve(cos(sols[2])*ca=Cbig[3,3],ca):
> C3:= solve(cc*cos(sols[2])=Cbig[1,1],cc):
> sols[1]:=arctan(S1,C1):
> sols[3]:=arctan(S3,C3):
>
> #Solve for Jacobian
> Xv:= vector([X1,X2,X3, sols[1], sols[2], sols[3]]):
> thetav:= vector([theta1,theta2,theta3,theta4,theta5,theta6]):
> J:=jacobian(Xv,thetav):
>
> C1 := x->matrix(3,3,[1,0,0,0,cos(x),sin(x),0,-sin(x),cos(x)]):
> C2 := x->matrix(3,3,[cos(x),0,-sin(x),0,1,0,sin(x),0,cos(x)]):
> C3 := x->matrix(3,3,[cos(x),sin(x),0,-sin(x),cos(x),0,0,0,1]):
>
> C1t := x->matrix(3,3,[1,0,0,0,cos(x),-sin(x),0,sin(x),cos(x)]):
> C2t := x->matrix(3,3,[cos(x),0,sin(x),0,1,0,-sin(x),0,cos(x)]):
> C3t := x->matrix(3,3,[cos(x),-sin(x),0,sin(x),cos(x),0,0,0,1]):
```

```
> #Location of each joint
>
> #arm length segments
> l1:=matrix(3,1,[0.15,0,0]):
> l2:=matrix(3,1,[0.85,0,0]):
> l3:=matrix(3,1,[0.85,0,0]):
> l4:=matrix(3,1,[0.15,0,0]):
> l5:=matrix(3,1,[0.15,0,0]):
>l6:=matrix(3,1,[0.15,0,0]):
>
>#TIP RESOLUTION ANALYSIS
>
> #Resolvers give +-4arcminutes
> #Controls Assignment
>
> #+-4 Minutes = =-4/(360*60)*PI()/180 radians = 0.0000032321 radians
> #1 degree = 0.0174533 radian = Pi/180 radian
> #http://www.onlineconversion.com/angles.htm
>
> #Vary these to produce different configurations
> theta1:=0*Pi/180:
> theta2:=0*Pi/180:
> theta3:=0*Pi/180:
> theta4:=0*Pi/180:
> theta5:=0*Pi/180:
> theta6:=89*Pi/180:
>
> #Vary these to introduce joint errors
> delta1:=0.0000032321:
> delta2:=0.0000032321:
> delta3:=0.0000032321:
> delta4:=0.0000032321:
> delta5:=0.0000032321:
> delta6:=0.0000032321:
>
>
> CommandedEEPos:=evalf(evalm(matrix(6,1,[X1,X2,X3, sols[1], sols[2],
sols[3]])));
```



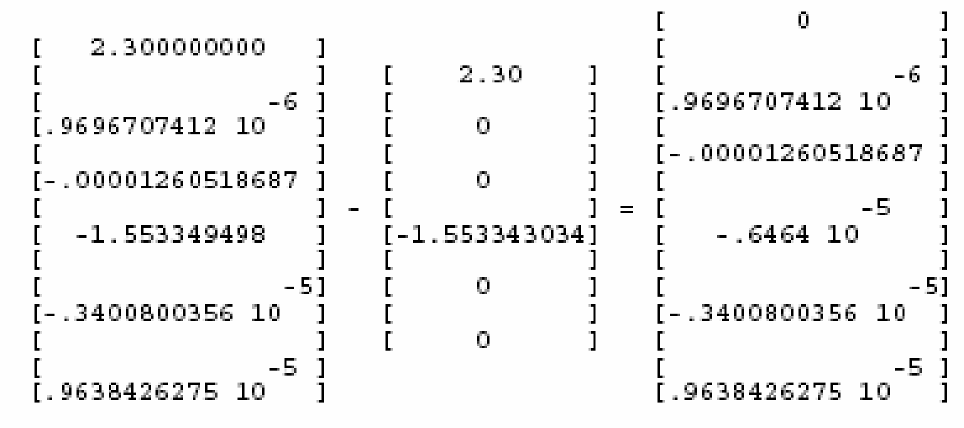
```
                           [    2.30    ]
                           [            ]
                           [     0      ]
                           [            ]
                           [     0      ]
        CommandedEEPos :=  [            ]
                           [-1.553343034]
                           [            ]
                           [     0      ]
                           [            ]
                           [     0      ]
```

```
>
> theta1:=theta1+delta1:
> theta2:=theta2+delta2:
> theta3:=theta3+delta3:
> theta4:=theta4+delta4:
> theta5:=theta5+delta5:
> theta6:=theta6+delta6:
> ErroneousEEPos:=evalf(evalm(matrix(6,1,[X1,X2,X3, sols[1], sols[2],
sols[3]])));
>
```



```
                        [   2.300000000   ]
                        [                 ]
                        [              -6 ]
                        [.9696707412 10   ]
                        [                 ]
                        [-.00001260518687 ]
ErroneousEEPos :=       [                 ]
                        [  -1.553349498   ]
                        [                 ]
                        [               -5]
                        [-.3400800356 10  ]
                        [                 ]
                        [              -5 ]
                        [.9638426275 10   ]
```

```
> DeltaX:=evalm(ErroneousEEPos)-evalm(CommandedEEPos)=evalm(ErroneousEEPos-
CommandedEEPos);
DeltaX :=
```



```
                                              [        0        ]
[   2.300000000   ]                           [                 ]
[                 ]   [    2.30    ]          [              -6 ]
[              -6 ]   [            ]          [.9696707412 10   ]
[.9696707412 10   ]   [     0      ]          [                 ]
[                 ]   [            ]          [-.00001260518687 ]
[-.00001260518687 ]   [     0      ]          [                 ]
[                 ] - [            ]        = [            -5   ]
[  -1.553349498   ]   [-1.553343034]          [   -.6464 10     ]
[                 ]   [            ]          [                 ]
[               -5]   [     0      ]          [               -5]
[-.3400800356 10  ]   [            ]          [-.3400800356 10  ]
[                 ]   [     0      ]          [                 ]
[              -5 ]                           [              -5 ]
[.9638426275 10   ]                           [.9638426275 10   ]
```

Appendix 8.7 Detailed Mass Budget

Detailed DR Mass Budget

Tool Arm

Component	Component Type	Number	Design Ma	Margin (%)	Allocated Mass (kg)
DC Brushless Motor	Faulharber 3564 O24 B	6	0.309	5%	1.947
Worm Gearbox	FaulHarber G2.6	6	0.450	5%	2.835
Secondary Planetary Gearbox	Faulharber 30/1*	6	0.235	5%	1.482
Resolver	Harowe BRCT 300-P**	12	0.142	5%	1.789
mini-cams	Toshiba IK-52V	2	0.045	5%	0.095
Power Cabling		1	3.370	10%	3.373
Data Cabling		1	2.130	10%	2.343
Structure	Shoulder Fairing	3	4.436	10%	14.639
	Elbow Joint	1	4.436	10%	4.880
	Upper Boom	1	21.610	10%	23.771
	Lower Boom	1	11.284	10%	12.413
	Wrist Fairing	3	0.907	10%	2.991
	Joint Structure****	6	4.000	20%	28.800
Thermal Protection Blankets		1	1.066	10%	1.173
Motor Electronics***		12	0.100	20%	1.440
Heaters		14	0.100	10%	1.540
Collision Avoidance System	IR emitter CQX-19	28	0.005	5%	0.147
	IR detector	28	0.005	5%	0.147
			Tool Arm total		105.804 kg

Manipulator Arm

Component	Component Type	Number	Design Ma	Margin (%)	Allocated Mass (kg)
DC Brushless Motor	Faulharber 3564 O24 B	6	0.309	5%	1.9467
Worm Gearbox	FaulHarber G2.6	6	0.450	5%	2.835
Secondary Planetary Gearbox	Faulharber 30/1*	6	0.235	5%	1.482396
Resolver	Harowe BRCT 300-P**	12	0.142	5%	1.7892
mini-cams	Toshiba IK-52V	2	0.045	5%	0.0945
Power Cabling		1	3.370	10%	3.707
Data Cabling		1	1.920	10%	2.112
Structure	Shoulder Fairing	3	3.294	10%	10.87145
	Upper Boom	1	15.048	10%	16.55239
	Lower Boom	1	7.744	10%	8.517952
	Wrist Fairing	3	0.385	10%	1.27086
	Joint Structure****	6	3.000	20%	21.6
Thermal Protection Blankets		1	21.320	10%	23.452
Motor Electronics***		12	0.100	20%	1.44
Heaters		14	0.100	10%	1.54
Collision Avoidance System	IR emitter CQX-19	28	0.005	5%	0.147
	IR detector	28	0.005	5%	0.147
			Manipulator Arm total		99.50545 kg

Body

Component	Component Type	Number	Design Ma	Margin (%)	Allocated Mass (kg)
Data Cabling		1	0.640	10%	0.704
Power Cabling		1	1.040	10%	1.144
Laser Camera System	NepTec LCS	2	12.100	5%	25.41
LCS Pan and Tilt motors	Faulharber 3564 O24 B	6	0.309	5%	1.9467
Worm Gearbox	FaulHarber G2.6	2	0.450	5%	0.945
Secondary Gearbox	Faulharber 30/1*	2	0.235	5%	0.494132
Resolver	Harowe BRCT 300-P**	4	0.142	5%	0.5964
Tools	General Purpose Clip	26	0.300	10%	8.58
	Clockwise 7/16" Ratchet Tool	2	0.300	10%	0.66
	Right Angle Tool	2	0.300	10%	0.66
	RSU tool	2	0.300	10%	0.66
	Counter Clockwise 7/16" Ratchet T	2	0.300	10%	0.66
Motor Electronics***		4	0.100	20%	0.48
Heaters		8	0.100	10%	0.88
Collision Avoidance System	IR emitter CQX-19	6	0.005	5%	0.0315
	IR detector	6	0.005	5%	0.0315
Thermal Protection System		1	3.904	10%	4.294668
Structure		1	50.000	10%	55
			Body Mass Total		43.88323

Mass Budget Summary

sub total	249.193
margin	10%
Total Design (kg)	**274.1124433**

Notes:
*- exact mass
talk about backup tools… in case of loss
***sized from terrestrial boards with comparable functionality
****4.0 kilo based on reasonable estimate
*****mass of blankets calculated to be 0.1967 Kg/M^2 take fi
******0.6096x0.508x1.5 dimensions of DR box

Thermal Protection Calculations

Arms		
diameter (m)	0.15	
length (m)	2.3	
	surface area total	1.083849
	Mass of single TPS layer (kg/m^2)	0.1967
	layers needed	5
		1.065966
Body		
sides (m)	0.609	
	0.508	
	1.5	
	surface area total	3.969744
	layers needed	5
	Mass of single TPS layer (kg/m^2)	0.1967
		3.904243

Appendix 9 Data Sheets

Theta

> *"We have been using the ATI F/T for automotive seat testing since 1998. We are impressed with its ruggedness and reliability."*
> **Kevin Moore, Automotive Testing Technologies**

The Theta F/T transducer
The transducer is made of hardened stainless steel, and the standard mounting adapter is made of high-strength stainless steel.

BENEFITS AND FEATURES

Extremely High Strength

- Precision machined from high-strength stainless steel.
- Overload pin stops make this an especially rugged transducer.
- Maximum allowable overload values are 6.1 to 20 times rated capacities.

High Signal-to-Noise Ratio

Silicon strain gauges provide a signal 75 times stronger than conventional foil gauges. This signal is amplified, resulting in near-zero noise distortion.

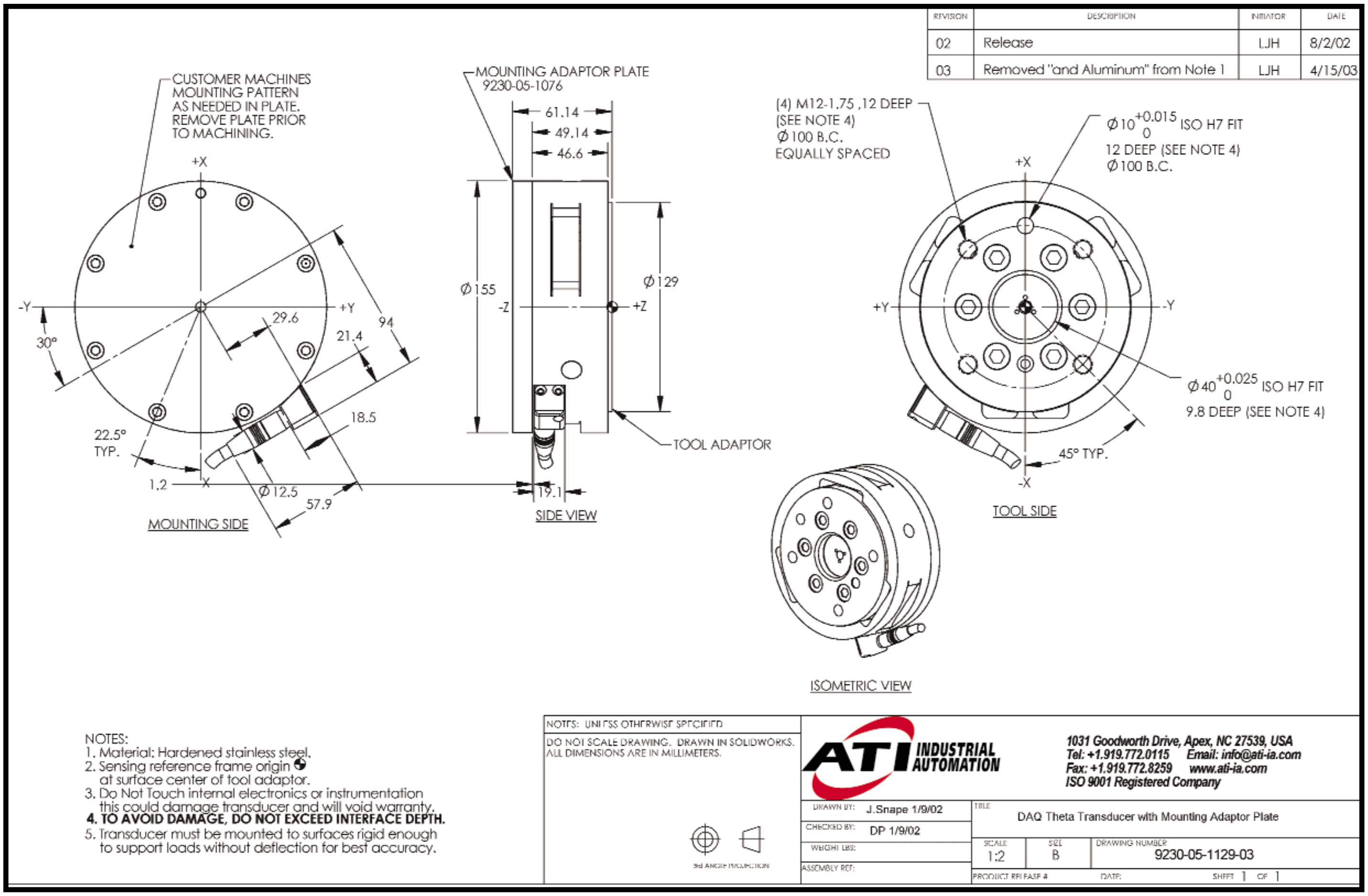
TYPICAL APPLICATIONS

- **Rehabilitation research**
- **Robotic assembly**
- **Orthopedic research**
- **Product testing**
- **Telerobotics**

English-Calibrated Sensing Ranges	**US-200-1000**		**US-300-1800**		**US-600-3600**	
Fx, Fy (±lb)	200		300		600	
Fz (±lb)	500		875		1500	
Tx, Ty (±in-lb)	1000		1800		3600	
Tz (±in-lb)	1000		1800		3600	
Resolution						
F/T System Type †	**CON**	**DAQ**	**CON**	**DAQ**	**CON**	**DAQ**
Fx, Fy (lb)	1/8	1/128	5/17	5/272	1/2	1/32
Fz (lb)	1/4	1/64	10/17	5/136	1	1/16
Tx, Ty (in-lb)	1/2	1/32	1 1/4	5/64	2	1/8
Tz (in-lb)	1/2	1/32	1 1/4	5/64	2	1/8

Metric-Calibrated Sensing Ranges	**SI-1000-120**		**SI-1500-240**		**SI-2500-400**	
Fx, Fy (±N)	1000		1500		2500	
Fz (±N)	2500		3750		6250	
Tx, Ty (±N-m)	120		240		400	
Tz (±N-m)	120		240		400	
Resolution						
F/T System Type †	**CON**	**DAQ**	**CON**	**DAQ**	**CON**	**DAQ**
Fx, Fy (N)	1	1/16	2	1/8	2	1/8
Fz (N)	1	1/16	2	1/8	4	1/4
Tx, Ty (N-m)	1/10	1/160	1/5	1/80	1/5	1/80
Tz (N-m)	1/20	1/320	1/10	1/160	1/5	1/80

Contact ATI for complex loading information. Resolutions are typical. *† CON = Controller F/T System, DAQ = 16-bit DAQ F/T System*



Single-Axis Overload	**English**	**Metric**
Fxy	±5700 lb	±25000 N
Fz	±14000 lb	±61000 N
Txy	±22000 in-lb	±2500 N-m
Tz	±24000 in-lb	±2700 N-m
Stiffness (Calculated)	**English**	**Metric**
X-axis & Y-axis force (Kx, Ky)	420x10^3 lb/in	74x10^6 N/m
Z-axis force (Kz)	710x10^3 lb/in	120x10^6 N/m
X-axis & Y-axis torque (Ktx, Kty)	3.0x10^6 in-lb/rad	340x10^3 N-m/rad
Z-axis torque (Ktz)	4.8x10^6 in-lb/rad	540x10^3 N-m/rad
Resonant Frequency (Measured)		
Fx, Fy, Tz	680 Hz	
Fz, Tx, Ty	820 Hz	
Physical Specifications	**English**	**Metric**
Weight †	11.0 lb	5000 g
Diameter †	6.10 in	155 mm
Height †	2.41 in	61.1 mm

† *Specifications include standard interface plates.*

Chapter 12. Brushless DC Motors

Topics to cover:

1. *Structures and Drive Circuits*
2. *Equivalent Circuit*
3. *Performance*
4. *Applications*

Introduction

Conventional dc motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid-state switches, maintenance-free motors were realised. These motors are now known as brushless dc motors.

In this chapter, the basic structures, drive circuits, fundamental principles, steady state characteristics, and applications of brushless dc motors will be discussed.

Structures and Drive Circuits

Basic structures

The construction of modern brushless motors is very similar to the ac motor, known as the permanent magnet synchronous motor. Fig.1 illustrates the structure of a typical three-phase brushless dc motor. The stator windings are similar to those in a polyphase ac motor, and the rotor is composed of one or more permanent magnets. Brushless dc motors are different from ac synchronous motors in that the former incorporates some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches as shown in Fig.2. The most common position/pole sensor is the Hall element, but some motors use optical sensors.

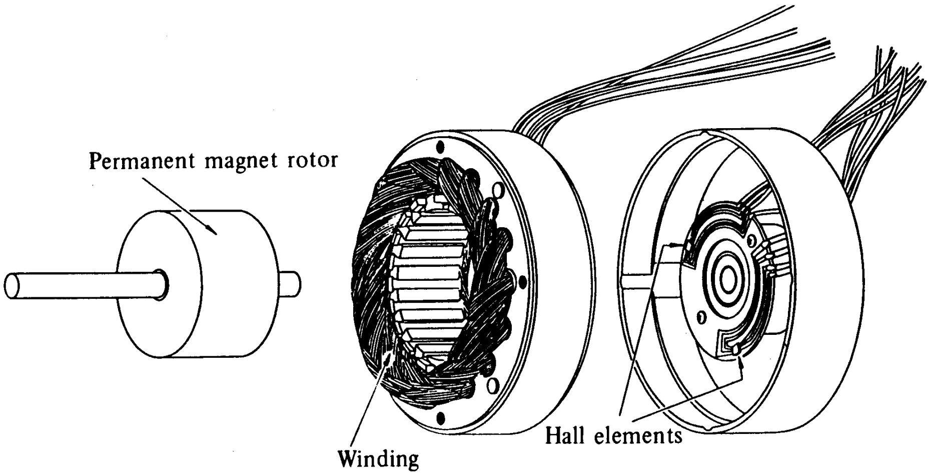


Fig.1 Disassembled view of a brushless dc motor (from Ref.[1] p58 Fig.4.1)

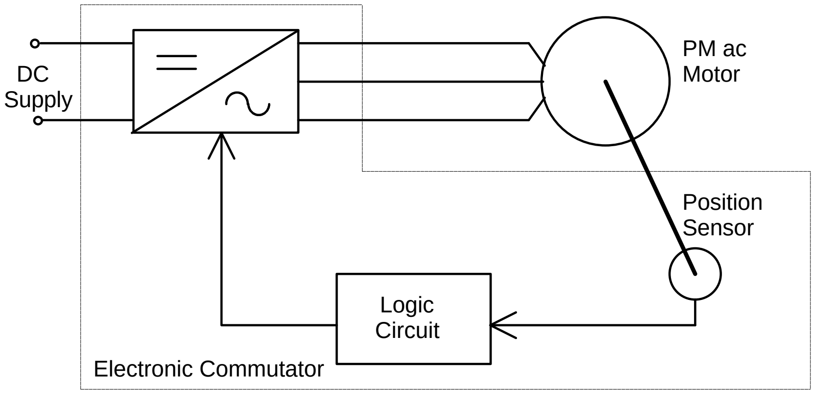


Fig.2 Brushless dc motor = Permanent magnet ac motor + Electronic commutator

Although the most orthodox and efficient motors are three-phase, two-phase brushless dc motors are also very commonly used for the simple construction and drive circuits. Fig.3 shows the cross section of a two-phase motor having auxiliary salient poles.

Comparison of conventional and brushless dc motors

Although it is said that brushless dc motors and conventional dc motors are similar in their static characteristics, they actually have remarkable differences in some aspects. When we compare both motors in terms of present-day technology, a discussion of their differences rather than their similarities can be more helpful in understanding their proper applications. Table 1 compares the advantages and disadvantages of these two types of motors. When we discuss the functions of electrical motors, we should not forget the significance of windings and commutation. Commutation refers to the process which converts the input direct current to alternating current and properly distributes it to each winding in the armature. In a conventional dc motor, commutation is undertaken by brushes and commutator; in contrast, in a brushless dc motor it is done by using semiconductor devices such as transistors.

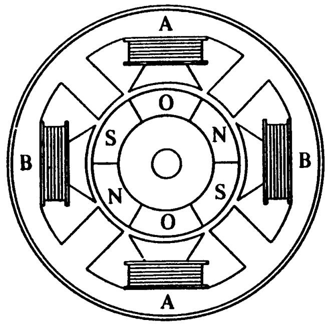


Fig.3 Two-phase motor having auxiliary salient poles (from Ref.[1] p95 Fig.5.22)

Table 1. Comparison of conventional and brushless DC motors

	Conventional motors	Brushless motors
Mechanical structure	Field magnets on the stator	Field magnets on the rotor Similar to AC synchronous motor
Distinctive features	Quick response and excellent controlability	Long-lasting Easy maintenance (usually no maintenance required)
Winding connections	Ring connection The simplest: Δ connection	The highest grade: Δ or Y-connected three-phase connection Normal: Y-connected three-phase winding with grounded neutral point, or four-phase connection The simplest: Two-phase connection
Commutation method	Mechanical contact between brushes and commutator	Electronic switching using transistors
Detecting method of rotor's position	Automatically detected by brushes	Hall element, optical encoder, etc.
Reversing method	By a reverse of terminal voltage	Rearranging logic sequencer

Drive circuits

(1) Unipolar drive

Fig.4 illustrates a simple three-phase unipolar-operated motor that uses optical sensors (phototransistors) as position detectors. Three phototransistors PT1, PT2, and PT3 are placed on the end-plate at 120^{o} intervals, and are exposed to light in sequence through a revolving shutter coupled to the motor shaft.

As shown in Fig.4, the north pole of the rotor now faces the salient pole P2 of the stator, and the phototransistor PT1 detects the light and turns transistor Tr1 on. In this state, the south pole which is created at the salient pole P1 by the electrical current flowing through the winding W1 is attracting the north pole of the rotor to move it in the direction of the arrow. When the north pole comes to the position to face the salient pole P1, the shutter, which is coupled to the shaft, will shade PT1, and PT2 will be exposed to the light and a current will flow through the transistor Tr2. When a current flows through the winding W2, and creates a south pole on salient pole P2, then the north pole in the rotor will revolve in the direction of the arrow and face the salient pole P2. At this moment, the shutter shades PT2, and the phototransistor PT3 is exposed to the light. These actions steer the current from the winding W2 to W3. Thus salient pole P2 is de-energized, while the salient pole P3 is energized and creates the south pole. Hence the north pole on the rotor further travels from P2 to P3 without stopping. By repeating such a switching action in sequence given in Fig.5, the permanent magnet rotor revolves continuously.

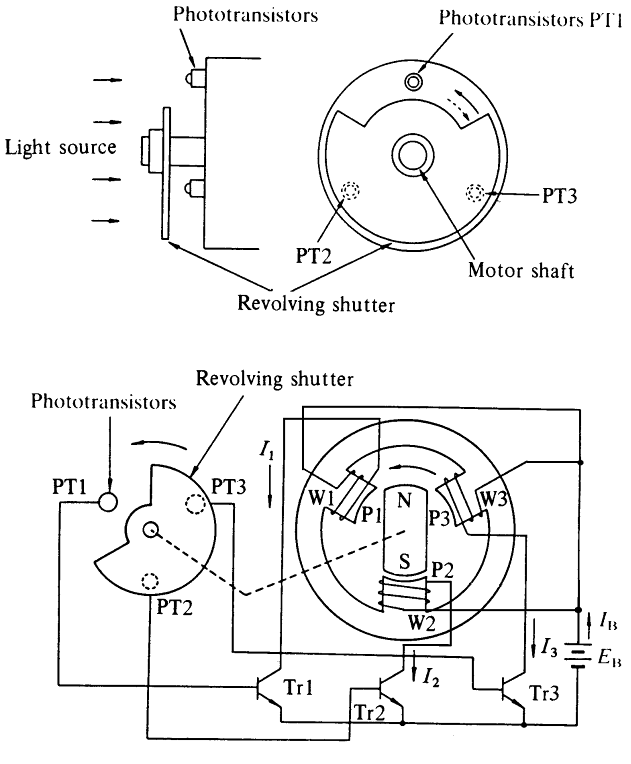


Fig.4 Three-phase unipolar-driven brushless dc motor
(from Ref.[1] p59 Fig.4.2 with winding directions swapped)

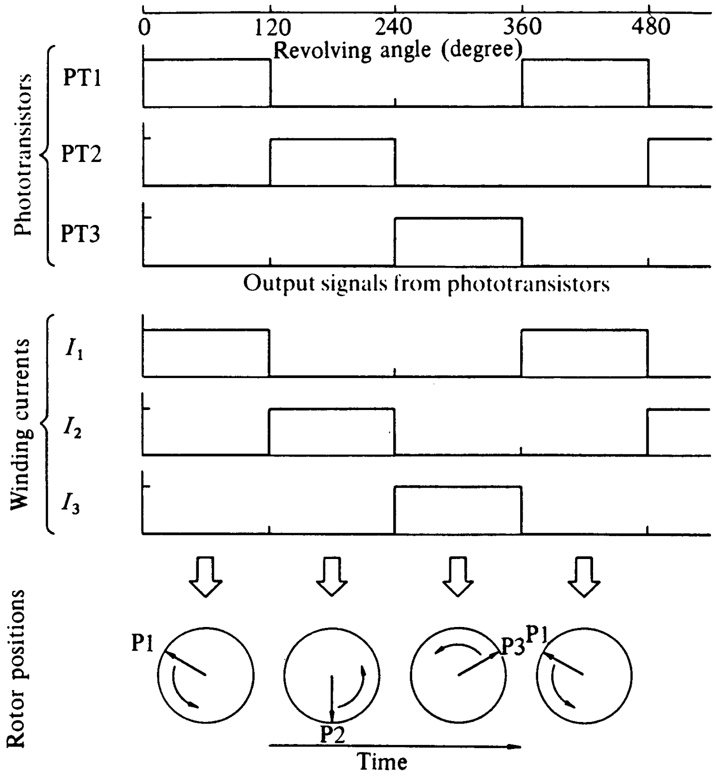


Fig.5 Switching sequence and rotation of stator's magnetic field (from Ref.[1] p60 Fig.4.3)

(2) Bipolar drive

When a three-phase (brushless) motor is driven by a three-phase bridge circuit, the efficiency, which is the ratio of the mechanical output power to the electrical input power, is the highest, since in this drive an alternating current flows through each winding as an ac motor. This drive is often referred to as 'bipolar drive'. Here, 'bipolar' means that a winding is alternatively energised in the south and north poles.

We shall now survey the principle of the three-phase bridge circuit of Fig.6. Here too, we use the optical method for detecting the rotor position; six phototransistors are placed on the end-plate at equal intervals. Since a shutter is coupled to the shaft, these photo elements are exposed in sequence to the light emitted from a lamp placed in the left of the figure. Now the problem is the relation between the ON/OFF state of the transistors and the light detecting phototransistors. The simplest relation is set when the logic sequencer is arranged in such a way that when a phototransistor marked with a certain number is exposed to light, the transistor of the same number turns ON. Fig.6 shows that electrical currents flow through Tr1, Tr4, and Tr5, and terminals U and W have the battery voltage, while terminal V has zero potential. In this state, a current will flow from terminal U to V, and another current from W to V as illustrated in Fig.7. We may assume that the solid arrows in this figure indicate the directions of the magnetic fields generated by the currents in each phase. The fat arrow in the centre is the resultant magnetic field in the stator.

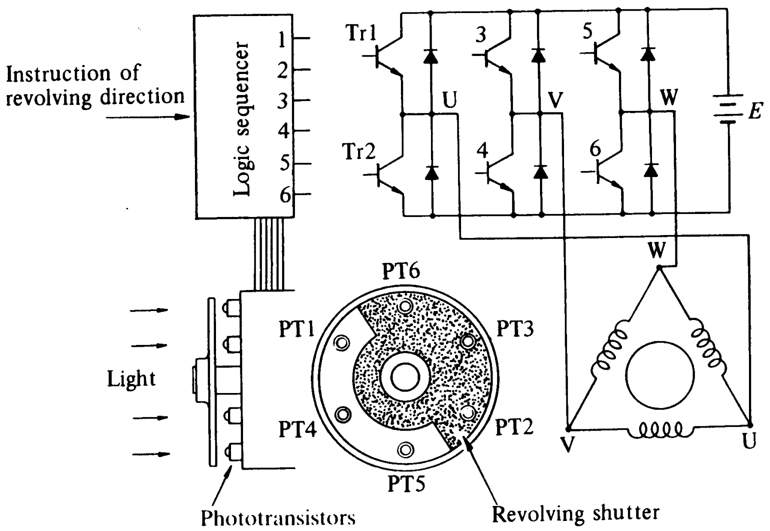


Fig.6 Three phase bipolar-driven brushless motor (from Ref.[1] p61, Fig.4.4)

The rotor is placed in such a position that the field flux will have a 90^{O} angle with respect to the stator's magnetic field as shown in Fig.7. In such a state a clockwise torque will be produced on the rotor. After it revolves through about 30^{O}, PT5 is turned OFF and PT6 ON which makes the stator's magnetic pole revolve 60^{O} clockwise. Thus when the rotor's south pole gets near, the stator's south pole goes away further to create a continuous clockwise rotation. The ON-OFF sequence and the rotation of the transistor are shown in Fig.8.

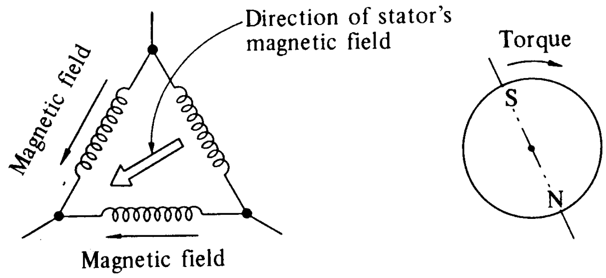


Fig.7 Stator's magnetic field in the shutter state of Fig.6, and the direction of torque (from Ref.[1] p62, Fig.4.5)

Tr 1	1	1	1	0	0	0
2	0	0	0	1	1	1
3	0	0	1	1	1	0
4	1	1	0	0	0	1
5	1	0	0	0	1	1
6	0	1	1	1	0	0

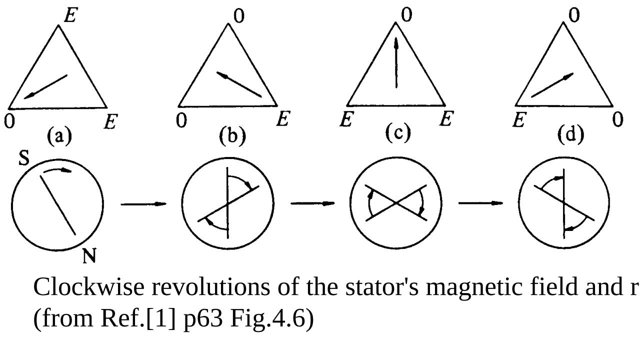
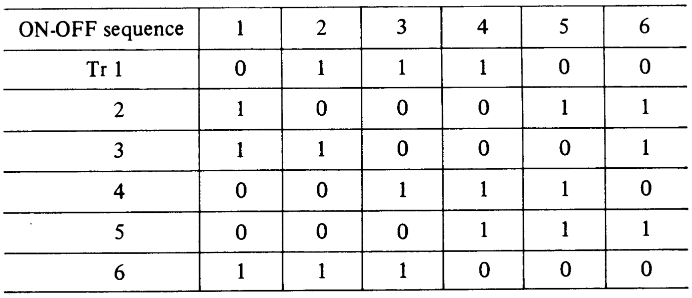


Fig.8 Clockwise revolutions of the stator's magnetic field and rotor (from Ref.[1] p63 Fig.4.6)

The rotational direction may be reversed by arranging the logic sequencer in such a way that when a photodetector marked with a certain number is exposed to light, the transistor of the same number is turned OFF. On the other hand, when a phototransistor is not exposed to light, the transistor of the same number is turned ON.

In the positional state of Fig.6, Tr2, 3, and 6 are ON, and the battery voltage E appears at terminal V, while U and W have zero electric potential. Then, as shown in Fig.9(a), the magnetic field in the stator is reversed, and the rotor's torque is counter-clockwise. After the motor revolves about 30°, Tr2 turns OFF and Tr1 ON. At this point, the field has revolved 60° and becomes as shown in (b). As the rotor produces another counter-clockwise torque, the counter-clockwise motion continues and the field becomes as shown in (c). This action is replaced in the sequence of (a)→(b)→(c)→(d)...... to produce a continuous counter-clockwise motion.



ON-OFF sequence	1	2	3	4	5	6
Tr 1	0	1	1	1	0	0
2	1	0	0	0	1	1
3	1	1	0	0	0	1
4	0	0	1	1	1	0
5	0	0	0	1	1	1
6	1	1	1	0	0	0

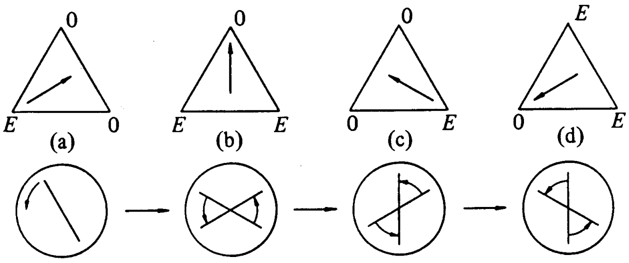


Fig.9 Counter-clockwise revolutions of the stator's magnetic field and rotor (from Ref.[1] p63 Fig.4.7)

The motor discussed above has Δ-connected windings, but it may also have Y-connected windings. Fig.10(a) shows a practical circuit which is used in a laser-beam printer or a hard-disc drive. As shown in Fig.10(b), three Hall elements are placed at intervals of 60° for detection of the rotor's magnetic poles. Because this motor has four magnetic poles, a mechanical angle of 60° corresponds to an electrical angle of 120°.

Equivalent Circuit and General Equations

The per phase equivalent circuit is shown in Fig.11 as following, where λ_m is the flux linkage of stator winding per phase due to the permanent magnet.

For steady state conditions, assuming v and e are sinusoidal at frequency ω, the equivalent circuit becomes the one shown in Fig.12, where X=ωL, and V, I, E, and λ_m are phasors with rms amplitudes. The steady state circuit equation can be written as

$$V = E + (R + jwL) I \tag{1}$$

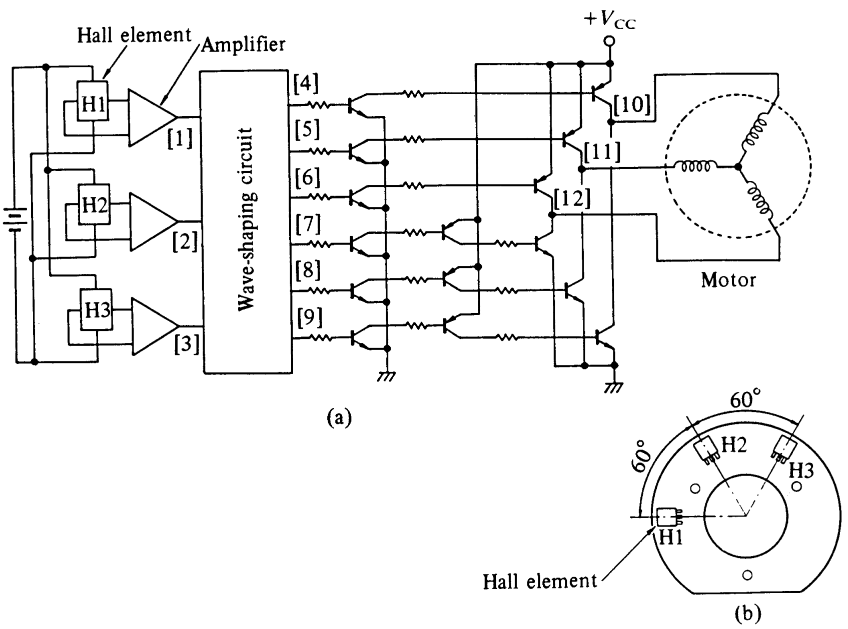


Fig.10 Practical circuit for a three-phase bipolar-driven motor, and arrangement of Hall elements (from Ref.[1] p80 Fig.5.1)

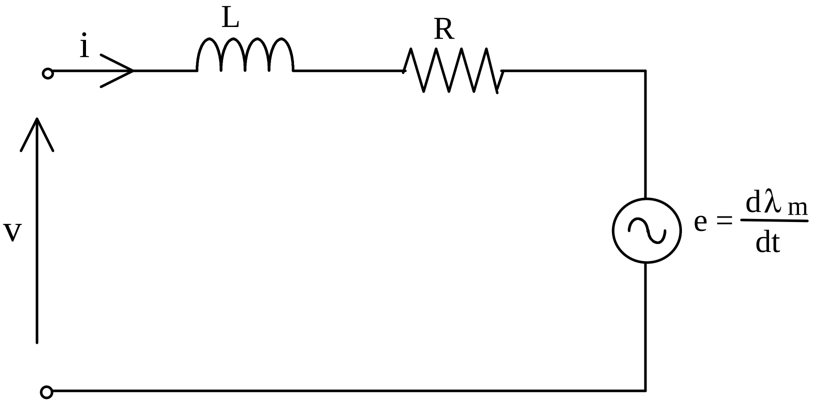


Fig.11 Dynamic per phase equivalent circuit of brushless dc motors

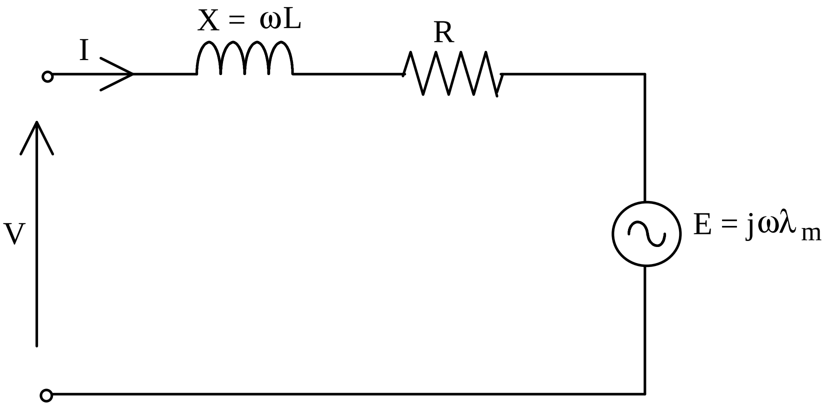


Fig.12 Steady state per phase equivalent circuit of brushless dc motors

For a maximum mechanical power at a given speed, *I* and *E* are in phase. This also gives maximum torque/ampere (minimum current/Nm). A brushless dc motor has position feedback from the rotor via Hall devices, optical devices, encoder etc. to keep a particular angle between *V* and *E*, since *E* is in phase with rotor position, and *V* is determined by the inverter supply to the motor. Assuming that $wL<<R$, when I is in phase with E, V will also be in phase with E. Thus the circuit can be analyzed using magnitudes of E, V, and I as if it were a dc circuit.

But first note that when E and I are in phase, the motor mechanical power output (before friction, windage, and iron losses) i.e. the electromagnetic output power is

$$P_{em} = m\,|E|\,|I| = mw\,|l_m|\,|I| \qquad (2)$$

where m is the number of phases, $|E|$, $|I|$, and $|\lambda_m|$ are the amplitudes of phasor E, I, and λ_m, and the electromagnetic torque is

$$T_{em} = \frac{P_{em}}{w_r} = \frac{mw\,|l_m||I|}{w_r} \qquad (3)$$

where $w_r = 2w/p$ is the rotor speed in Rad/s, and p the number of poles.

$$\therefore\ T_{em} = \frac{mp}{2}\,|l_m|\,|I| \qquad (4)$$

The actual shaft output torque is

$$T_{load} = T_{em} - T_{losses} \qquad (5)$$

where T_{losses} is the total torque due to friction, windage, and iron losses.

Dropping the amplitude (modulus) signs, we have

$$T_{em} = \frac{mp}{2}\,l_m\,I \qquad (6)$$

and in terms of rotor speed

$$E = \frac{p}{2}\,w_r\,l_m \qquad (7)$$

Performance of Brushless DC Motors

Speed-Torque (T~w) curve

Still assuming $wL<<R$ and position feed back keeps V and E (and hence I) in phase, the voltage equation can be simplified in algebraic form as

$$V = E + RI \qquad (8)$$

Substituting relations of $E\sim w_r$ and $T\sim I$, we obtain

$$V = \frac{p}{2} w_r l_m + \frac{2R}{mpl_m} T_{em} \qquad (9)$$

and

$$\therefore \; w_r = \frac{V}{pl_m/2} - \frac{R}{m(pl_m/2)^2} \; T_{em} \qquad (10)$$

The corresponding *T~w* curve is shown in Fig.13 for a constant voltage.

Efficiency

Efficiency is defined as the ratio of output power and input power, i.e.

$$h = \frac{P_{out}}{P_{in}} \qquad (11)$$

where $P_{in} = mVI$, and $P_{out} = T_{load} w_r$.

In term of the power flow,

$$P_{in} = P_{cu} + P_{Fe} + P_{mec} + P_{out} \qquad (12)$$

where $P_{cu} = mRI^2$ is the copper loss due to winding resistance, P_{Fe} the iron loss due to hysteresis and eddy currents, and P_{mec} the mechanical loss due to windage and friction.

Applications

Brushless dc motors are widely used in various applications. Two examples of them are illustrated in the following.

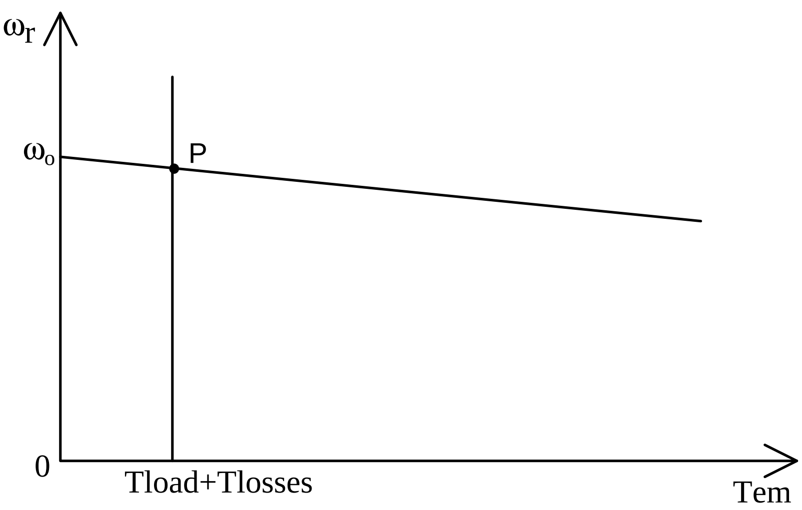


Fig.13 *T~w* curve of a brushless dc motor with a constant voltage supply

Laser printer

In a laser printer, a polygon mirror is coupled directly to the motor shaft and its speed is controlled very accurately in the range from 5000 to 40,000 rpm. When an intensity-modulated laser beam strikes the revolving polygon mirror, the reflected beam travels in different direction according to the position of the rotor at that moment. Therefore, this reflected beam can be used for scanning as shown in Fig.14. How an image is produced is explained, using Fig.15 and the following statements:

(1) The drum has a photoconductive layer (e.g. Cds) on its surface, with photosensitivity of the layer being tuned to the wavelength of the laser. The latent image of the information to be printed formed on the drum surface by the laser and then developed by the attracted toner.

(2) The developed image is then transferred to normal paper and fixed using heat and pressure.

(3) The latent image is eliminated.

A recent brushless dc motor designed for a laser printer is shown in Fig.16, and its characteristic data are given in Table 2.

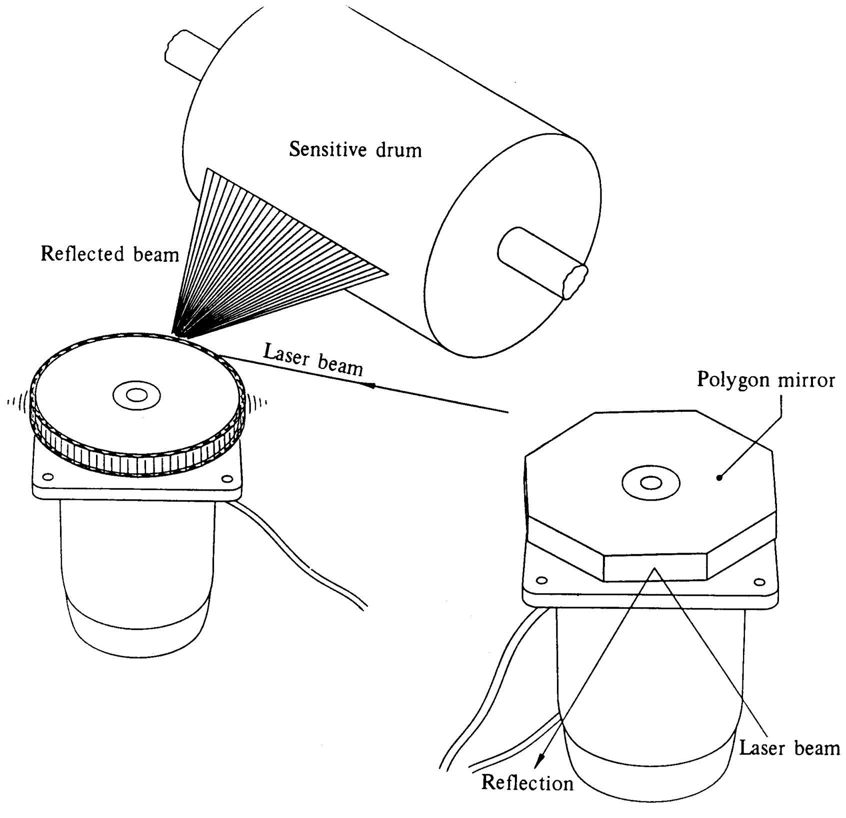


Fig.14 Role of motors for laser printers; (right) a brushless dc motor driving a polygon mirror, and (above) how to scan laser beams (from Ref.[1] p82 Fig.5.3)

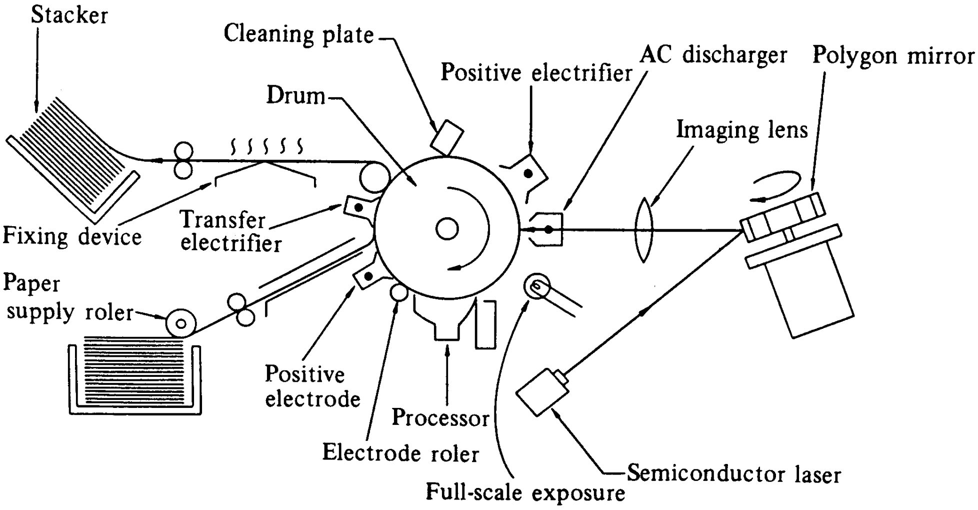


Fig.15 Principles of laser printers (from Ref.[1] p82 Fig.5.4)

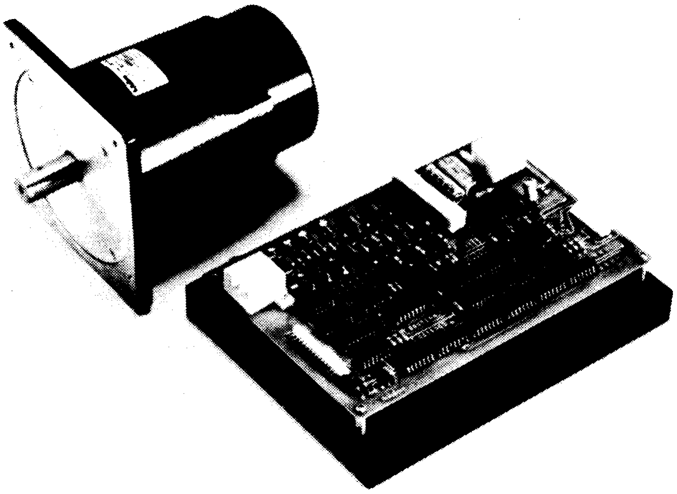


Fig.16 Brushless dc motor for a laser printer (from Ref.[1] p83 Fig.5.5

Table 2 Characteristics of three-phase bipolar type brushless motors

Item	Manufacturer Model	Nippon Densan Corporation 09PF8E4036
Voltage	V	±24±1.2
Output	W	36
Rated torque	10^{-1} N m	0.294
Starting torque	10^{-1} N m	0.588
Starting time	s	3 (at non-inertial load)*
Rated speed	r.p.m.	6000, 9000, 12 000 selection
Rated current	A	3.5
Temperature	°C	5 ~ 45
Stability	per cent	±0.01
		Three-phase Δ connection

* A non-inertial load is a load applied by using a pulley and a weight

Hard disk drive

As the main secondary memory device of the computer, hard disks provide a far greater information storage capacity and shorter access time than either a magnetic tape or floppy disk. Formerly, ac synchronous motors were used as the spindle motor in floppy or hard disk drives. However, brushless dc motors which are smaller and more efficient have been developed for this application and have contributed to miniaturization and increase in memory capacity in computer systems. Table 3 compares a typical ac synchronous motor with a brushless dc motor when they are used as the spindle motor in an 8-inch hard disk drive. As is obvious from the table, the brushless dc motor is far superior to the ac synchronous motor. Although the brushless dc motor is a little complicated structurally because of the Hall elements or ICs mounted on the stator, and its circuit costs, the merits of the brushless dc motor far outweigh the drawbacks.

Table 3 Comparison of an ac synchronous motor and a brushless dc motor for an 8-inch hard disk drive

	AC synchronous motor	Brushless DC motor
Power supply: direct current, low voltage (for extension and interchangeability)	Inverter required	Direct current, low voltage (12–24 V)
Speed adjustment	Since speed depends on the frequency, regional adaptability is low	Adjustable independent of frequency
Adjustment of starting time	Adjustment not possible	Adjustment possible
Temperature rise	High	Low
Efficiency	Low (approx 30 per cent)	High (40–50 per cent)
Output to volume ratio	Small (bad)	Large (good)
Speed control	Fixed	Feedback control
Structure/cost	Simple, low cost	Slightly complicated, control circuit is not so expensive by the use of ICs

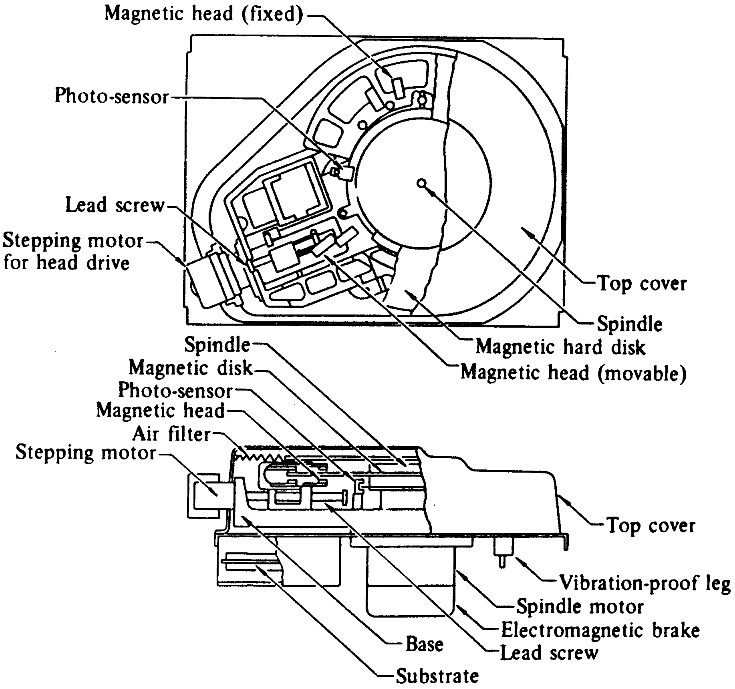


Fig.17 An example of hard disk drive (single disk type) (from Ref.[1] p86 Fig.5.9)

The hard disk drive works as follows (see Fig.17): The surface of the aluminium disk is coated with a film of magnetic material. Data is read/written by a magnetic head floating at a distance of about 0.5 μm from the disk surface due to the airflow caused by the rotating disk, and this maintains a constant gap. Therefore, when the disk is stopped or slowed down, the head may touch the disk and cause damage to the magnetic film. To prevent this, this spindle motor must satisfy strict conditions when starting the stopping.

Table 4 lists the basic characteristic data of brushless dc motors used in 8-inch hard disk drives (Fig.18).

Table 4 Characteristics of a three-phase unipolar motor designed for the spindle drive in a hard disk drive (from Ref.[1] p87 Table 5.3)

	Manufacturer	**Nippon Densan Corporation**	
Item	**Model**	**09FH9C4018**	**09FH9C4022**
Voltage	V	24±2.4	24±2.4
Output	W	18	22
Rated torque	10^{-1} N m	0.490	0.588
Starting torque	10^{-1} N m	1.47	1.96
Starting time	s	1.35	1.55
Rated speed	r.p.m.	3600	3600
Rated current	A	2.0	2.4
Temperature	°C	0~50	
Stability	per cent	±1.0	
Inertia	10^{-6} kg m^2	1380	1670
Braking method		Electromagnetic method	
Number of disks		2	4

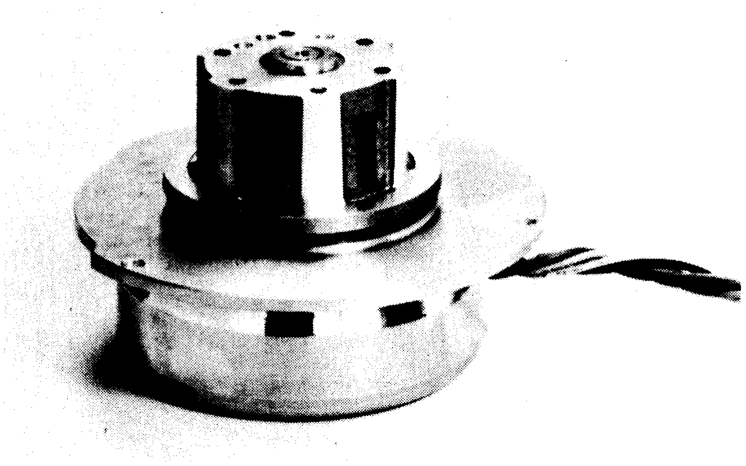


Fig.18 A brushless dc motor used for 8-inch hard disk drives (from Ref.[1] p87 Fig.5.10)

REFERENCES

[1] T. Kenjo, "Permanent magnet and brushless dc motors", Oxford, 1985

[2] T.J.E. Miller, "Brushless permanent magnet and reluctance motor drive", Oxford, 1989

EXERCISES

1. Describe the essential features of a brushless dc motor (alternatively called a self-synchronous motor).

2. What additional features would be required for a brushless dc servomotor with torque and position control?

3. Sketch the power circuit for a 3-phase brushless dc motor.

4. Calculate the supply frequency required for a twelve pole motor to rotate at (a) 360 rpm, and (b) 3600 rpm.

5. A brushless dc motor has 3 phases and 4 poles. The generated emf is 220 V rms sinusoidal at 1000 rpm (open circuit voltage when tested as generator with a drive motor). Calculate
   (a) the emf constant (V/Rad/s);
   (b) the torque constant (Nm/A) with optimum position feedback angle;
   (c) the speed/torque curve, if the resistance per phase is 4 Ω;
   (d) the supply frequency at 1000 rpm;
   (e) curves of input power, output power and efficiency against torque, assuming friction and iron losses are zero;
   (f) the frequency and speed at which $X=\omega L$ is equal to the resistance R, if the phase inductance is 5 mH;
   (g) what is the effect of (f) on the speed/torque curve i.e. the effect of $L>0$ and $\omega L>R$ as speed increases?

6. A brushless dc motor has 3 phases and 6 poles. The electromagnetic torque is 4 Nm with a current of 0.5 A rms. Friction and iron losses produce a constant retarding torque of 0.1 Nm. The resistance and inductance per phase are 70 Ω and 50 mH. Assume optimum position feedback. Calculate
   (a) the torque and emf constants;
   (b) the emf generated for a speed of 600 rpm;
   (c) the speed of the motor for a supply voltage of 200 V (ac rms per phase) with no external load;
   (d) the speed, current and efficiency for an external load of 4 Nm and a supply voltage of 200 V ac rms;
   (e) the supply frequency for (d), and check $\omega L<R$.

Planetary Gearheads

7,081 oz-in

Motor and Gearhead combinations:
G6.1 fits motor series GNM5440 & GNM5480

Series G6.1

See beginning of the PMDC Gearhead Section for Ordering Information

		G6.1
Housing material		metal
Backlash, at no-load		≤ 1.5°
Shaft load, max.:		
– radial	lbs	180
– axial	lbs	33.7 for ratio 8:1 45.0 for ratios 16.8 to 45.3 56.3 for ratios 68.9 and up

Series G6.1 with Motor Series GNM 5440

reduction ratio	weight without motor		length with motor GNM 5440		output torque continuous operation		intermittent operation		direction of rotation (reversible)	efficiency
	Kg	oz	mm	in	M max. Nm	M max. oz-in	M max. Nm	M max. oz-in		%
134.5:1	3.20	112.9	287	11.3	50	7,081	130	18,410	=	55
187.5:1	3.20	112.9	287	11.3	50	7,081	130	18,410	=	55

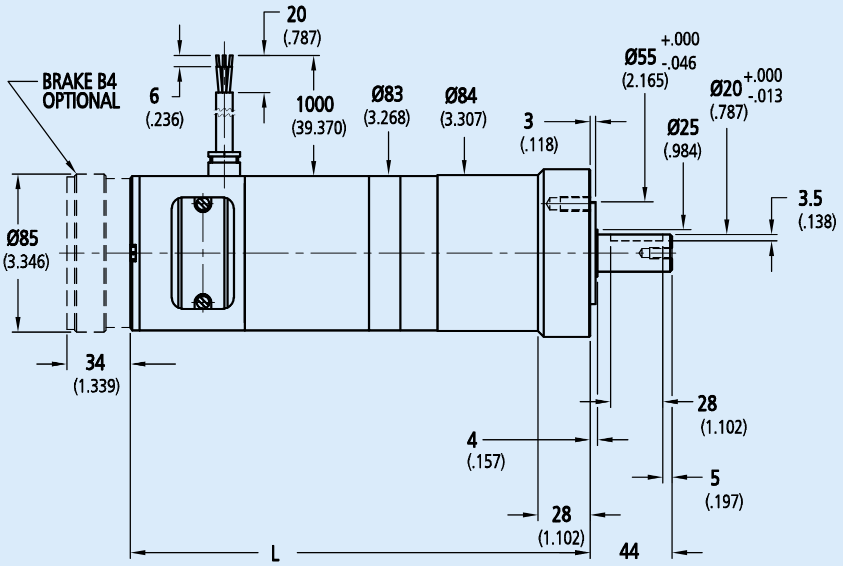
Series G6.1 with Motor Series GNM 5480

reduction ratio	weight without motor		length with motor GNM 5480		output torque continuous operation		intermittent operation		direction of rotation (reversible)	efficiency
	Kg	oz	mm	in	M max. Nm	M max. oz-in	M max. Nm	M max. oz-in		%
8:1	2.30	81.1	290	11.42	5.8	821	36	5,098	=	85
16.8:1	2.90	102	314	12.36	11	1,558	70	9,913	=	70
23.2:1	2.90	102	314	12.36	15	2,124	92	13,028	=	70
32.8:1	2.90	102	314	12.36	21	2,974	125	17,702	=	70
45.3:1	2.90	102	314	12.36	29	4,107	130	18,410	=	70
68.9:1	3.20	113	327	12.87	39	5,523	130	18,140	=	55
95.1:1	3.20	113	327	12.87	50	7,081	130	18,410	=	55
134.5:1	3.20	113	327	12.87	50	7,081	130	18,410	=	55

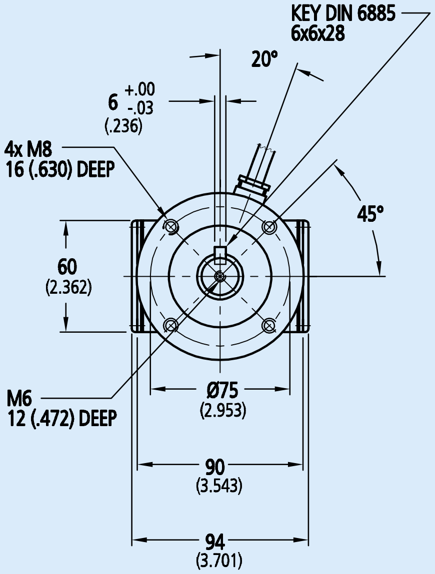
For notes on technical data refer to "Technical Information". Specifications subject to change without notice. MME0402

Series G6.1

Dimensional outlines for G6.1 with GNM5440 & GNM5480



GNM 54... + G6.1

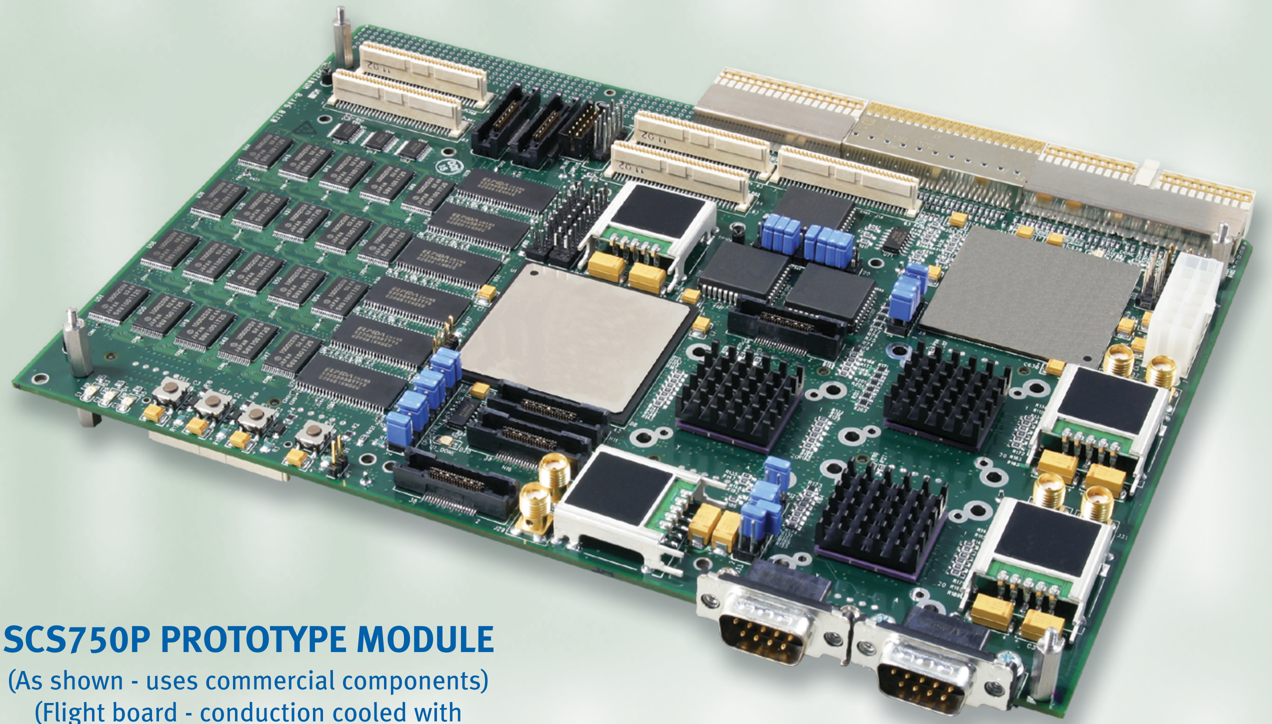


Front View

MODEL	RATIO	L DIMENSIONS - mm(in)
5440	134.5:1 - 185.7:1	287 (11.299)
5480	8:1	290 (11.417)
	16.8:1 - 45.3:1	314 (12.362)
	68.9:1 - 134.5:1	327 (12.874)

SCS750A™

SUPER COMPUTER FOR SPACE



SCS750P PROTOTYPE MODULE

(As shown - uses commercial components)
(Flight board - conduction cooled with
space qualified components)

- One (1) upset every 300 years in a GEO Orbit
- Up to 1000X Performance of Current Space Processor Boards
- Highest Space-Qualified Performance @ 1800 MIPS
- Demonstrated Radiation Tolerance
  - Silicon-On-Insulator (SOI) Processors
  - Actel RTAX-S Radiation Tolerant FPGAs
  - RAD-PAK® & RAD-STAK™ Packaged Memories
- Triple Modular Redundant Processing
- Advanced Error Corrected SDRAM
- Ultimate Upgradeability
- Software Selectable Power Consumption from 7-25 watts
- Standard Development Platform – Compatible with IBM's PowerPC750™

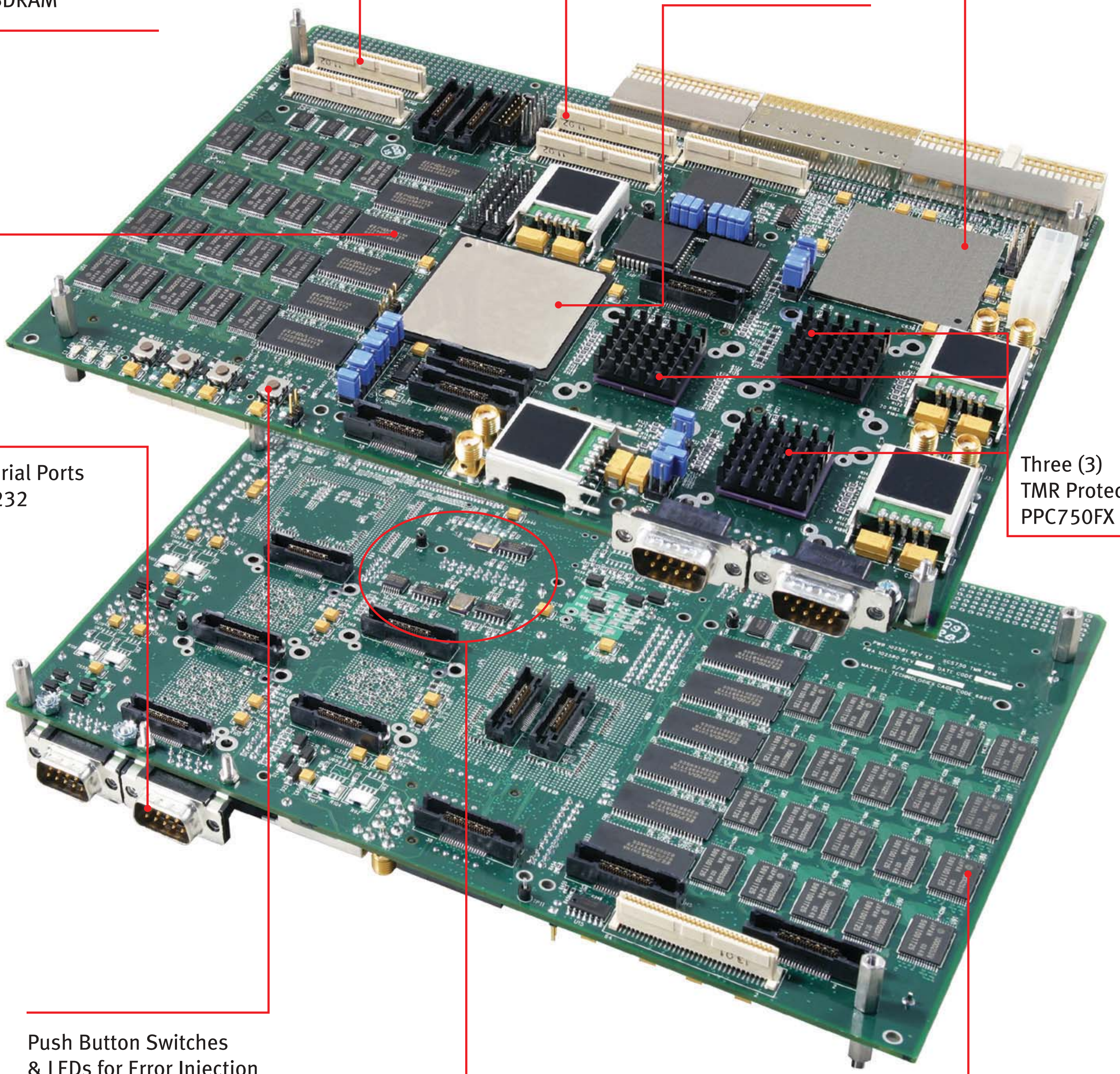
The **SCS750A** single board computer is Maxwell’s answer to the space industry’s need for high-performance computing and on-board data processing while providing excellent reliability/upset immunity. There is a trend to perform data management and manipulation on the spacecraft, which requires a large amount of processing power. This next generation super computer will enable future satellite designs to dramatically increase error-free, on-board data processing, mission planning and critical decision-making.

The **SCS750A** has been designed to operate in a cPCI system targeting high performance computing and memory for the most demanding space applications. Its design decisions have been driven by a guarantee of the highest reliability and performance. Maxwell has developed a comprehensive radiation mitigation strategy to provide total dose hardness, latchup immunity and upset error mitigation for the **SCS750A**. Maxwell's **SCS750A** has become the benchmark of which all future space processor boards will be measured.

Maxwell™ TECHNOLOGIES

SCS750AP Prototype Layout

(As shown - uses commercial components)
(Flight board - conduction cooled with space qualified components)



PMC Slots for
Engineering Development

Reed-Solomon
EDAC Protected
SDRAM

System Controller
FPGA w/TMR and
Reed-Solomon Logic

PCI-PCI Bridge

2 Serial Ports
RS-232

Three (3)
TMR Protected
PPC750FX

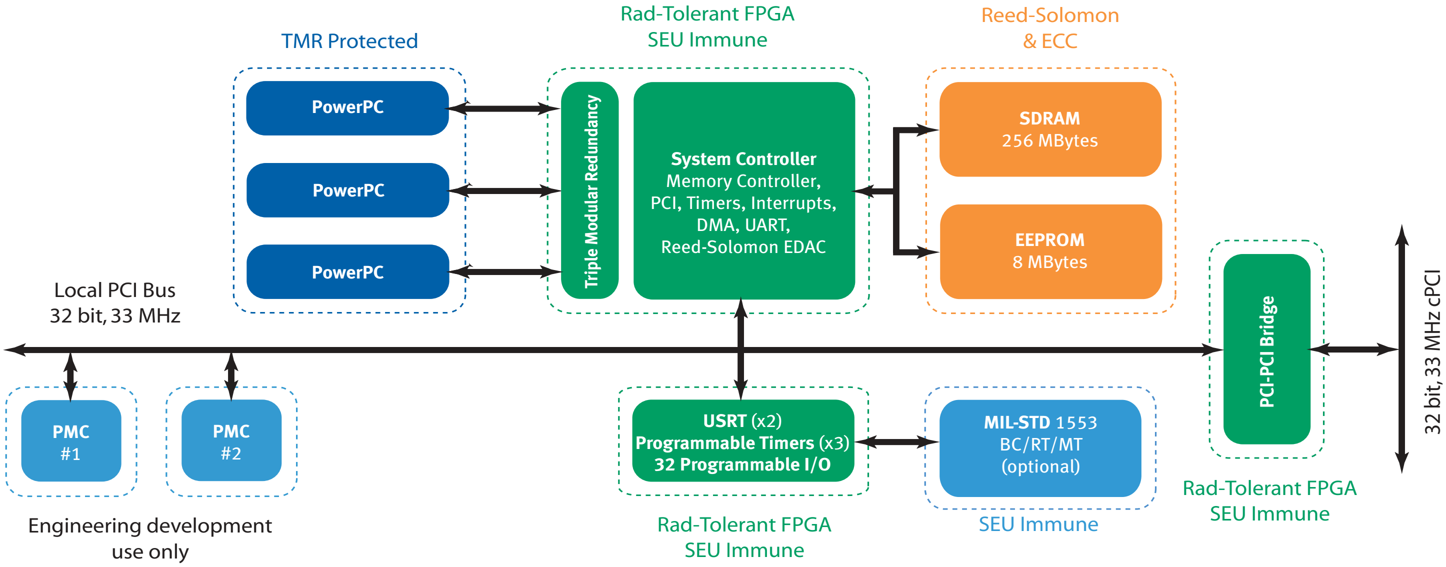
Push Button Switches
& LEDs for Error Injection
and Board Reset

Clock Distribution

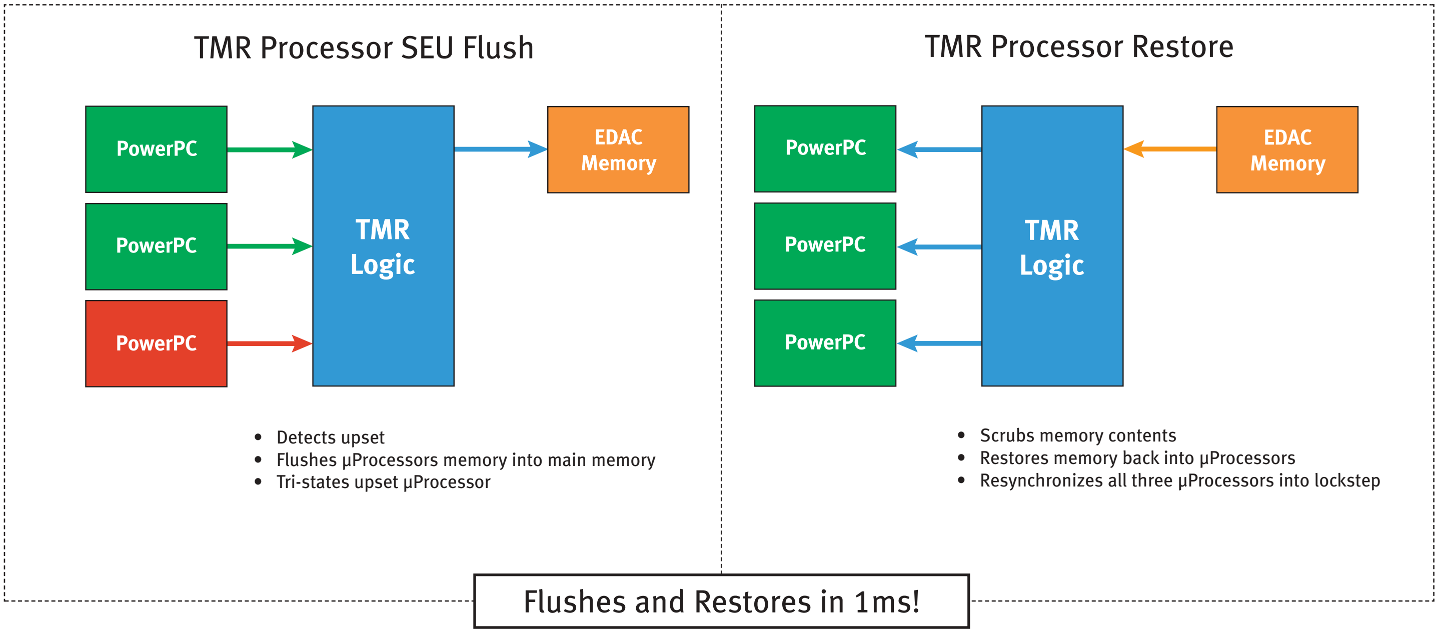
EDAC-Protected
EEPROM

SCS750AP - For hardware & software development & integration
- 2 UARTs (RS-232) vs. 1 UART (LVDS) on AD, AE & AF Models
- 4 Mb EEPROM vs. 8 Mb EEPROM on AD, AE & AF Models

SCS750A Block Diagram



Triple Modular Redundancy Protection

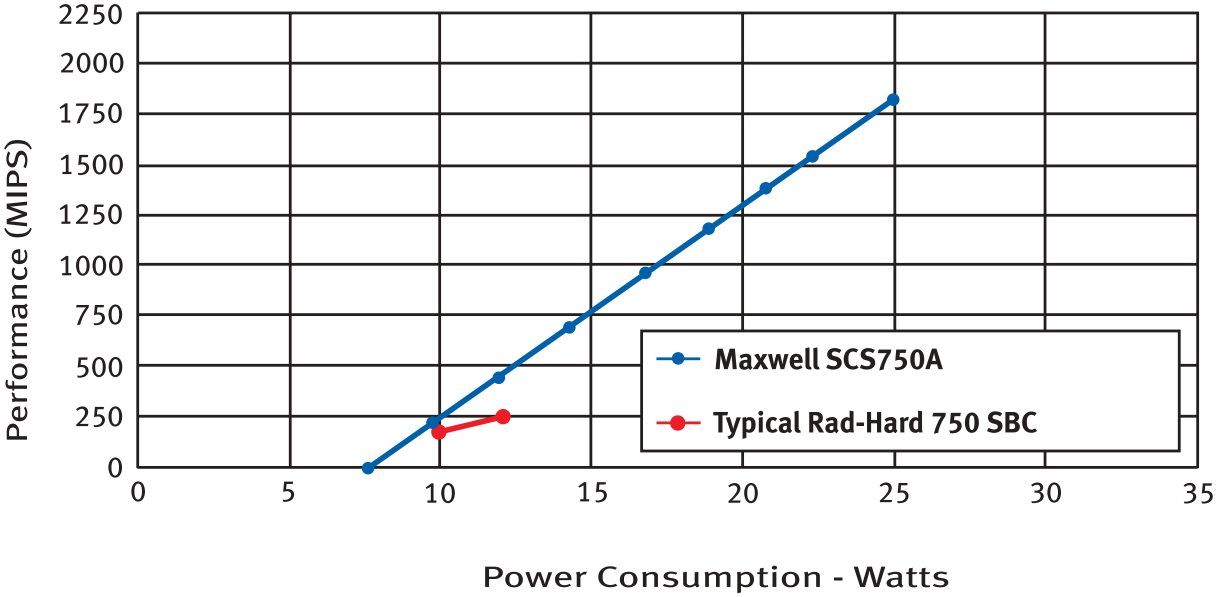


- Detects upset
- Flushes µProcessors memory into main memory
- Tri-states upset µProcessor

- Scrubs memory contents
- Restores memory back into µProcessors
- Resynchronizes all three µProcessors into lockstep

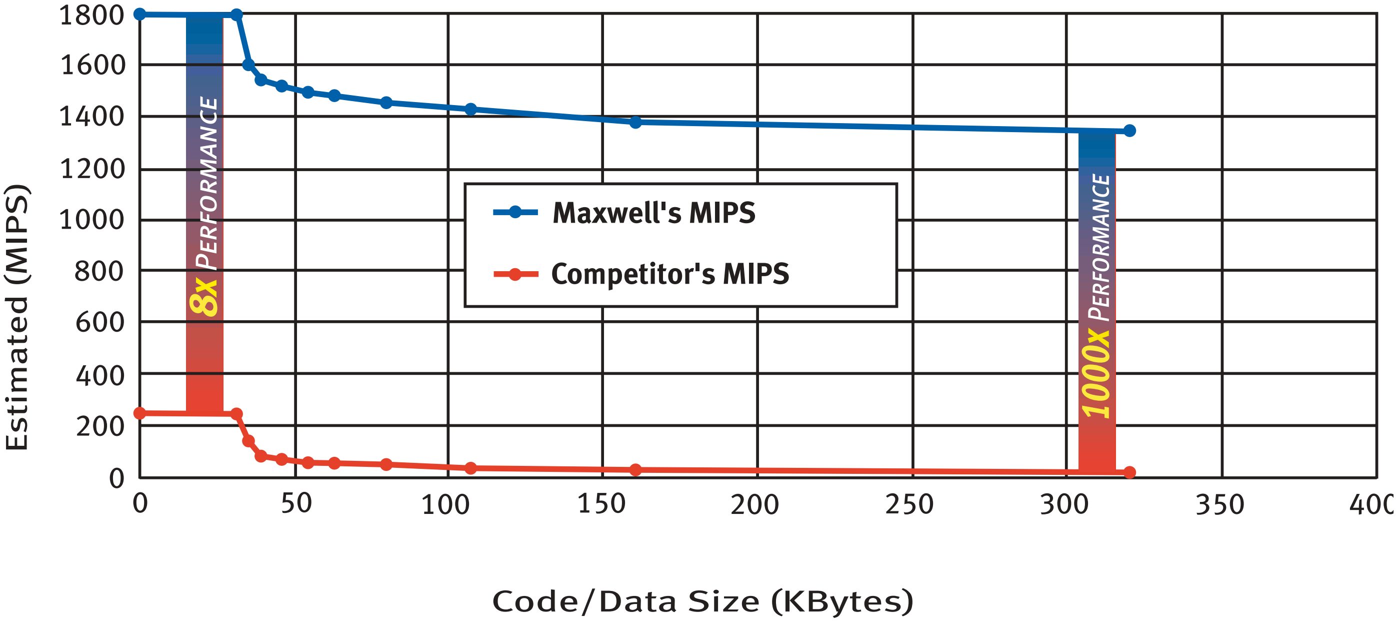
Flushes and Restores in 1ms!

Software Selectable Power Consumption



Note: Peak performance listed is based on competitors data sheets and lists their maximum performance

Estimated MIPS vs. Code/Data Size



Techical Specifications

RADIATION TOLERANCE

- > 300 Years without an uncorrected upset, SEU rate < 9 E-6 upsets/day
  - Entire board in a GEO Orbit (without 1553)
- TID: > 100 krad (Si) - Orbit dependent
- SEL (th): > 80 MeV-cm^2/mg - All parts except SDRAM
  ≈ 50 MeV-cm^2/mg - SDRAM

PROCESSORS

(3) FULLY TMR PROTECTED PROCESSORS

- PowerPC 750FX™ on Silicon on Insulator (SOI), 0.13um
- 2.32 Dhrystone MIPS/MHz
- > 1800 Dhrystone MIPS @ 800MHz
- 400 to 800MHz - Software Selectable Core Clock Rate
- 50MHz PowerPC Local Bus

PROCESSOR CACHE

L1 CACHE

- 32 KByte Instruction with Parity
- 32 KByte Data with Parity

L2 CACHE

- 512 KByte on-chip with ECC @ CPU Core Clock Rate

MEMORY

VOLATILE

- 256 MByte SDRAM - Reed-Solomon Protected - Double Device Correction

NON-VOLATILE

- 8 MByte EEPROM - ECC Protected
  - 7.0 MByte EEPROM available to user
  - 0.5 MByte Primary SuROM
  - 0.5 MByte Secondary SuROM (Autoswap on Primary Failure)

INTERFACES

cPCI BUS

- 6U
- 3.3V
- 32 bit, 33MHz
- Master/Target & Syscon/Peripheral

1553

- BC/RT/MT
- SEU Immune

SERIAL

- UART (Asynchronous), LVDS
- (2) USRTs (Synchronous), LVDS

PROGRAMMABLE I/O

- 32 Programmable General Purpose I/O (GPIO)

POWER

- 7 - 25 watts (typical) dependent on clock rate/MIPS requirements
- 5V for 1553 interface, 3.3V for rest of board

OPERATING SYSTEM

- VxWorks, Tornado

TEMPERATURE

- -40°C to +70°C (Rail)

WEIGHT

- 1.5 Kg (3.3 Lbs.) Max

ORDERING INFORMATION

SCS750AF - FLIGHT CONFIGURATION

- Rad-Tolerant, Class “S” or Equivalent Components
- Conduction Cooled

SCS750AE - ENGINEERING CONFIGURATION

- Rad-Tolerant, Class B/883 Components
- Conduction Cooled

SCS750AD - ENGINEERING DEVELOPMENT CONFIGURATION

- Commercial Components, ACTEL FPGAs
- Full Hardware & Software Compatibility w/ AE & AF Models
- Conduction Cooled

SCS750AP - PROTOTYPE CONFIGURATION

- Commercial Components, Xilinx FPGAs
- Similar functionality to AD, AE & AF Models
- Convection Cooled

All models are available with an optional 1553 interface

Board Support Package

- Detailed Specification
- User Manual
  - Interface Control Documents
  - Software User’s Manual (SUM)
- VxWorks® Runtime License
- Certificate of Conformance
- Startup ROM Source Code
- Functional Test Procedure
  - Test Plan
  - Test Log
- Functional Test Report
- Environmental Test Procedure (Flight Only)
  - Test Plan
  - Test Log
- Environmental Test Report (Flight Only)

For the most current information on Maxwell products, visit: www.maxwell.com

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FAX: +1 (858) 503 3301
EMAIL: info@maxwell.com

All specifications are subject to change.

Planetary Gearheads

92.9 lb-in

Motor and Gearhead combinations:
GP48.2 fits motor series GNM2636A & GNM2670A

Series GP48.2

			GP48.2
Housing material			metal
Backlash, at no-load			≤ 2.0°
Shaft load, max.:			
– radial	lbs		40.5
– axial	lbs		33.8

Series GP48.2 with Motor Series GNM 2670A

reduction ratio	weight without motor Kg	weight without motor oz	length with motor GNM 2670A mm	length with motor GNM 2670A in	output torque continuous operation M max. Nm	output torque continuous operation M max. lb-in	output torque intermittent operation M max. Nm	output torque intermittent operation M max. lb-in	direction of rotation (reversible)	efficiency %
5:1	0.37	13.1	198	7.80	1	8.85	3	26.6	=	90
6:1	0.37	13.1	198	7.80	1.3	11.5	3.5	31.0	=	90
7.66:1	0.37	13.1	198	7.80	1	8.85	3	26.6	=	90
21:1	0.56	19.8	214.5	8.44	3.2	28.3	12	106.2	=	85
25:1	0.56	19.8	214.5	8.44	4	35.4	14.5	128.3	=	85
30:1	0.56	19.8	214.5	8.44	4.8	42.5	14.5	128.3	=	85
36:1	0.56	19.8	214.5	8.44	5.5	48.7	16	141.6	=	85
46;1	0.56	19.8	214.5	8.44	5.6	49.6	16	141.6	=	85
59:1	0.56	19.8	214.5	8.44	6	53.1	16	141.6	=	85
94:1	0.74	26.1	231.5	9.11	7.5	66.4	18	159.3	=	80
125:1	0.74	26.1	231.5	9.11	8.5	75.2	20	177.0	=	80
150:1	0.74	26.1	231.5	9.11	9	79.7	20	177.0	=	80

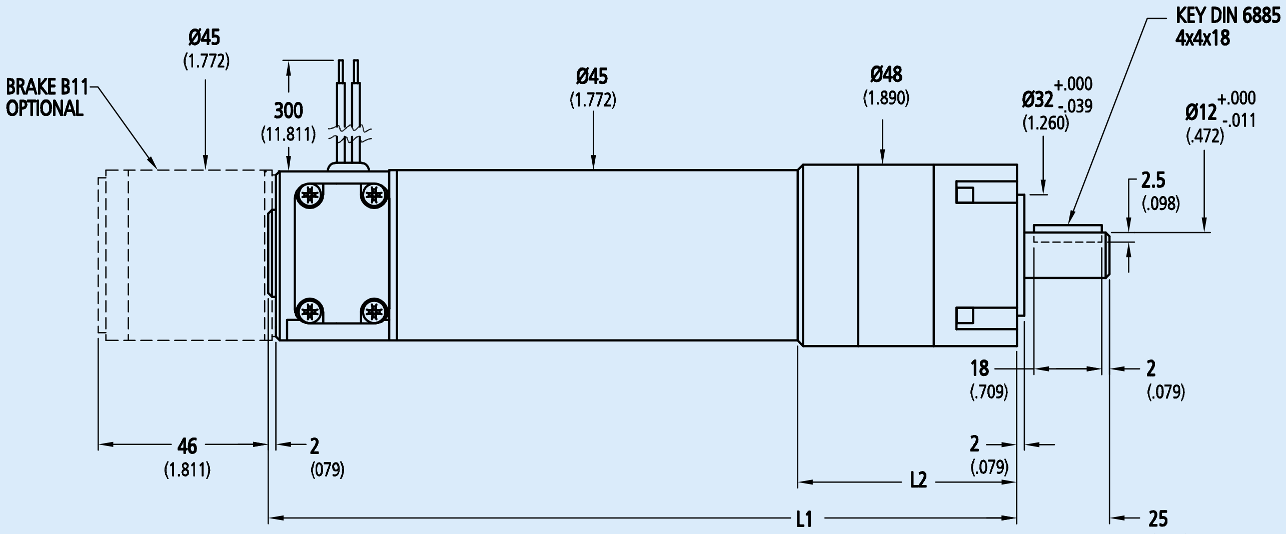
Series GP48.2 with Motor Series GNM 2636A

reduction ratio	weight without motor Kg	weight without motor oz	length with motor GNM 2636A mm	length with motor GNM 2636A in	output torque continuous operation M max. Nm	output torque continuous operation M max. lb-in	output torque intermittent operation M max. Nm	output torque intermittent operation M max. lb-in	direction of rotation (reversible)	efficiency %
180:1	0.74	26.1	187.5	7.38	10.5	92.9	20	177.0	=	80
216:1	0.74	26.1	187.5	7.38	10.5	92.9	20	177.0	=	80
293:1	0.74	26.1	187.5	7.38	10.5	92.9	20	177.0	=	80
352:1	0.74	26.1	187.5	7.38	10.5	92.9	20	177.0	=	80
450:1	0.74	26.1	187.5	7.38	9	79.7	18	159.3	=	80

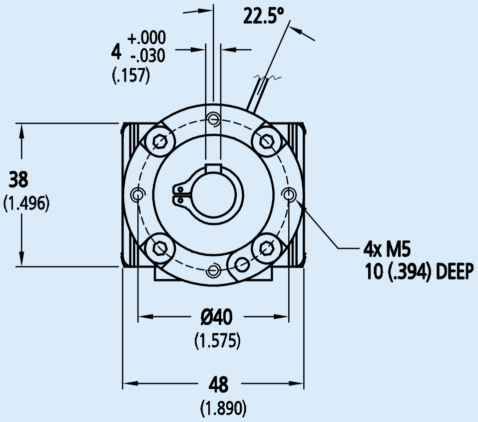
For notes on technical data refer to "Technical Information". Specifications subject to change without notice. MME0603

Series GP48.2

Dimensional outlines for GP48.2 with GNM2636 & GNM2670



GNM 26... + G48.2



Front View

MOTOR TYPE	RATIO	DIMENSION mm (in)	
		L1	L2
GNM 2670 A	5:1 - 7.66:1	198 (7.795)	58 (2.283)
GNM 2670 A	21:1 - 59:1	214.5 (8.445)	74.5 (2.933)
GNM 2670 A	94:1 - 150:1	231.5 (9.114)	91.5 (3.602)
GNM 2636 A	180:1 - 450:1	187.5 (7.382)	91.5 (3.602)

For notes on technical data refer to “Technical Information”. Specifications subject to change without notice. MME0603

EM6607

Ultra-low power microcontroller with 4 high drive outputs

Features

- Low Power typical 1.8µA active mode
  typical 0.5µA standby mode
  typical 0.1µA sleep mode
  @ 1.5V, 32kHz, 25 °C
- Low Voltage 1.2 to 3.6 V
- ROM 2k × 16 (Mask Programmed)
- RAM 96 × 4 (User Read/Write)
- 2 clocks per instruction cycle
- RISC architecture
- 5 software configurable 4-bit ports
- 1 High drive output port
- Up to 20 inputs (5 ports)
- Up to 16 outputs (4 ports)
- buzzer three tone
- Serial Write buffer – SWB
- Supply Voltage level detection (SVLD).
- Analogue and timer watchdog
- 8 bit timer / event counter
- Internal interrupt sources (timer, event counter, prescaler)
- External interrupt sources (portA + portC)

Description

The EM6607 is a single chip low power, mask programmed CMOS 4-bit microcontroller. It contains ROM, RAM, watchdog timer, oscillation detection circuit, combined timer / event counter, prescaler, voltage level detector and a number of clock functions. Its low voltage and low power operation make it the most suitable controller for battery, stand alone and mobile equipment. The EM6607 microcontroller is manufactured using EM's Advanced Low Power CMOS Process.
In 24 Pin package it is direct replacement for EM6603.

Typical Applications

- sensor interfaces
- domestic appliances
- clocks
- security systems
- bicycle computers
- automotive controls
- TV & audio remote controls
- measurement equipment
- R/F and IR. control
- motor driving

Figure 1. Architecture

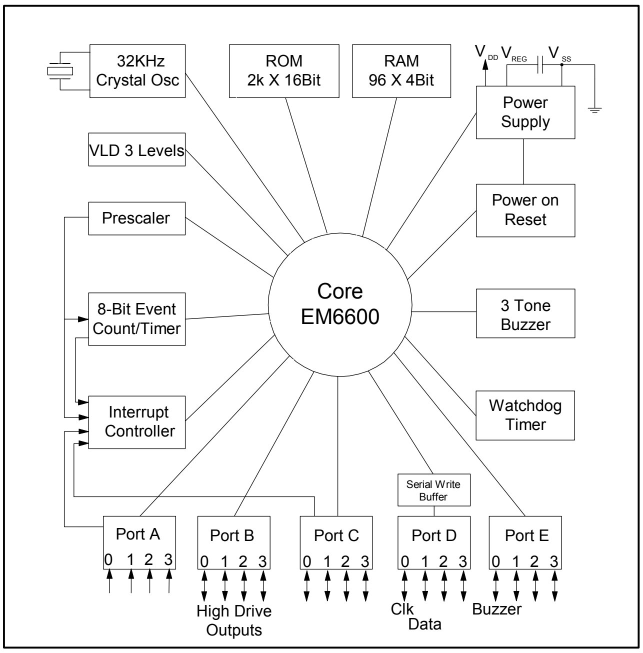
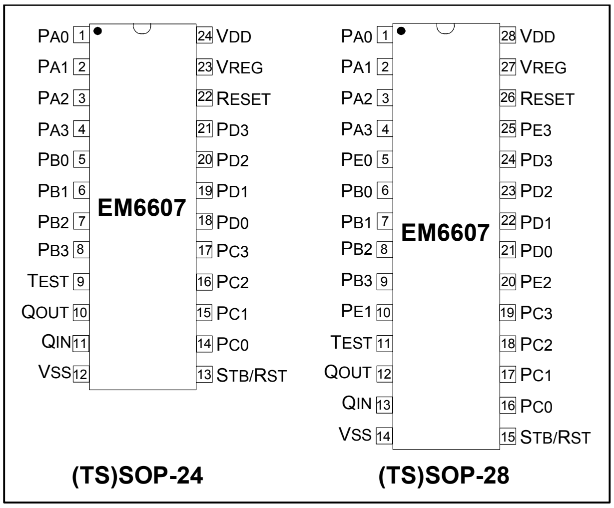


Figure 2. Pin Configuration



EM6607 at a glance

☐ Power Supply
- Low Voltage, low power architecture including internal voltage regulator
- 1.2V ... 3.3 V battery voltage
- 1.8µA in active mode
- 0.5µA in standby mode
- 0.1µA in sleep mode @ 1.5V, 32kHz, 25 °C
- 32 kHz Oscillator or external clock

☐ RAM
- 96 x 4 bit, direct addressable

☐ ROM
- 2048 x 16 bit metal mask programmable

☐ CPU
- 4 bit RISC architecture
- 2 clock cycles per instruction
- 72 basic instructions

☐ Main Operating Modes and Resets
- Active mode (CPU is running)
- Standby mode (CPU in Halt)
- Sleep mode (No clock, Reset State)
- Initial reset on Power-On (POR)
- External reset pin
- Watchdog timer (time-out) reset
- Oscillation detection watchdog reset
- Reset with input combination on PortA

☐ 4-Bit Input PortA
- Direct input read
- Debounced or direct input selectable (reg.)
- Interrupt request on input's rising or falling edge, selectable by register.
- Pull-down or Pull-up selectable by metal mask
- Software test variables for conditional jumps
- PA3 input for the event counter
- Reset with input combination on PortA (metal option)

☐ 4-Bit Input/Output PortB
- Separate input or output selection by register
- Pull-up, Pull-down or none, selectable by metal mask if used as Input
- Buzzer output on PB0 (24-pin) / PE0 (28-pin)

☐ 4-Bit Input/Output PortC
- Input or Output port as a whole port
- Debounced or direct input selectable (reg.)
- Interrupt request on input's rising or falling edge, selectable by register.
- Pull-up, pull-down or none, selectable by metal mask if used as input
- CMOS or N-channel open drain mode

☐ 4-Bit Input/Output PortD
- Input or Output port as a whole port
- Pull-up, Pull-down or none, selectable by metal mask if used as Input
- CMOS or N-channel open drain mode
- Serial Write Buffer clock and data output

☐ 4-Bit Input/Output PortE
- Separate input or output selection by register
- Pull-up, Pull-down or none, selectable by metal mask if used as Input

☐ Serial (output) Write Buffer
- max. 256 bits long clocked with 16/8/2/1kHz
- automatic send mode
- interactive send mode : interrupt request when buffer is empty

☐ Buzzer Output
- if used output on PB0 (24 pin) or PE0 (28 pin)
- 3 tone buzzer - 1kHz, 2kHz, 2.66kHz/4kHz (TBC)

☐ Prescaler
- 32kHz output possible on the STB/RST pin
- 15 stage system clock divider down to 1 Hz
- 3 interrupt requests: 1Hz/8Hz/32Hz
- Prescaler reset (from 8kHz to 1Hz)

☐ 8-bit Timer / Event Counter
- 8-bit auto-reload count-down timer
- 6 different clocks from prescaler
- or event counter from the PA3 input
- parallel load
- interrupt request when comes to 00 hex.

☐ Supply Voltage Level Detector
- 3 software selectable levels (1.3V, 2.0V, 2.3V or user defined between 1.3V and 3.0V)
- Busy flag during measure
- Active only on request during measurement to reduce power consumption

☐ Interrupt Controller
- 9 external interrupt sources: 4 from PortA, 4 from PortC.
- 3 internal interrupt sources, prescaler, timer and Serial Write Buffer
- Each interrupt request is individually selectable
- Interrupt request flag is cleared automatically on register read

Table of Contents

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1 Pin Description for EM6607

Pin Nb 24 pin	Pin Nb 28 pin	Pin Name	Function	Remarks
1	1	port A, 0	input 0 port A	interrupt request; tvar 1
2	2	port A, 1	input 1 port A	interrupt request; tvar 2
3	3	port A, 2	input 2 port A	interrupt request; tvar 3
4	4	port A, 3	input 3 port A	interrupt request; event counter input
-	5	port E, 0	input / output 0 port E	buzzer output in 28 pin package
5	6	port B, 0	input / output 0 port B	buzzer output in 24 pin package
6	7	port B, 1	input / output 1 port B	
7	8	port B, 2	input / output 2 port B	
8	9	port B, 3	input / output 3 port B	
-	10	port E, 1	input / output 1 port E	
9	11	test	test input terminal	for EM test purpose only (internal pull-down)
10	12	Q_{out}/osc 1	crystal terminal 1	
11	13	Q_{in}/osc 2	crystal terminal 2 (input)	Can accept trimming capacitor tw. V_{SS}
12	14	V_{SS}	negative power supply terminal	
13	15	STB/RST	strobe / reset status	µC reset state + port B, C, D write
14	16	port C, 0	input / output 0 port C	interrupt request
15	17	port C, 1	input / output 1 port C	interrupt request
16	18	port C, 2	input / output 2 port C	interrupt request
17	19	port C, 3	input / output 3 port C	interrupt request
-	20	port E, 2	input / output 2 port E	
18	21	port D, 0	input / output 0 port D	SWB Serial Clock Output
19	22	port D, 1	input / output 1 port D	SWB Serial Data Output
20	23	port D, 2	input / output 2 port D	
21	24	port D, 3	input / output 3 port D	
-	25	port E, 3	input / output 3 port E	
22	26	RESET	reset terminal	Active high (internal pull-down)
23	27	V_{REG}	internal voltage regulator	Needs typ. 100nF capacitor tw. V_{SS}
24	28	V_{DD}	positive power supply terminal	

Table 1. Pin Description

Figure 3. Typical Configuration: V_{DD} 1.4V up to 3.3V

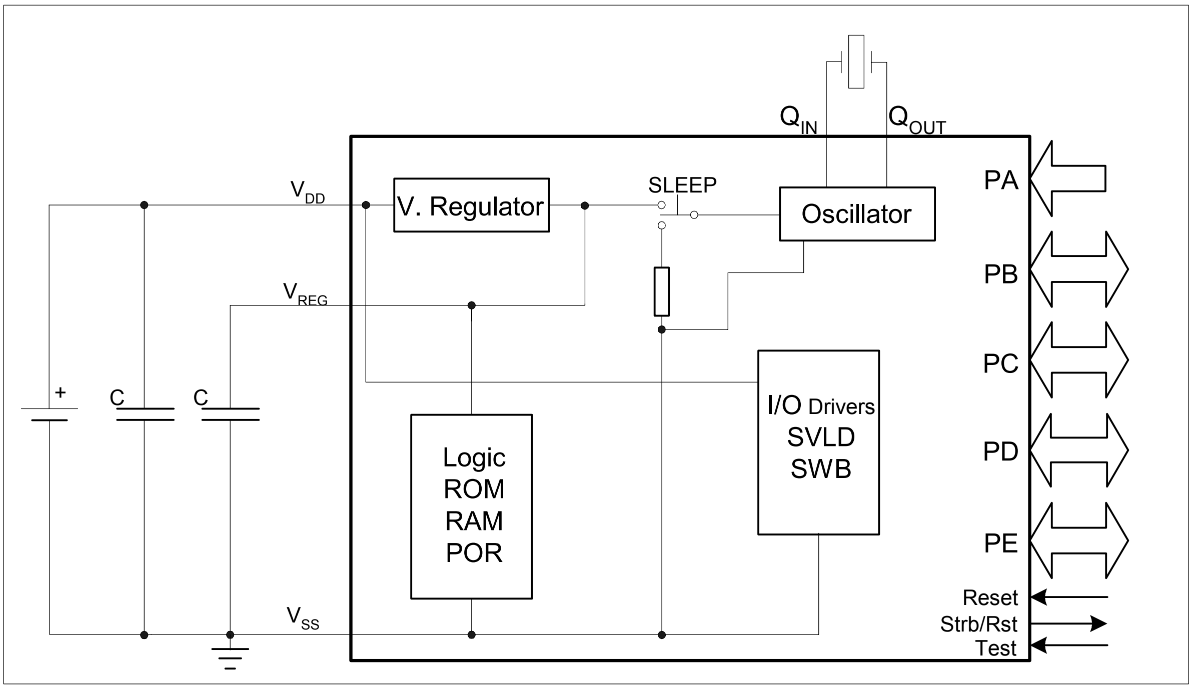
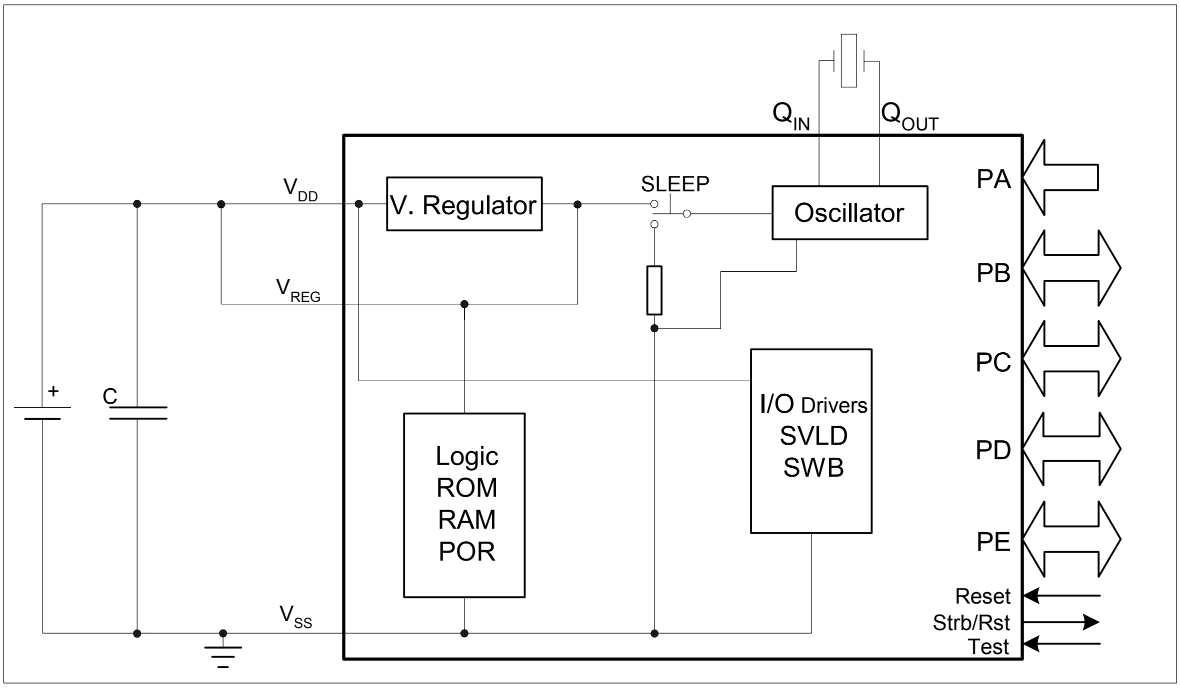


Figure 4. Typical Configuration: V_{DD} 1.2V up to 1.8V



2 Operating modes

The EM6607 has two low power dissipation modes: STANDBY and SLEEP. Figure 5 is a transition diagram for these modes.

2.1 Active Mode

The active mode is the actual CPU running mode. Instructions are read from the internal ROM and executed by the CPU. Leaving active mode via the halt instruction to go into standby mode, the **Sleep** bit write to go into Sleep mode or a reset from port A to go into reset mode.

2.2 STANDBY Mode

Executing a HALT instruction puts the EM6607 into STANDBY mode. The voltage regulator, oscillator, Watchdog timer, interrupts and timer/event counter are operating. However, the CPU stops since the clock related to instruction execution stops. Registers, RAM, and I/O pins retain their states prior to STANDBY mode. A RESET or an Interrupt request cancel STANDBY mode.

2.3 SLEEP MODE

Writing the SLEEP* bit in the IntRq* register puts the EM6607 in SLEEP mode. The oscillator stops and most functions of the EM6607 are inactive. To be able to write the SLEEP bit, the SLmask bit must be first set to 1 in register WD. In SLEEP mode only the voltage regulator and RESET input are active. The RAM data integrity is maintained. SLEEP mode may be cancelled only by a RESET at the terminal pin of the EM6607 or by the selected port A input reset combination. This combination is a metal option, see paragraph 15.1.2. The RESET port must be high for at least 10µsec.

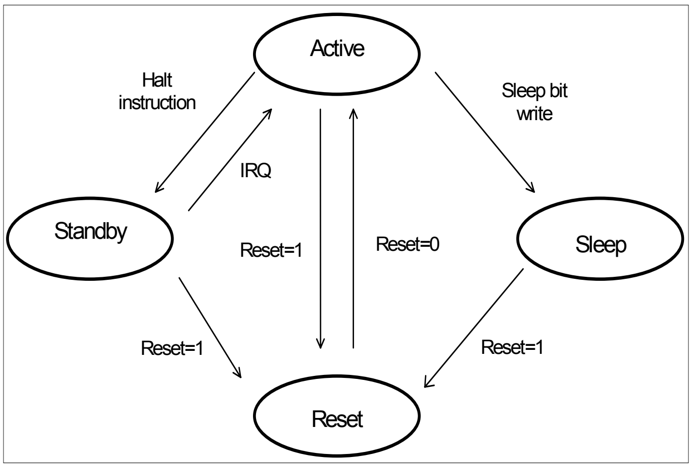


Figure 5. Mode Transition Diagram

Due to the cold start characteristics of the oscillator, waking up from SLEEP mode may take some time to guarantee that the oscillator has started correctly. During this time the circuit is in RESET state and the strobe output STB/RST is high. Waking up from SLEEP mode clears the **SLEEP** flag but not the **SLmask** bit. By reading **SLmask** it can therefore determine if the EM6607 was powered up (**SLmask** = 0), or woken from SLEEP mode (**SLmask** = 1).

Table 1. IntRq register

Bit	Name	Reset	R/W	Description
3	**INTPR**	0	R	Prescaler interrupt request
2	**INTTE**	0	R	Timer/counter interrupt request
1	**INTPC**	0	R	PortC Interrupt request
0	**INTPA**	0	R	PortA Interrupt request
2	**SLEEP**	0	W*	SLEEP mode flag

* Write bit 2 only if **SLmask**=1

Table 2. **Watchdog register - <u>WD</u>**

Bit	Name	Reset	R/W	Description
3	**WDRST**	-	R/W	Watchdog timer reset
2	**Slmask**	-	R/W	SLEEP mask bit
1	**WD1**	0	R	WD Timer data 1/4 Hz
0	**WD0**	0	R	WD Timer data 1/2 Hz

Table 3 shows the status of different EM6607 blocks in these three main operating modes.

Table 3. **Internal state in Active, Stand-by and Sleep mode**

Peripheral /// EM6607 mode	**ACTIVE** mode	**STAND-BY** mode	**SLEEP** mode
POR (static)	On	On	On
Voltage regulator	On	On	On (Low-Power)
Quartz 32768 Hz oscillator	On	On	Off
Clocks (Prescaler & RC divider)	On	On	Off
CPU	Running	In HALT – Stopped	Stopped
Peripheral register	“On”	“On” retain value	retain value
RAM	“On”	retain value	retain value
Timer/Counter	“On”	“On” if activated before	stopped
Supply Voltage Level Det.=SVLD	can be activated	can not be activated	Off
PortA /C, Reset pad debounced	Yes	Yes	No
Interrupts / events	Yes - possible	Yes - possible	No – not possible
Watch-Dog timer	On / Off (soft selectable)	On / Off (soft selectable)	No
Analogue Watchdog (osc.detect)	On/Off (soft select.)	“On” if activated before	Off

3 Power Supply

The EM6607 is supplied by a single external power supply between V_{DD} and V_{SS}, the circuit reference being at V_{SS} (ground). A built-in voltage regulator generates V_{REG} providing regulated voltage for the oscillator and internal logic. Output drivers are supplied directly from the external supply V_{DD}. A typical connection configuration is shown in figure 4.

For V_{DD} less then 1.4V it is recommended that V_{DD} is connected directly to V_{REG} connected

For V_{DD} >1.8V then the configuration shown in Figure 4 should be used.

---

*registers are marked in bold and underlined like **<u>IntRq</u>**

*Bits/Flags in registers are marked in bold only like **SLEEP**

IK-52V / IK-53V

features

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- Weighs 46g (1.59 oz.)
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- C-Mount Lens Mount
- 659(H) x 494(V) resolution
- 1 lux@F1.4 sensitivity
- 60 dB S/N Ratio

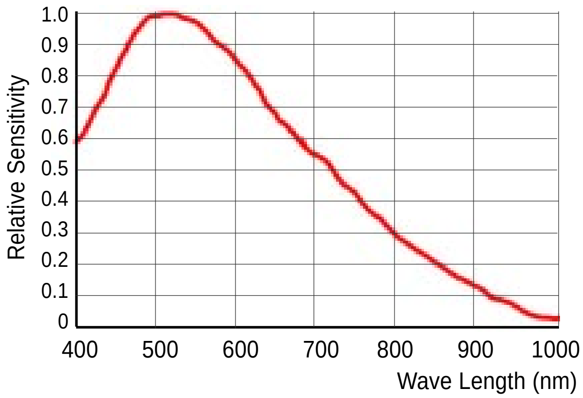
IK-52V / IK-53V

specifications

Power Supply	12 VDC (+10.5VDC - +15VDC)
Power Consumption	120mA (DC + 12V)
Image Sensor	IK-52V: Progressive Scan 1/2 inch CCD IK-53V: Progressive Scan 1/3 inch CCD
Effective Pixels	659 (H) x 494 (V)
Horizontal Resolution	500 TV Lines
Pixel Size	IK-52V: 9.9 µm (H) x 9.9 µm (V) IK-53V: 7.4 µm (H) x 7.4 µm (V)
Scan Frequency	Horizontal: 31.469 kHz, Vertical: 59.94 Hz
Synchronizing System	Internal/External (HD/VD) (HD/VD inut/output area selected by rear panel switch
Sync Modes	All pixels scanning, Partial scanning, 1-pulse trigger sync-reset, Pulse width trigger sync-reset, 1-pulse trigger sync-nonreset, Pulse width trigger sync-nonreset, Reset restart
Standard Subject Illumination	400 lux F5.6 (Gain off)
Minimum Subject Illumination	1 lux, F1.4, manual gain set to maximum
S/N Ratio	60dB
Video Output	1.0V (p.p)
Output Impedance	75 Ohm, unbalanced
IR Filter	None
Lens Mount	C-Mount
Gain Switch	Off (0dB) / On (0 to 18dB)
Electronic Shutter Settings	Off (1/60),1/100, 1/250, 1/500, 1/1000, 1/2000, 1/4000, 1/10000, 1/50000, 1/100000
Rear Panel Settings	Mode/Sensitivity/Sync in-out
Weight	45g (1.59 oz.)
Dimensions	29mm (W) x 29mm (H) x 29mm (D)
Connector	Hirose Part Number: HR10A-10R-12PB
Environmental	Operating Temperature: 0° to +40° Centigrade Storage Temperature: -20° to +60° Centigrade Humidity: less than 90% relative Vibration: 70m/S^2 (10 to 200 Hz) Shock; 700m/S^2

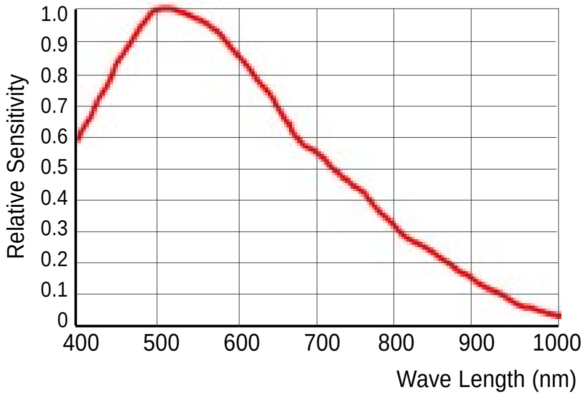
Spectra Sensitivity Characteristics

IK-53V 1/3-Inch CCD Camera



Spectra Sensitivity Characteristics

IK-52V 1/2-Inch CCD Camera



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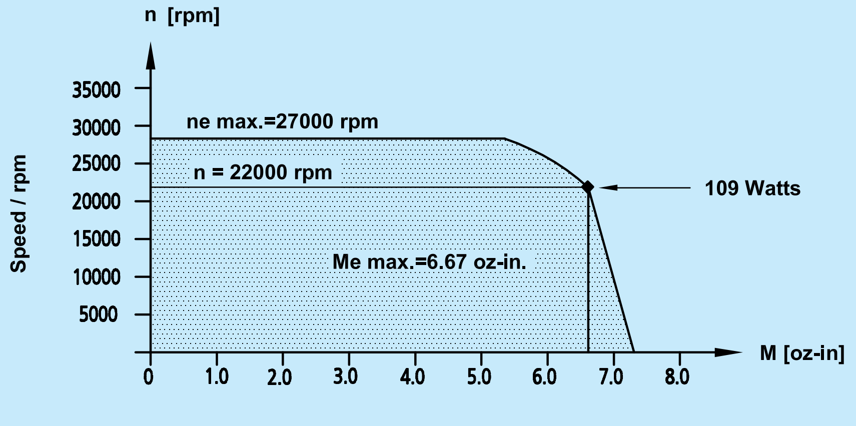
Drive Electronics: BLD 5608, BLD 5606, MCBL 2805,
MCBL 3603, MCBL 5004

Series 3564 ... B

		3564 K	012 B	024 B	036 B	048 B	
1	Nominal voltage	U_N	12	24	36	48	Volt
2	Terminal resistance, phase-phase	R	0.6	1.2	2.8	4.4	Ω
3	Output power [1]	$P_{2\,max.}$	109	101	101	101	W
4	Efficiency	$\eta_{max.}$	81	81	81	82	%
5	No-load speed	n_o	7,850	11,300	11,550	12,200	rpm
6	No-load current (with shaft ø 4.0 mm)	I_o	0.206	0.189	0.131	0.109	A
7	Stall torque	M_H	41.2	52.5	53.7	56.8	oz-in
8	Friction torque, static	C_o	0.156	0.156	0.156	0.156	oz-in
9	Friction torque, dynamic	C_v	$3.4 \cdot 10^{-5}$	$3.4 \cdot 10^{-5}$	$3.4 \cdot 10^{-5}$	$3.4 \cdot 10^{-5}$	oz-in/rpm
10	Speed constant	k_n	658	475	324	258	rpm/V
11	Back-EMF constant	k_E	1.521	2.107	3.089	3.877	mV/rpm
12	Torque constant	k_M	2.06	2.85	4.18	5.24	oz-in/A
13	Current constant	k_I	0.49	0.35	0.24	0.19	A/oz-in
14	Slope of n-M curve	$\Delta n/\Delta M$	191	219	219	219	rpm/oz-in
15	Terminal inductance, phase-phase	L	96	194	427	678	µH
16	Mechanical time constant	τ_m	10	11	11	11	ms
17	Rotor inertia	J	$4.81 \cdot 10^{-4}$	$4.81 \cdot 10^{-4}$	$4.81 \cdot 10^{-4}$	$4.81 \cdot 10^{-4}$	oz-in-sec^2
18	Angular acceleration	$\alpha_{max.}$	86	109	111	118	$\cdot 10^3$rad/s^2
19	Thermal resistance	$R_{th\,1} / R_{th\,2}$	2.5 / 6.3				°C/W
20	Thermal time constant	τ_{w1} / τ_{w2}	23 / 1,175				s
21	Operating temperature range		–30 to +125 (– 22 to +257)				°C (°F)
22	Shaft bearings		ball bearings, preloaded				
23	Shaft load max.:						
	– radial at 3,000/20,000 rpm (7.4 mm (0.291 in) from mounting flange)		389 / 263				oz
	– axial at 3,000/20,000 rpm (push-on only)		180 / 108				oz
	– axial at standstill (push-on only)		472				oz
24	Shaft play:						
	– radial	≤	0.015 (0.0006)				mm (in)
	– axial	=	0				mm (in)
25	Housing material		aluminum, black anodized				
26	Weight		10.9				oz
27	Direction of rotation		electronically reversible				
	Recommended values						
28	Speed up to [2]	$n_{e\,max.}$	27,000	27,000	27,000	27,000	rpm
29	Torque up to [1] [2]	$M_{e\,max.}$	6.67	6.23	6.22	6.23	oz-in
30	Current up to [1] [2]	$I_{e\,max.}$	3.68	2.50	1.71	1.36	A

[1] at 22,000 rpm
[2] thermal resistance $R_{th\,2}$ by 55% reduced



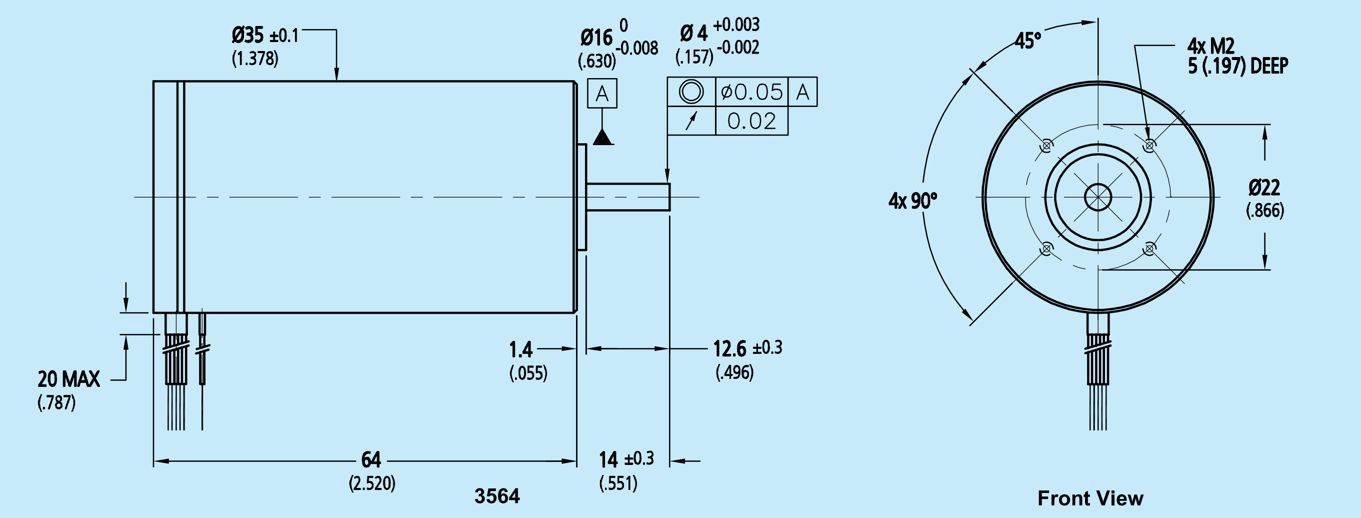
Recommended area for continuous operation

Option:
K1000: Motors in autoclavable version.

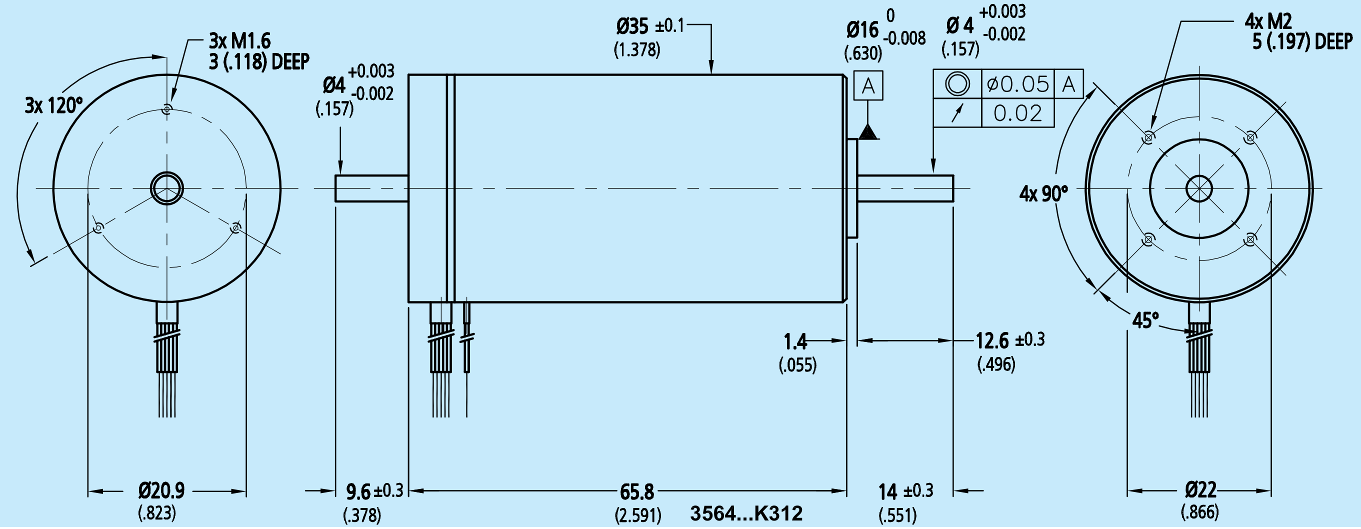
K1155: Motors for operation with Motion Controller MCBL 2085.

Series 3564 ... B

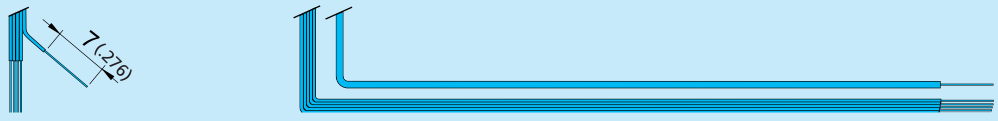
3564 K ... B



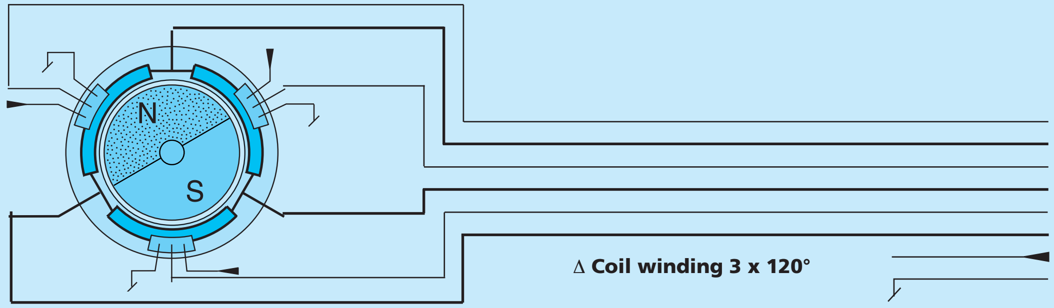
3564 K ... B K312 with rear shaft



Cable and connection information



Cable
Single wires, material PTFE
Length 300 mm ± 15 mm
(11.8 ± 0.6 in)
3 conductors, 20 AWG
5 conductors, 26 AWG



Δ Coil winding 3 x 120°

Connection

	Function	Color
A	Hall sensor	green
A	Phase	brown
B	Hall sensor	blue
B	Phase	orange
C	Hall sensor	grey
C	Phase	yellow
+5V	Logical supply	red
GND	Logical	black

Brushless DC-Motors

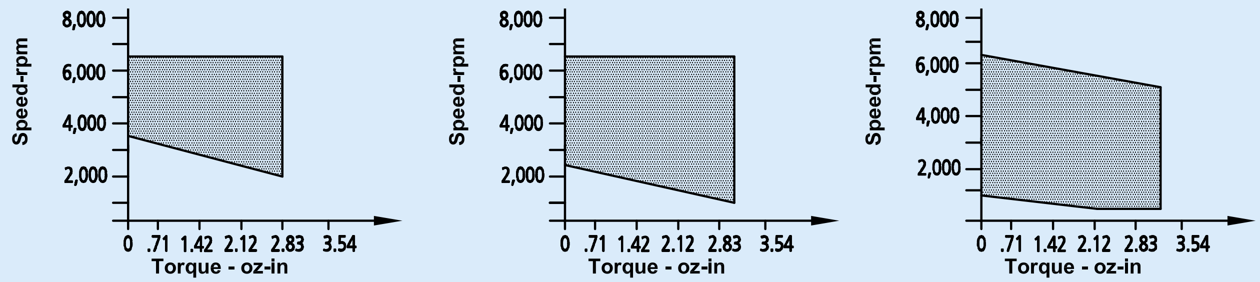
15.5 Watt

with integrated Drive Electronics

Series 3153 ... BRE

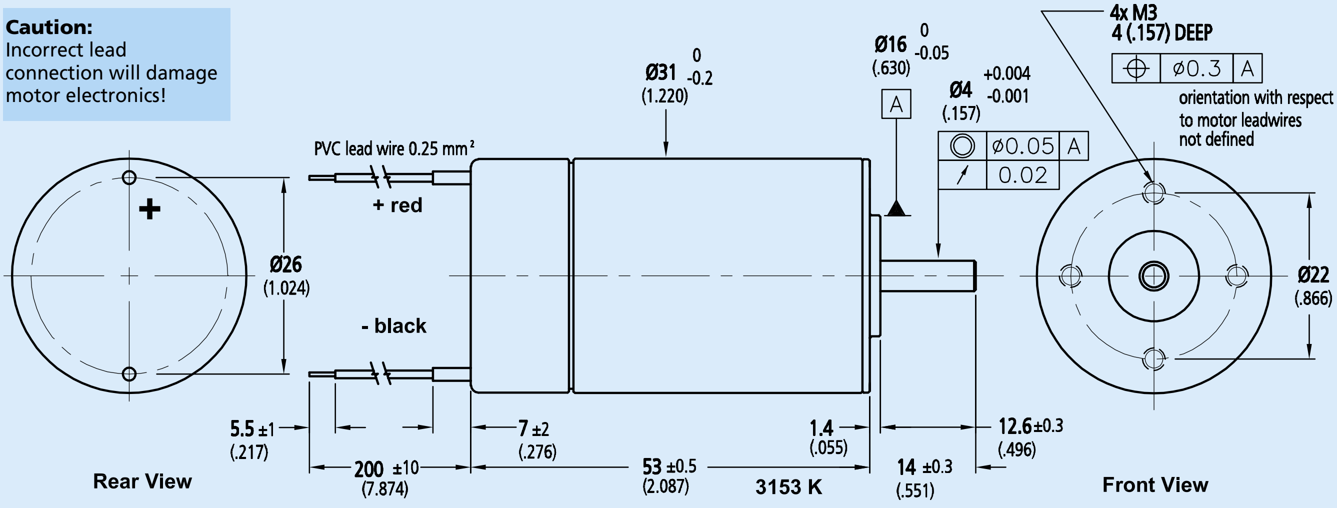
	3153 K		009 BRE	012 BRE	024 BRE	
Nominal voltage [1]	U_N		9	12	24	Volt
No-load speed	n_o		5,100	5,100	5,200	rpm
No-load current (with shaft ø 0.12 in)	I_o		0.129	0.100	0.059	A
Starting torque	M_A		4.67	4.67	4.67	oz-in
Torque constant	k_M		2.34	3.12	6.10	oz-in/A
Slope of n-M curve	$\Delta n/\Delta M$		395	340	314	rpm/oz-in
Rotor inertia	J		$17 \cdot 10^{-4}$	$17 \cdot 10^{-4}$	$17 \cdot 10^{-4}$	oz-in-sec²
Operating temperature range		0 to +70 (32 to +158)				°C (°F)
Shaft bearings		ball bearings, preloaded				
Shaft load max.:						
– shaft diameter		4 (0.157)				mm (in)
– radial at 3,000 rpm (3 mm (0.118 in) from mounting face)		108				oz
– axial at 3,000 rpm		18				oz
– axial at standstill		180				oz
Shaft play:						
– radial	≤	0.015 (0.0006)				mm (in)
– axial	=	0				mm (in)
Housing material		mounting face in aluminum, housing in plastic				
Weight		5.75				oz
Direction of rotation		not reversible - clockwise rotation, viewed from the front face				
[1] The supply voltage range for the integrated electronics is:		min. 5 ... max. 30				V DC

Recommended values						
Speed range	n_e		500 – 6,500			rpm
Torque up to	$M_{e\ max.}$		2.8	3.0	3.3	oz-in
Current up to (thermal limits)	$I_{e\ max.}$		1.30	1.00	0.60	A



Recommended Speed-Torque Range

Caution:
Incorrect lead connection will damage motor electronics!



Planetary Gearheads

40 lb-in

For combination with:
DC-Micromotors: 2338, 2342, 2642, 2657, 3557
Brushless DC-Servomotors: 2444, 3056, 3564
DC-Motor-Tacho Combinations: 2342

Series 30/1

	30/1
Housing material	metal
Geartrain material	steel [1]
Recommended max. input speed for:	
– continuous operation	4,000
Backlash, at no-load	≤ 1°
Bearings on output shaft	ball bearings
Shaft load, max.:	
– radial (15 mm (0.591 in) from mounting face)	≤ 34 lb
– axial	≤ 34 lb
Shaft press fit force, max.	≤ 45 lb
Shaft play (on bearing output):	
– radial	≤ 0.0006 in
– axial	= 0.006 in
Operating temperature range	– 30 to +100 °C (–22 to +212 °F)

Specifications

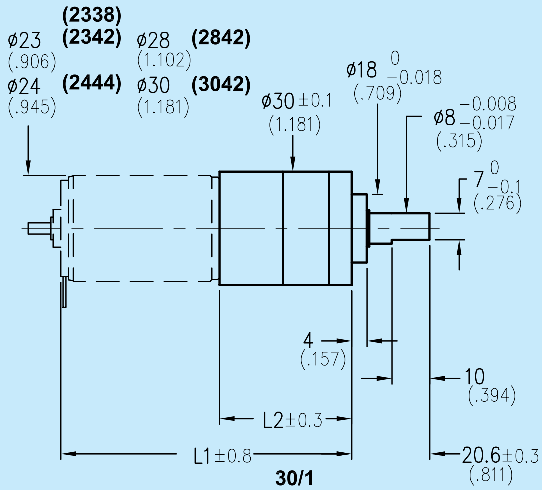
reduction ratio (nominal)	weight without motor	length without motor L2		length with motor 2444 S L1		2342 S 2642 W L1		3056 K L1		2657 W 3557 W L1		3564 K L1		output torque continuous operation M max.		intermittent operation M max.		direction of rotation (reversible)	efficiency
	oz	mm	(in)	mm	(in)	mm	(in)	mm	(in)	mm	(in)	mm	(in)	lb-in		lb-in			%
3.71 : 1	3.8	27.1	(1.07)	71.1	(2.80)	69.1	(2.72)	84.5	(3.33)	85.5	(3.37)	92.5	(3.64)	13		27		=	88
14 : 1	4.9	35.1	(1.38)	79.1	(3.11)	77.1	(3.04)	92.5	(3.64)	93.5	(3.68)	100.5	(3.96)	3	(40)	4	(53)	=	80
43 : 1	6.0	43.1	(1.70)	87.1	(3.43)	85.1	(3.35)	100.6	(3.96)	101.6	(4.00)	108.6	(4.28)	11	(40)	14	(53)	=	70
66 : 1	6.0	43.1	(1.70)	87.1	(3.43)	85.1	(3.35)	100.6	(3.96)	101.6	(4.00)	108.6	(4.28)	16	(40)	21	(53)	=	70
134 : 1	7.2	51.2	(2.02)	95.2	(3.75)	93.2	(3.67)	108.6	(4.28)	109.6	(4.31)	116.6	(4.59)	31	(40)	40	(53)	=	60
159 : 1	7.2	51.2	(2.02)	95.2	(3.75)	93.2	(3.67)	108.6	(4.28)	109.6	(4.31)	116.6	(4.59)	40	(40)	53	(53)	=	60
246 : 1	7.2	51.2	(2.02)	95.2	(3.75)	93.2	(3.67)	108.6	(4.28)	109.6	(4.31)	116.6	(4.59)	40	(40)	53	(53)	=	60
415 : 1	8.3	59.2	(2.33)	103.2	(4.06)	101.2	(3.98)	116.6	(4.59)	117.6	(4.63)	124.6	(4.91)	40	(40)	53	(53)	=	55
592 : 1	8.3	59.2	(2.33)	103.2	(4.06)	101.2	(3.98)	116.6	(4.59)	117.6	(4.63)	124.6	(4.91)	40	(40)	53	(53)	=	55
989 : 1	8.3	59.2	(2.33)	103.2	(4.06)	101.2	(3.98)	116.6	(4.59)	117.6	(4.63)	124.6	(4.91)	40	(40)	53	(53)	=	55
1,526 : 1	8.3	59.2	(2.33)	103.2	(4.06)	101.2	(3.98)	116.6	(4.59)	117.6	(4.63)	124.6	(4.91)	40	(40)	53	(53)	=	55

---

[1] Gearheads with ratio ≥ 14:1 have plastic gears in the input stage. For extended life performance, the gearheads are available with all steel gears and heavy duty lubricant as type 30/1 S.

- (*) add 1.4 mm (0.055 in) to L2 column to account for larger mounting flange.
- The values for the torque rating indicated in parenthesis, are for gearheads, type 30/1 S with all steel gears.

Note: Reduction ratios have been rounded off.
Exact values are available upon request.



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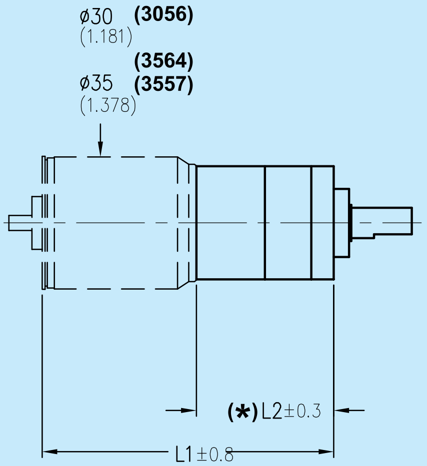

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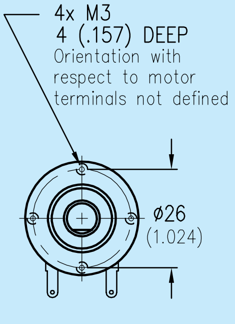
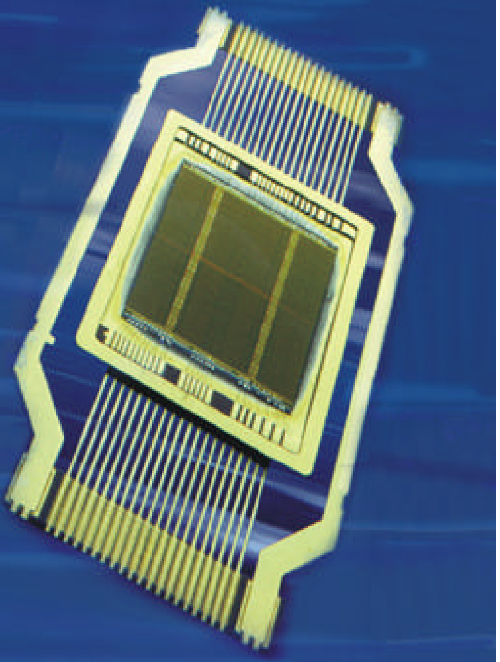


Front View

BAE SYSTEMS

Radiation Hardened Memory



Providing a family of high-quality, high-performance radiation hardened memory products to meet our customers' needs

BAE SYSTEMS in Manassas, Virginia, with more than 17 years of experience supporting our space customers, offers a wide range of radiation hardened static random access memory (SRAM) devices produced on our line qualified by the Defense Department's rigorous Qualified Manufacturer Listing (QML) program.

Our radiation hardened SRAMs range from 64K to 4M in density. All are built in epitaxial bulk complementary metal oxide semiconductor (CMOS) processes in our QML-qualified 1.0 micrometer, 0.8 micrometer and 0.5 micrometer technologies. We also offer parts that operate with 2.5, 3.3, and 5.0 Volt power supplies.

To meet special customer needs, our radiation hardened multi-chip packaging technology is also available for high-performance, high-reliability space applications. Packaging is available for the 1M SRAMs in 40-lead flat packs (256K-pin compatible), and 32-lead flat packs.

BAE SYSTEMS' rad-hard SRAMs are being used in a variety of important programs for NASA, defense and commercial satellite applications.

Our Products

The 1M SRAMs offer 25, 30 and 40ns access times in our proven epitaxial bulk (0. 5 micrometer) process. With total dose hardness greater than 1x10 rad(Si), dose rate upset of greater than 1x10rad(Si)/ sec, latchup immunity, and a tested Single Event Upset (SEU) rate of less than 1x10 errors/ bit-day. This product offers the highest density radiation hardened SRAM without compromising cycle performance.

Our 2M SRAM offering utilizes two 1M die in a dual package to achieve the best size, volume and power in the industry.

Currently under development, the 4M SRAM is fabricated in our 0.5 micrometer CMOS technology. Feature enhancements provide an L of 0.35 micrometers. The configuration is 512K x 8 and is offered in 40-lead flat packs compatible with the 1M SRAM.

Packaging is available for the 1M SRAMs in 40-lead flat packs (256K-pin compatible), and 32-lead flat packs.

Radiation Hardened SRAM Offerings

	64K	*256K* *30ns, 40ns, 60ns*	*1M* *25ns, 30ns, 40ns*	*2M* *30ns, 40ns*	*4M*
Organization	8K x 8	32K x 8	1M x 1, 256K x 4, 128K x 8	256K x 8 128K x 16	512K x 8
Operation	Asynchronous	Asynchronous	Asynchronous	Asynchronous	Asynchronous
Power Supply	5.0 V ± 10%	5.0 V ± 10%, 3.3 V ±5%	5.0 V ± 10%, 3.3 V ± 5%, 2.5 V ±10%	5.0 V ± 10%, 3.3 V ± 5%, 2.5 V ±10%	3.3 V 2.5V
I/O	CMOS or TTL	CMOS or TTL	CMOS or TTL	CMOS or TTL	CMOS or TTL
Technology	Bulk CMOS on EPI	Bulk CMOS on EPI	Bulk CMOS on EPI	Bulk CMOS on EPI	Bulk CMOS on EPI
Minimum Feature Size	1.0 µm	0.8 µm	0.5 µm	0.5 µm	0.35 µm
Cell Design	6T + 2R	6T + 2R	6T + 2R	6T + 2R	6T + 2R
Redundancy	4 W/L (+4 BL for x1)	8 W/L, 8 BL	16 W/L, 16 BL	16 W/L, 16 BL	32 W/L, 32 BL
Read/Write Performance (Post Rad)	<55 nsec (33 nsec typical)	<30 nsec (19 nsec typical)	<25 nsec (19 nsec typical)	<30 nsec (19 nsec typical)	<20 nsec
Power (Post Rad) *• Standby* *• Active*	<10 mW <50 mW/Hz	<10 mW <20 mW/Hz	<10 mW <20 mW/MHz	<20 mW <30 mW/MHz	<10 mW <5 mW/MHz
Package	36 FP, 32 LCC	36 FP, 40 FP, 28 DIP	40 FP, 32 FP	40 FP Dual Chip	40 FP

Our radiation hardened SRAMS range from 64K to 4M in density

The 256K SRAM, fabricated in our QML-qualified, 0. 8 micrometer process, offers 30 and 40ns access times, with total dose, dose rate upset and SEU characteristics identical to those of the 1M SRAM.

Packaging options for the 256K products include 36-lead flat pack, 40-lead flat pack, 28-pin Dual-Inline Package (DIP).

The Importance of QML-Qualification

BAE SYSTEMS in Manassas, was the first producer of space-qualified, rad-hard semiconductors to obtain QML-qualified status. This achievement, attained after an extensive validation audit by a team of government and industry experts, assures customers that quality management procedures, processes and controls are in place from design, through wafer fabrication and module packaging, to final customer delivery. BAE SYSTEMS is the only supplier to obtain 1.0 micrometer, 0.8 micrometer, 0.5 micrometer CMOS and multi-chip packaging QML-qualification

QML-qualification means that quality is built into the production process rather than verified at the end of the line by expensive and destructive testing of individual products. QML also means continuous process improvement, focusing on enhanced quality and reliability, along with shortened product introduction and cycle time.

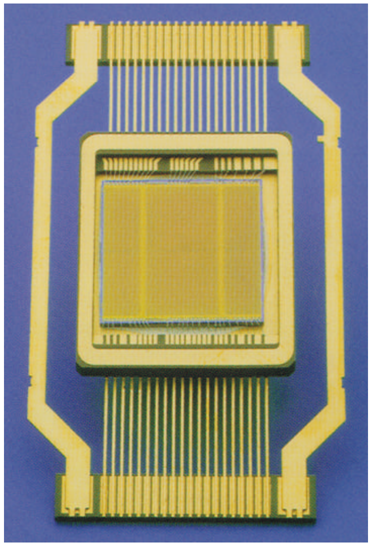
Manufacturing Process

Wafer Fabrication

Our plant provides a clean room facility of more than 25, 000 square feet, including the latest, advanced lithographic equipment. Using Statistical Process Control (SPC), our wafer fabrication process assures quality and reliability in real time, rather than after screening and qualification at the end of the manufacturing process.

Rad-Hard Specifications SRAMS	
Total Dose -rad(Si)	>1 x 10^6
SEU -errors/bit-day	<1 x 10^{11}
Latchup	Immune
Dose Rate Upset -rad(Si)/sec	>1 x 10^9
Survivability -rad(Si)/sec	>1 x 10^{12}
Neutron Fluence -n/cm^2	>1 x 10^{14}

Rad-Hard 1M Static RAM



Assembly

BAE SYSTEMS offers QML-qualified high-pin-count flip-chip, wire bond assembly and high I/ O, QML-qualified multi-chip packaging, supported by inline assembly monitors and SPC. Our package development methodology addresses the electrical and physical parameters of each package used in production.

Quality Assurance

Our product assurance system encompasses all employees – operators, process engineers and assurance personnel. Using inline electrical data as well as physical data, the BAE SYSTEMS wafer acceptance methodology assures product quality before assembly begins.

Every lot is continuously monitored for reliability at the wafer and assembly level, using test structures as well as product testing. Test structures are placed on all wafers to allow correlation and checks within wafers, wafer-to-wafer and lot-to-lot. Fully-screened V-level and Q-level procedures are available to meet customers' needs. Lower-cost engineering devices also are available for system breadboards and engineering models.

Every lot is continuously monitored

BAE SYSTEMS

Cleared for Public Domain Release
DoD/98-S-3120
7/98

BAE SYSTEMS
An ISO 9001, AS9000, ISO 14001,
and SEI CMM Level 4 Company
9300 Wellington Road, Manassas, VA 20110-4122
866-530-8104
http://www.baesystems-iews.com/space/

0980_Rad-Hard_SRAMs.ppt

The property data has been taken from proprietary materials in the MatWeb database. Each property value reported is the average of appropriate MatWeb entries and the comments report the maximum, minimum, and number of data points used to calculate the value. The values are not necessarily typical of any specific grade, especially less common values and those that can be most affected by additives or processing methods.

Physical Properties	**Metric**	**English**	**Comments**
Density	1.26 - 1.8 g/cc	0.0455 - 0.065 lb/in³	Average = 1.57 g/cc; Grade Count = 11
Mechanical Properties			
Hardness, Barcol	60 - 65	60 - 65	Average = 63.3; Grade Count = 3
Tensile Strength, Ultimate	64.19 - 2100 MPa	9310 - 305000 psi	Average = 810 MPa; Grade Count = 11
Tensile Modulus	13 - 520 GPa	1890 - 75400 ksi	Average = 190 GPa; Grade Count = 10
Flexural Modulus	6.41 - 38 GPa	930 - 5510 ksi	Average = 17.1 GPa; Grade Count = 5
Flexural Yield Strength	110 - 380 MPa	16000 - 55100 psi	Average = 200 MPa; Grade Count = 5
Compressive Yield Strength	110 - 1720 MPa	16000 - 249000 psi	Average = 530 MPa; Grade Count=11
Compressive Modulus	11 - 15 GPa	1600 - 2180 ksi	Average = 12.3 GPa; Grade Count=3
Shear Strength	30 - 120 MPa	4350 - 17400 psi	Average = 64.3 MPa; Grade Count = 7
Thermal Properties			
CTE, linear 20°C	9 - 14 µm/m-°C	5 - 7.78 µin/in-°F	Average = 12 µm/m-°C; Grade Count=4
Heat Capacity	1 - 1.2 J/g-°C	0.239 - 0.287 BTU/lb-°F	Average = 1.1 J/g-K; Grade Count = 3
Thermal Conductivity	6 - 400 W/m-K	41.6 - 2780 BTU-in/hr-ft²-°F	Average = 110 W/m-K; Grade Count = 9

http://matweb.com/search/SpecificMaterial.asp?bassnum=O1780

Subcategory: 7000 Series Aluminum Alloy; Aluminum Alloy; Metal; Nonferrous Metal

Close Analogs:

Composition Notes: Composition for AA 7075 (not Alclad 7075 specifically).
Aluminum content reported is calculated as remainder.
Composition information provided by the Aluminum Association and is not for design.

Key Words: Alclad 7075-O; Alclad 7075-O

Component	Wt. %	Component	Wt. %	Component	Wt. %
Al	87.1 - 91.4	Mg	2.1 - 2.9	Si	Max 0.4
Cr	0.18 - 0.28	Mn	Max 0.3	Ti	Max 0.2
Cu	1.2 - 2	Other, each	Max 0.05	Zn	5.1 - 6.1
Fe	Max 0.5	Other, total	Max 0.15		

Material Notes:
Data points with the AA note have been provided by the Aluminum Association, Inc. and are NOT FOR DESIGN.

Click here to view available vendors for this material.

Mechanical Properties	Metric	English	Comments
Ultimate Tensile Strength	221 MPa	32000 psi	AA; Typical
Tensile Yield Strength	96.5 MPa	14000 psi	AA; Typical
Elongation at Break	17 %	17 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Modulus of Elasticity	71.7 GPa	10400 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Shear Strength	152 MPa	22000 psi	AA; Typical

Processing Properties			
Annealing Temperature	413 °C	775 °F	
Solution Temperature	466 - 482 °C	870 - 900 °F	

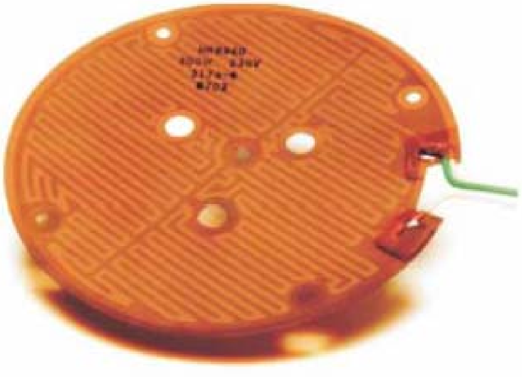
http://www.gtsculpture.com/designwiki/HomePage

Kapton™ Heaters

200°C

Kapton is a thin, semitransparent material with excellent dielectric strength. Kapton heaters are ideal for applications with space and weight limitations, or where the heater will be exposed to vacuum, oil, or chemicals.

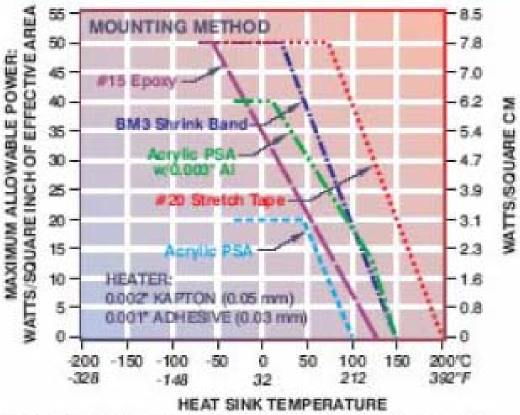
- FEP internal adhesive for use to 200°C
- UL component recognition available
- Suitable for vacuum environments (NASA-RP-1061)
- NASA approved materials for space applications (S-311-P-079)
- Resistant to most chemicals: acids, solvents, bases (except NaOH)
- Radiation resistant to 10^6 rads if built with polyimide-insulated leads (custom option)
- Can be made in very small sizes
- Fluid immersible models available (not standard)



Typical applications

- Medical diagnostic instruments: Heat sample trays, cuvettes, reagent bottles, etc.
- Warm satellite components
- Protect aircraft electronic and mechanical devices against cold at high altitudes
- Stabilize optoelectronic components
- Test or simulate integrated circuits
- Enable cold weather operation of outdoor electronics such as card readers or LCD's
- Maintain constant temperature in analytic test equipment

Maximum watt density, Kapton™ heaters



Example: At 50°C, the maximum power for a heater mounted with acrylic PSA is 18 W/in².

Specifications for catalog models

Temperature range: -200 to 200°C (-328 to 392°F). Upper limit with 0.003" (0.08 mm) foil backing is 150°C (302°F).

Material: Kapton/FEP, 0.002"/0.001" (0.05/0.03 mm).

Resistance tolerance: ±10% or ±0.5 Ω, whichever is greater.

Dielectric strength: 1000 VRMS.

Minimum bend radius: 0.030" (0.8 mm).

Leadwire: Red PTFE insulated, stranded.
Current capacity (based on 100°C max. ambient temp.):

AWG 30	AWG 26	AWG 24	AWG 20
3.0 A	5.0 A	7.5 A	13.5 A

Maximum heater thickness:

Over element	0.012" (0.3 mm)
Over leads	
AWG 30 (0.057 mm²)	0.050" (1.3 mm)
AWG 26 (0.141 mm²)	0.060" (1.5 mm)
AWG 24 (0.227 mm²)	0.065" (1.7 mm)
AWG 20 (0.563 mm²)	0.085" (2.2 mm)

Add 0.005" (0.1 mm) to above dimensions for foil backing.

Dimensional tolerance:

6" (150 mm) or less	±0.03" (±0.8 mm)
6.01 to 12" (150 to 300 mm)	±0.06" (±1.5 mm)
Over 12" (300 mm)	±0.12" (±3.0 mm)

Custom options

- Custom shapes and sizes to 10 × 22" (250 × 560 mm) with FEP adhesive; 12 × 72" (300 × 1830 mm) with WA/ULA
- Custom resistance to 450 Ω/in² (70 Ω/cm²)
- WA or ULA adhesive (see page A-8); preferred for custom designs below 150°C
- Available with surface mount sensors, connectors, even integral controllers
- TÜV or UL approval is optional
- Tighter resistance tolerance
- See section J for custom design assistance

*Kapton™ is the DuPont tradename for polyimide

Stock Kapton™ Heaters

These heaters are normally available from stock for immediate shipment. Voltage and wattage values are for reference only. Heaters may be operated at other voltages if they do not exceed the maximum allowable watt density ratings.

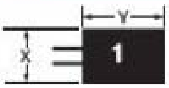
See section D for these and other models with additional ordering options:

- ◆ Greater selection of resistances
- ◆ Variable lead length
- ◆ More backing options
- ◆ UL recognition

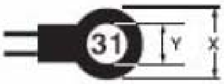
How to order stock heaters

HK5160R157L12	**Model number**
A	**Heater backing:** A = No adhesive -200 to 200°C B = Acrylic PSA -32 to 100°C
HK5160R157L12A ← Sample part number	

Type (configuration)



LEAD LENGTH:
12" (305 mm)

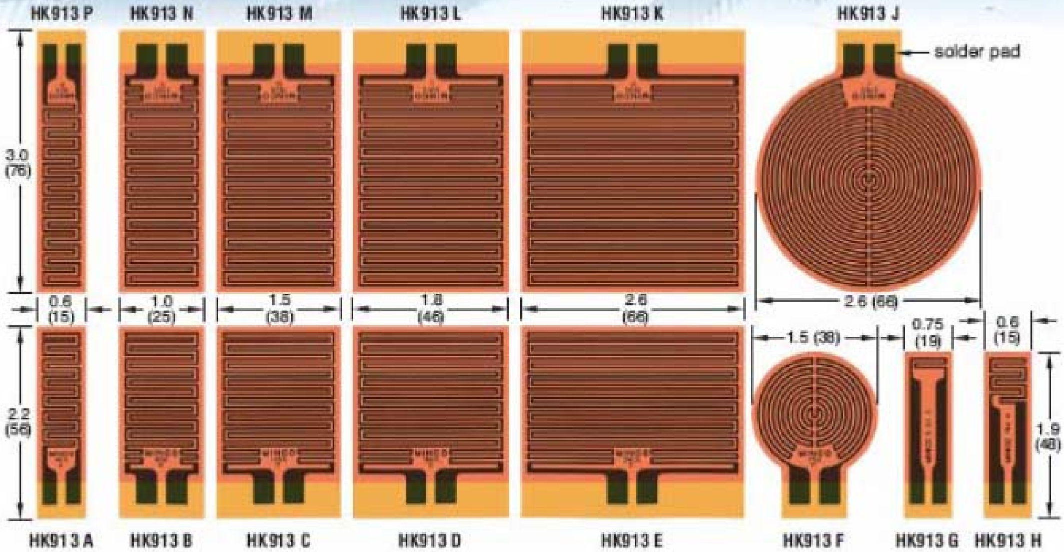


TAB DIMENSIONS:
AWG 30: 0.40" × 0.25" (10.2 × 6.4 mm)
AWG 24/26: 0.40" × 0.40" (10.2 × 10.2 mm)

Size (inches)		Size (mm)		Type	Resistance in ohms*	Typical power	Effective area (in²)	Lead AWG	Model number
X	Y	X	Y						
0.50	2.00	12.7	50.8	1 ■	157	5 W at 28 V	0.79	30	HK5160R157L12
0.50	4.00	12.7	101.6	1 ■	78.4	10 W at 28 V	1.67	30	HK5161R78.4L12
0.50	6.00	12.7	152.4	1 ■	52.3	15 W at 28 V	2.35	30	HK5162R52.3L12
1.00	1.00	25.4	25.4	1 ■	157	5 W at 28 V	0.82	30	HK5163R157L12
1.00	2.00	25.4	50.8	1 ■	78.4	10 W at 28 V	1.76	30	HK5164R78.4L12
1.00	3.00	25.4	76.2	1 ■	52.3	15 W at 28 V	2.70	30	HK5165R52.3L12
1.00	5.00	25.4	127.0	1 ■	529	25 W at 115 V	4.41	30	HK5166R529L12
1.00	10.00	25.4	254.0	1 ■	264	50 W at 115 V	8.96	30	HK5167R264L12
1.00	15.00	25.4	381.0	1 ■	176	75 W at 115 V	13.51	30	HK5168R176L12
2.00	2.00	50.8	50.8	1 ■	661	20 W at 115 V	3.59	30	HK5169R661L12
2.00	3.00	50.8	76.2	1 ■	441	30 W at 115 V	5.50	30	HK5170R441L12
2.00	4.00	50.8	101.6	1 ■	331	40 W at 115 V	7.41	30	HK5171R331L12
2.00	6.00	50.8	152.4	1 ■	220	60 W at 115 V	11.23	30	HK5172R220L12
2.00	12.00	50.8	304.8	1 ■	110	120 W at 115 V	22.69	24	HK5173R110L12
3.00	3.00	76.2	76.2	1 ■	294	45 W at 115 V	8.41	30	HK5174R294L12
3.00	5.00	76.2	127.0	1 ■	176	75 W at 115 V	14.23	30	HK5175R176L12
3.00	10.00	76.2	254.0	1 ■	88.2	150 W at 115 V	28.75	24	HK5176R88.2L12
3.00	15.00	76.2	381.0	1 ■	58.8	225 W at 115 V	43.30	24	HK5177R58.8L12
4.00	4.00	101.6	101.6	1 ■	165	80 W at 115 V	15.20	30	HK5178R165L12
4.00	8.00	101.6	203.2	1 ■	82.7	160 W at 115 V	30.84	24	HK5179R82.7L12
4.00	12.00	101.6	304.8	1 ■	55.1	240 W at 115 V	46.48	24	HK5180R55.1L12
5.00	5.00	127.0	127.0	1 ■	106	125 W at 115 V	24.02	24	HK5181R106L12
5.00	10.00	127.0	254.0	1 ■	52.9	250 W at 115 V	48.57	24	HK5182R52.9L12
5.00	15.00	127.0	381.0	1 ■	35.3	375 W at 115 V	73.12	24	HK5183R35.3L12
10.00	10.00	254.0	254.0	1 ■	26.4	500 W at 115 V	97.52	20	HK5184R26.4L12
10.00	15.00	254.0	381.0	1 ■	17.6	750 W at 115 V	146.92	20	HK5185R17.6L12
0.50	0.09	12.7	2.4	31 ○	25.0	1 W at 5 V	0.13	30	HK5186R25.0L12
1.00	0.09	25.4	2.4	31 ○	157	5 W at 28 V	0.68	26	HK5187R157L12
3.00	0.12	76.2	3.1	31 ○	378	35 W at 115 V	6.61	26	HK5188R378L12

*Resistance tolerance is ±10% or ±0.5 Ω, whichever is greater

HK913 Heater Kit



Dimensions in inches (mm)

The HK913 heater kit permits low-cost evaluation and prototyping of Thermofoil heaters. Available from stock, it contains 14 heating elements you can arrange in more than 1000 combinations. When ordering the complete kit, one sheet (6 × 12") of acrylic PSA is included for easy installation. Specify acrylic PSA for individual heaters, if desired.

Specifications

Temperature range: -200 to 200°C (-328 to 392°F), -32 to 100°C (-26 to 212°F) with acrylic PSA.
Material: Kapton/FEP, 0.002"/0.001" (0.05/0.03 mm).
Resistance tolerance: ±15%.
Minimum bend radius: 0.030" (0.8 mm).

How to order

HK913	Model number
E	Individual element code from table (leave blank for entire kit)
HK913E ← Sample part number	

Element code	Size (inches)	Size (mm)	Resistance in ohms	Effective area (in²)
A	0.6 × 2.2	15 × 56	40	0.58
B	1.0 × 2.2	25 × 56	80	1.20
C	1.5 × 2.2	38 × 56	120	1.86
D	1.8 × 2.2	46 × 56	160	2.45
E	2.6 × 2.2	66 × 56	240	3.67
F	1.5 Dia.	38 Dia.	75	1.03
G	0.75 × 1.9	19 × 48	5.5	0.04
H	0.6 × 1.9	15 × 48	15	0.21
J	2.6 Dia.	66 Dia.	275	4.49
K	2.6 × 3.0	66 × 76	360	5.59
L	1.8 × 3.0	46 × 76	240	3.75
M	1.5 × 3.0	38 × 76	180	2.87
N	1.0 × 3.0	25 × 76	120	1.87
P	0.6 × 3.0	15 × 76	60	0.94

http://sourses

http://www.servosystems.com/harowe_resolvers.htm

http://www.polysci.com/docs/DigitalResolverDS.pdf

http://www.globalspec.com/specifications/spechelpall?name=motion_controllers&comp=44

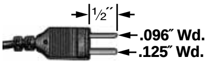
used resolver reference:
http://www.dynapar-encoders.com/harowe/sections/product/size11_specs1.htm

resolver mass reference
http://www.amci.com/resolvers/resolvers.r11.asp

Thermocouple Probes

For information about thermocouples, see page 487.

Air/Immersion Thermocouple Probes with Flat-Pin (Mini) Connector



Flat-Pin (Mini) Connector

1


2


3


4&5


6


7-9


Probes have male flat-pin (mini) connectors. *Note:* Response times listed below are approximate.

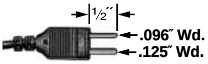
Styles 1&2—Have perforated probe tips for measuring ambient air temperatures. *Style 2* has a brass clip to secure probe to a surface.

Styles 3-6—Have bendable stems that adjust to area being tested. Designed to measure air temperatures and for immersing into liquids.

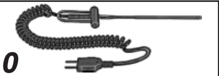
Styles 7-9—Have bare tips for measuring ambient air temperatures and flat-surface temperatures.

Probe Type (Temp. Range)	Probe Lg.	Response Time, sec.	Max. Cable Temp.		Each
(1) Type 302 SS Probes (⅛″ dia.) with 4-ft. Coiled PVC Cable					
J (−40° to +500° F)	4″	10	176° F	3868K42	$47.85
K (−40° to +500° F)	4″	10	176° F	3868K43	47.85
T (−40° to +500° F)	4″	10	176° F	3868K44	47.85
(2) Type 302 SS Probes (¼″ dia.) with 46″ Fiberglass Cable					
J (−40° to +896° F)	2⅛″	10	896° F	3868K641	47.85
K (−40° to +896° F)	2⅛″	10	896° F	3868K642	47.85
T (−40° to +896° F)	2⅛″	10	896° F	3868K643	47.85
(3) Type 316 SS Probes (⅛″ dia.) without Cable					
J (+32° to +1400° F)	12″	0.5	———	39095K61	15.10
J (+32° to +1400° F)	18″	0.5	———	39095K62	16.20
J (+32° to +1400° F)	24″	0.5	———	39095K63	17.30
J (+32° to +1400° F)	36″	0.5	———	39095K241	19.50
K (+32° to +1600° F)	12″	0.5	———	39095K64	15.10
K (+32° to +1600° F)	18″	0.5	———	39095K65	16.20
K (+32° to +1600° F)	24″	0.5	———	39095K66	17.30
K (+32° to +1600° F)	36″	0.5	———	39095K242	19.50
T (−328° to +700° F)	12″	0.5	———	39095K67	15.10
T (−328° to +700° F)	18″	0.5	———	39095K68	16.20
T (−328° to +700° F)	24″	0.5	———	39095K69	17.30
T (−328° to +700° F)	36″	0.5	———	39095K243	19.50
(4) Type 316 SS Probes (⅛″ dia.) with 3-ft. Fiberglass Cable					
J (+32° to +1400° F)	12″	0.5	900° F	39095K51	24.20
J (+32° to +1400° F)	18″	0.5	900° F	39095K52	26.40
J (+32° to +1400° F)	24″	0.5	900° F	39095K53	26.40
(4) Type 316 SS Probes (⅛″ dia.) with 3-ft. Fiberglass Cable (Cont.)					
K (+32° to +1600° F)	12″	0.5	900° F	39095K54	$24.20
K (+32° to +1600° F)	18″	0.5	900° F	39095K55	26.40
K (+32° to +1600° F)	24″	0.5	900° F	39095K56	26.40
T (−328° to +700° F)	12″	0.5	900° F	39095K57	24.20
T (−328° to +700° F)	18″	0.5	900° F	39095K58	26.40
T (−328° to +700° F)	24″	0.5	900° F	39095K59	26.40
(5) Type 316 SS Probes (1⁄16″ dia.) with 3-ft. PVC Cable					
J (+32° to +1400° F)	7″	0.3	221° F	39095K95	57.51
K (+32° to +1600° F)	7″	0.3	221° F	39095K96	57.51
T (−328° to +700° F)	7″	0.3	221° F	39095K97	57.51
(6) Type 316 SS Probe (3⁄16″ dia.) with 3-ft. Type 302 SS Cable					
J (+32° to +1400° F)	24″	1	400° F	39095K11	105.84
K (+32° to +1600° F)	24″	1	400° F	39095K12	105.84
(7) Bare-Tip Probes (3⁄16″ dia.) with 3-ft. PTFE Cable					
J (−40° to +400° F)	⅛″	7	400° F	6441T671	20.82
K (−40° to +400° F)	⅛″	7	400° F	6441T672	20.82
T (−40° to +400° F)	⅛″	7	400° F	6441T673	20.82
(8) Bare-Tip Probes (3⁄16″ dia.) with 15-ft. PTFE Cable					
J (−40° to +400° F)	⅛″	7	400° F	6441T821	42.34
K (−40° to +400° F)	⅛″	7	400° F	6441T822	42.34
T (−40° to +400° F)	⅛″	7	400° F	6441T823	42.34
(9) Bare-Tip Probes (3⁄16″ dia.) with 4-ft. Fiberglass Cable					
J (−40° to +896° F)	⅛″	9	896° F	6441T941	27.05
K (−40° to +896° F)	⅛″	9	896° F	6441T942	27.05
T (−40° to +896° F)	⅛″	9	896° F	6441T943	27.05

Penetration/Immersion Thermocouple Probes with Flat-Pin (Mini) Connector



Flat-Pin (Mini) Connector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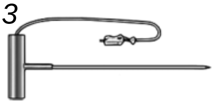
11


12

13


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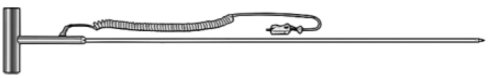


15


16-18


19-20


Designed for penetrating into soft materials and for immersing into liquids. These thermocouple probes are made of Type 304 stainless steel. All have male flat-pin (mini) connectors. *Note:* Response times listed below are approximate.

Styles 10-12 & 14—Have a self-retracting coiled cable.

Styles 16-18—Have a green PFA-coated stem.

Probe Type (Temp. Range)	Probe Lg.	Response Time, sec.	Max. Cable Temp.		Each
(10) Straight-Tip Probes (⅛″ dia.) with 4-ft. Coiled PVC Cable					
J (−40° to +500° F)	4½″	4	176° F	39105K76	$47.85
K (−40° to +500° F)	4½″	4	176° F	39105K72	47.85
T (−40° to +500° F)	4½″	4	176° F	39105K91	47.85
(11) Reduced-Tip Probes (3⁄32″ dia.) with 4-ft. Coiled PVC Cable					
J (−40° to +500° F)	6″	3	176° F	39105K651	54.78
K (−40° to +500° F)	6″	3	176° F	39105K652	54.78
T (−40° to +500° F)	6″	3	176° F	39105K653	54.78
(12) Reduced-Round-Tip Probes (1⁄16″ dia.) w/4-ft. Coiled PVC Cable					
J (−40° to +932° F)	12″	1	176° F	39105K411	106.93
K (−40° to +932° F)	12″	1	176° F	39105K412	106.93
T (−40° to +662° F)	12″	1	176° F	39105K423	106.93
(13) Pointed Probes (¼″ dia.) w/T-Handle and 5-ft. Type 304 SS Cable					
J (−310° to +1400° F)	10″	10	900° F	39105K211	98.78
K (−418° to +1652° F)	10″	10	900° F	39105K212	98.78
T (−418° to +750° F)	10″	10	700° F	39105K313	98.78
(14) Heavy Duty Pointed-Tip Probes (5⁄16″ dia.) with T-Handle and 6-ft. Coiled Polyurethane Cable					
K (−166° to +400° F)	36″	15	220° F	9261T36	187.04
K (−166° to +400° F)	48″	15	220° F	9261T48	212.22
K (−166° to +400° F)	60″	15	220° F	9261T62	233.70
(15) Chisel-Tip Probes (1⁄16″ dia.) with 3-ft. PVC Cable					
J (−40° to +500° F)	4″	3	220° F	39105K511	89.45
K (−40° to +500° F)	4″	3	220° F	39105K512	89.45
T (−40° to +500° F)	4″	3	220° F	39105K513	89.45
(16) PFA-Coated Round-Tip Probes (⅛″ dia.) w/32″ Type 304 SS Cable					
J (−325° to +500° F)	12″	0.25	550° F	9260T31	115.80
J (−325° to +500° F)	16″	0.25	550° F	9260T71	134.40
K (−325° to +500° F)	12″	0.25	550° F	9260T37	115.80
K (−325° to +500° F)	16″	0.25	550° F	9260T77	134.40
(17) PFA-Coated Round-Tip Probes (3⁄16″ dia.) with 32″ Type 304 SS Cable					
J (−325° to +500° F)	12″	0.25	550° F	9260T33	$115.80
J (−325° to +500° F)	16″	0.25	550° F	9260T73	134.40
K (−325° to +500° F)	12″	0.25	550° F	9260T39	115.80
K (−325° to +500° F)	16″	0.25	550° F	9260T79	134.40
(18) PFA-Coated Round-Tip Probes (¼″ dia.) w/32″ Type 304 SS Cable					
J (−325° to +500° F)	12″	0.25	550° F	9260T35	115.80
J (−325° to +500° F)	16″	0.25	550° F	9260T75	134.40
K (−325° to +500° F)	12″	0.25	550° F	9260T41	115.80
K (−325° to +500° F)	16″	0.25	550° F	9260T81	134.40
(19) Hypodermic-Tip Probes (1⁄16″ dia.) with 32″ Type 304 SS Cable					
J (−325° to +600° F)	2″	0.25	550° F	9262T22	80.40
J (−325° to +600° F)	6″	0.25	550° F	9262T24	85.20
J (−325° to +1500° F)	2″	0.25	550° F	9262T52	84.00
J (−325° to +1500° F)	6″	0.25	550° F	9262T54	88.80
K (−325° to +600° F)	2″	0.25	550° F	9262T32	80.40
K (−325° to +600° F)	6″	0.25	550° F	9262T34	85.20
K (−325° to +1500° F)	2″	0.25	550° F	9262T62	84.00
K (−325° to +1500° F)	6″	0.25	550° F	9262T64	88.80
(20) Hypodermic-Tip Probes (5⁄64″ dia.) with 32″ Type 304 SS Cable					
J (−325° to +600° F)	2″	0.25	550° F	9262T26	80.40
J (−325° to +600° F)	6″	0.25	550° F	9262T28	85.20
J (−325° to +1500° F)	2″	0.25	550° F	9262T56	84.00
J (−325° to +1500° F)	6″	0.25	550° F	9262T58	88.80
K (−325° to +600° F)	2″	0.25	550° F	9262T36	80.40
K (−325° to +600° F)	6″	0.25	550° F	9262T38	85.20
K (−325° to +1500° F)	2″	0.25	550° F	9262T66	84.00
K (−325° to +1500° F)	6″	0.25	550° F	9262T68	88.80

Worm Gearheads

1,133 oz-in

Motor and Gearhead combinations:
G2.6 fits motor series GNM3150
G3.1 fits motor series GNM5440

Series G2.6 & G3.1

See beginning of the PMDC Gearhead Section for Ordering Information

		G2.6	G3.1
Housing material		metal	metal
Backlash, at no-load		≤ 1.5°	≤ 1.5°
Shaft load, max.:			
– radial	lbs	33.8	45
– axial	lbs	13.5	18

Series G2.6 with Motor Series GNM 3150

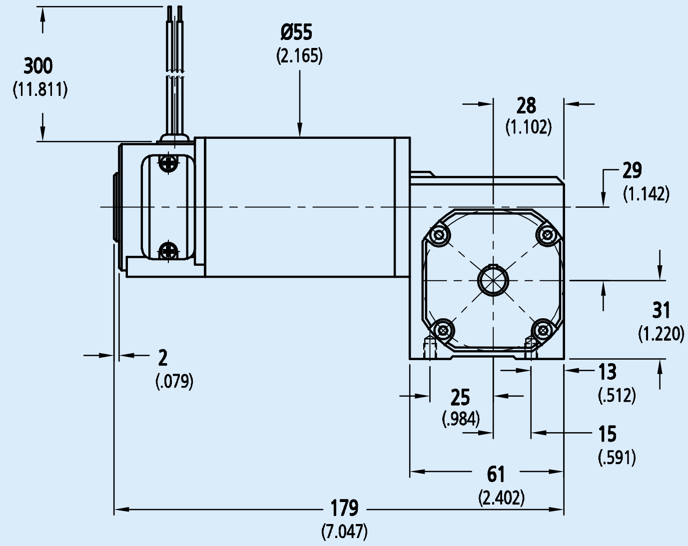
reduction ratio	weight without motor		length with motor GNM 3150		output torque continuous operation		output torque intermittent operation		direction of rotation (reversible)	efficiency
	Kg	lbs	mm	in	M max. Nm	M max. oz-in	M max. Nm	M max. oz-in		%
4.8:1	0.45	0.99	179	7.05	0.7	99.1	7	991.3	=	82
9.33:1	0.45	0.99	179	7.05	1.3	184.1	7	991.3	=	80
12:1	0.45	0.99	179	7.05	1.6	226.6	7	991.3	=	80
14.5:1	0.45	0.99	179	7.05	2.0	283.2	7	991.3	=	78
20:1	0.45	0.99	179	7.05	2.4	339.9	8	1,132.9	=	70
25:1	0.45	0.99	179	7.05	2.7	382.4	8	1,132.9	=	66
30:1	0.45	0.99	179	7.05	3.0	424.8	7	991.3	=	67
36:1	0.45	0.99	179	7.05	2.5	354.0	5	708.1	=	63

Series G3.1 with Motor Series GNM 5440

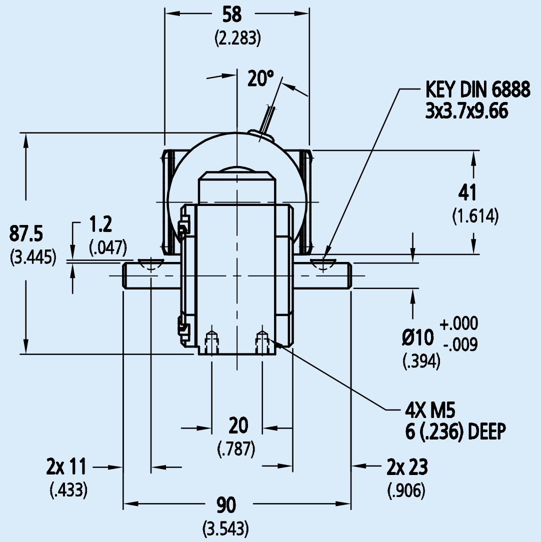
reduction ratio	weight without motor		length with motor GNM 5440		output torque continuous operation		output torque intermittent operation		direction of rotation (reversible)	efficiency
	Kg	lbs	mm	in	M max. Nm	M max. oz-in	M max. Nm	M max. oz-in		%
5.6:1	1.0	2.20	251	9.88	2.7	382.3	13	1,841	=	85
9.33:1	1.0	2.20	251	9.88	2.8	396.5	13	1,841	=	85
14.5:1	1.0	2.20	251	9.88	3.8	538.1	13	1,841	=	82
17:1	1.0	2.20	251	9.88	4.2	549.8	13	1,841	=	78
30:1	1.0	2.20	251	9.88	8	1,133	13	1,841	=	72
35:1	1.0	2.20	251	9.88	8	1,133	13	1,841	=	69

Series G2.6 & G3.1

Dimensional outlines for 3150 + G2.6

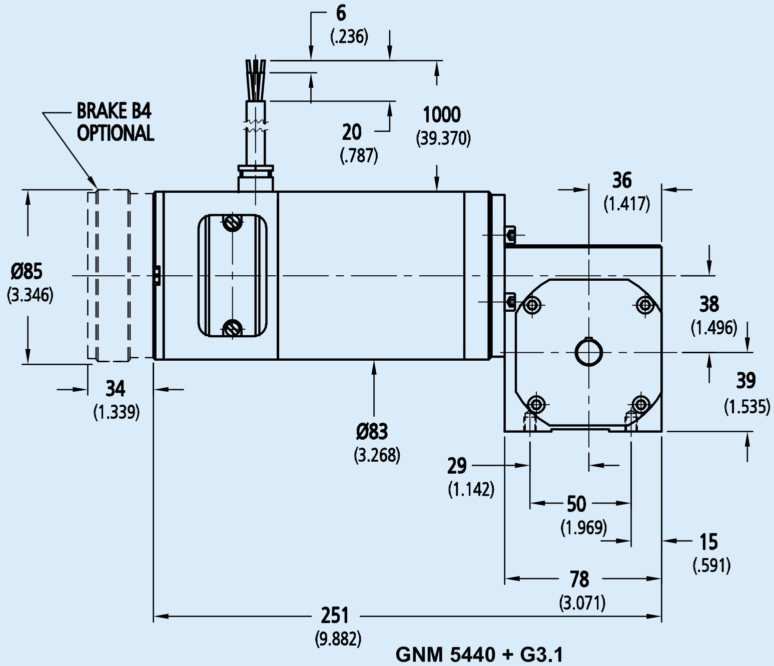


GNM 3150 + G2.6

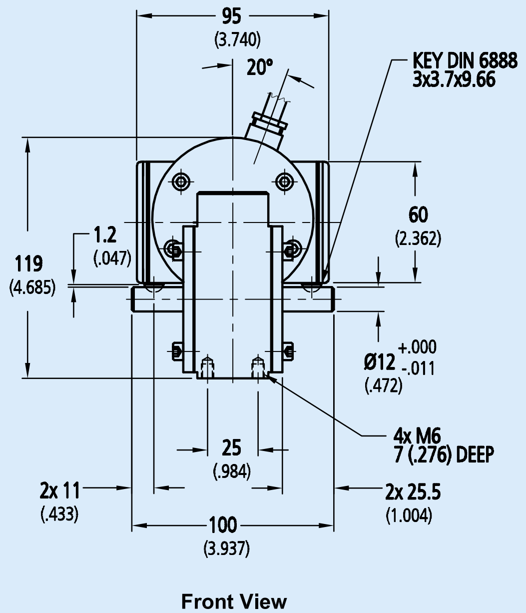


Front View

Dimensional outlines for 5440 + G3.1



GNM 5440 + G3.1



Front View

For notes on technical data refer to "Technical Information". Specifications subject to change without notice. MME0402

Worm Gearheads

1,133 oz-in

Motor and Gearhead combinations:
G2.6 fits motor series GNM3150
G3.1 fits motor series GNM5440

Series G2.6 & G3.1

See beginning of the PMDC Gearhead Section for Ordering Information

		G2.6	G3.1
Housing material		metal	metal
Backlash, at no-load		≤ 1.5°	≤ 1.5°
Shaft load, max.:			
– radial	lbs	33.8	45
– axial	lbs	13.5	18

Series G2.6 with Motor Series GNM 3150

reduction ratio	weight without motor		length with motor GNM 3150		output torque continuous operation		output torque intermittent operation		direction of rotation (reversible)	efficiency
	Kg	lbs	mm	in	M max. Nm	M max. oz-in	M max. Nm	M max. oz-in		%
4.8:1	0.45	0.99	179	7.05	0.7	99.1	7	991.3	=	82
9.33:1	0.45	0.99	179	7.05	1.3	184.1	7	991.3	=	80
12:1	0.45	0.99	179	7.05	1.6	226.6	7	991.3	=	80
14.5:1	0.45	0.99	179	7.05	2.0	283.2	7	991.3	=	78
20:1	0.45	0.99	179	7.05	2.4	339.9	8	1,132.9	=	70
25:1	0.45	0.99	179	7.05	2.7	382.4	8	1,132.9	=	66
30:1	0.45	0.99	179	7.05	3.0	424.8	7	991.3	=	67
36:1	0.45	0.99	179	7.05	2.5	354.0	5	708.1	=	63

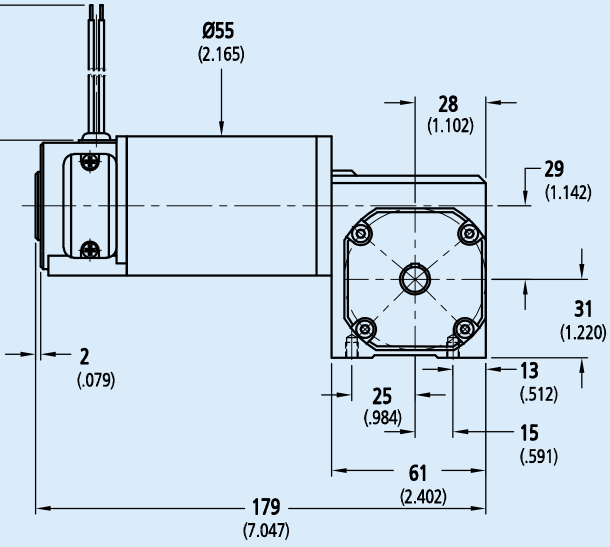
Series G3.1 with Motor Series GNM 5440

reduction ratio	weight without motor		length with motor GNM 5440		output torque continuous operation		output torque intermittent operation		direction of rotation (reversible)	efficiency
	Kg	lbs	mm	in	M max. Nm	M max. oz-in	M max. Nm	M max. oz-in		%
5.6:1	1.0	2.20	251	9.88	2.7	382.3	13	1,841	=	85
9.33:1	1.0	2.20	251	9.88	2.8	396.5	13	1,841	=	85
14.5:1	1.0	2.20	251	9.88	3.8	538.1	13	1,841	=	82
17:1	1.0	2.20	251	9.88	4.2	549.8	13	1,841	=	78
30:1	1.0	2.20	251	9.88	8	1,133	13	1,841	=	72
35:1	1.0	2.20	251	9.88	8	1,133	13	1,841	=	69

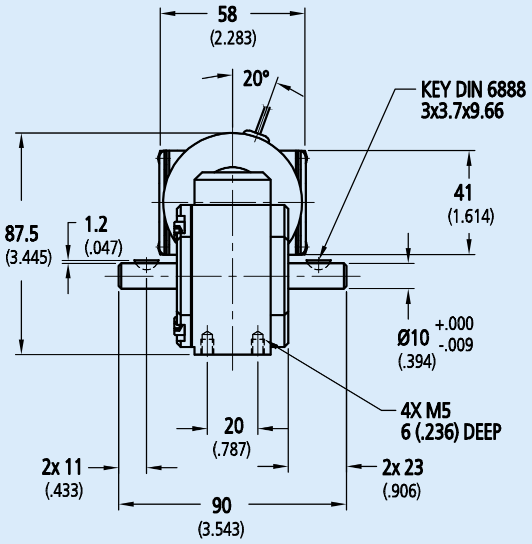
For notes on technical data refer to "Technical Information". Specifications subject to change without notice. MME0402

Series G2.6 & G3.1

Dimensional outlines for 3150 + G2.6

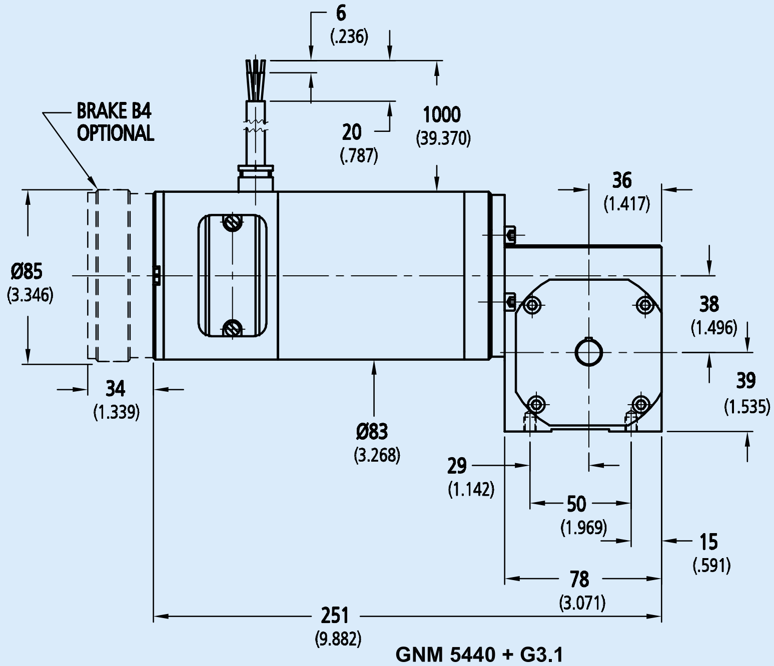


GNM 3150 + G2.6

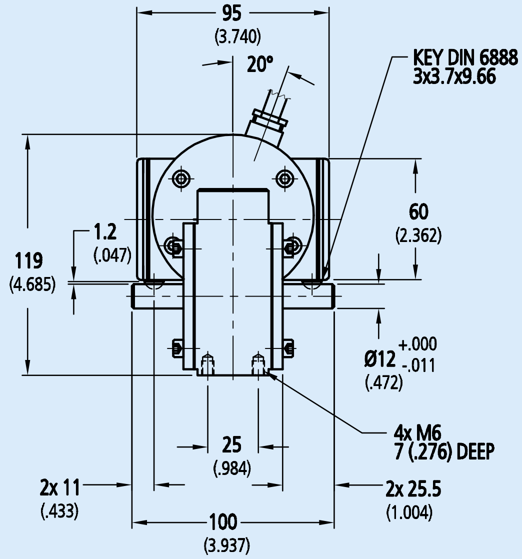


Front View

Dimensional outlines for 5440 + G3.1



GNM 5440 + G3.1



Front View

For notes on technical data refer to "Technical Information". Specifications subject to change without notice. MME0402

Appendix 10 Interface Control Document

HERO & Frontier Robotics

Interface Control Document

HERO
Michael Trauttmansdorff (Operations)
Mohammad Alam (Systems)
Stephanie Allen (Electrical)
Kristian Dixon (Propulsion/Orbital Dynamics)
Wassim Abu-Zent (Mechanical)

Frontier Robotics
Mark Baldesarra (Systems)
Bruce Cameron (Operations)
Nicolas Lee (Software)
Filip Stefanovic (Propulsion/Control)
Brendan Wood (Mechanical)

Rev. A
October 21, 2004

ICD Table of Contents

1 ICD Nomenclature

DR – Dexterous Robot
GA – Grapple Arm
RSS – Robotic Servicing System
HST – Hubble Space Telescope
HRV – Hubble Rescue Vehicle
EE – End Effector
FRGF - Flight Releasable Grapple Fixture

2 ICD Mechanical Interface

2.1 Structure

The EE on the GA is a modified Canadarm end effector that is designed to capture the standard GF that is used on the HST. It has two cameras mounted on the exterior of the EE. Only one will be used during docking, and the second is available to provide a backup in case the primary camera fails. The cameras are angled 120° away from each other around the EE with the same relative vertical position and orientation. The 120° offset is derived from the symmetry of the cams in the GF. If the primary camera fails during docking with the HST, the EE can rotate 120° and the backup camera will switch on. In this new configuration, the tracking system can use the visual data as before without recalibration.

The DR grapple fixture will be located on the side of the main body. This will be the most accessible location on the DR while it is in its stowed position, therefore facilitating the initial capture of the DR by the GA. The GF will have the same basic structure as the FRGF with some additions. First, the GF will include two electrical ports to provide power and data connection to link the DR to its support systems in the EM through wires in the GA. Corresponding ports will be placed on the EE, and both will be located on the outside of the GF and EE at 60° and 180° from the primary target. Second, the EE cannot rotate to use its backup camera in the event of failure since the ports must align to its corresponding port on the DR. Thus the DR grapple fixture will have two targets, orientated 120° from each other, and if needed the backup camera will use the backup target for capture.

Both the mechanical and electrical connections will be simultaneously made during capture. This requires high accuracy in rotation when the EE contacts with the GF back plate so that the electrical ports mate properly. The rotational accuracy is provided by teeth that are recessed away from the EE, shown in Appendix 6.1.1 and 6.1.2. A detail of the teeth is shown in Appendix 6.1.3. These teeth match opposing teeth on the DR GF and align the EE to within the position tolerance of the electrical port. The teeth are recessed so they do not damage the HST GF or otherwise interfere with the HST capture.

2.2 DR Stow Configuration

The DR will be stowed on the exterior of the EM during launch, proximity and capture operations. This location was chosen over an interior bay to simplify the removal and return of the DR. Exterior stowage eliminates the need for doors to be manipulated, simplifies the configuration of the DR and gives the GA a wider work area when grappling the DR. In order to secure the DR to the EM, clamps will be located on the EM and corresponding ‘towel bars’ on the DR. Three such fixtures will be located on each arm (shoulder, elbow, and wrist) with two additional fix points on the main body. The GA will signal ground control when it has securely grappled the DR and the stowage clamps will be opened by ground control. Similarly, when the GA has returned the DR to the stow location, a signal will be sent and the clamps closed.

In addition to these physical connections, the DR will need to be electrically connected to the EM in order to monitor and maintain the temperature of its electronics. To accomplish this two connectors (primary and backup), each carrying a low power and 1553 data bus wire, will mate the DR to the EM before it is grappled by the GA. The connectors will be located on the front of the DR, which is facing the EM while stowed. When the GA signals the successful capture of the DR GF, these connections will be shut down. Furthermore, when the GA is returning the DR to its stow location for deorbit, it is not necessary to reconnect the electrical interface as the DR is no longer needed. Drawings detailing the stow configuration can be found in Appendix 6.2.

2.3 Capture Envelope

The capture envelope for the GF is defined in Figure 14.4.2.1 in the FRGF document, reproduced in Appendix 6.3. This envelope ensures firstly that the EE is moving at correct speeds during the approach to the GF, and secondly that it is in the correct position to reduce the chances for damage to either the EE or the DR. The DR stowage configuration accommodates this capture envelope since the GF is positioned away from any other components on the EM and nothing on the spacecraft interferes with the capture envelope.

2.4 Loading

The dominant interface force is 355 N and results from applying 50ft-lb of torque at the DR end effector. The dominant torque is 445 Nm and results from stopping a 1000lb mass. Note that these numbers include a factor of safety of 1.75. The interface will have the necessary stiffness and strength to withstand these loads. The details of these calculations can be found in Appendix 6.4.

The DR also imposes a cable load requirement on the GA, requiring 3.4 kg of cabling and associated accessories to be routed through the GA. This imposes structural requirements as well as adding to the force required from each of the motors. Using the estimation that a 100-wire bundle requires 5 Nm of torque, we have 3.2 Nm needed for the 64 wires (details in Section 3 - Electrical Interface) routed through the GA. See Appendix 6.5 for cable mass calculations.

2.5 Thermal

A common temperature range will be defined for both EE and GF in order to minimize thermal gradients between the GA and the DR. A temperature range between -20°C and 20°C has been selected based on requirements for actuators and electronics in the EE. The DR grapple fixture will equilibrate with the GA end effector once a mechanical connection has been made. The temperature range for the EE during operation will be between -10°C and 65°C as required.

In order to isolate the GF from the main body of the DR, as well as the EE from the GA, ceramic blocks will separate the two structures. This will ensure that any active heating of the DR electronics or structure will not result in temperature fluxes at the interface.

3 ICD Electrical Interface

We require that the FRGF interface with the GA will have in total two connectors. One connector would be the primary connector for power and data (32 pins in total), while the other connector is identical and will be completely redundant for both power and data (also containing 32 pins). This way we meet the single fault tolerant requirement so that if one connector fails, the other connector can be used to continue the mission. In total, 36 pins are needed for power cables and 28 pins for data cables. A breakdown of the connections is given in Table 3.1 below and details are provided in Appendix 6.6.

	Connector 1	**Connector 2**	**Total Pins**
Low Power 115 V	8	8	16
High Power 24 V	10	10	20
1553 Data Bus	4	4	8
Video Line	4	4	8
Sensors RS232	4	4	8
LCS RS422	2	2	4
Pin Total	32	32	64

Table 3.1 - GA/DR Electrical Interface Requirements

A trade-off that has been considered is to have 4 connectors: a connector for the primary power, a connector for the back-up power, a connector for the primary data, and a connector for the back-up data. This has the advantage that it is more than single fault tolerant, and that if one connector fails for any of the power or data, the other connector can take over while the second system would still have two connectors for use. The disadvantage with this is that it would greatly tighten the mating envelope and hence increase the accuracy requirement of the mating. It has been deemed unnecessary and so it has been decided that two connectors are sufficient, each with a full power and data system.

All separate structures for the GA and DR will be electrically linked to provide a common ground. We assume that the GA structure will be electrically linked to the EM structure, so that the DR structure will also be the same potential as the EM structure and hence will not cause a shock upon contact when retrieving WF/PC2 or WFC3.

4 ICD Software Interface

4.1 Coordinate Systems

The origin of the DR coordinate system will be located at the base of the FRGF grapple pin. The x-axis is along the line joining the two laser identifiers on the Grapple fixture. The y-axis is perpendicular to the x-axis along same plane. The z-axis will be perpendicular to the base plate of the stow fixture.

The origin of the GA coordinate system is the base of the GA at the shoulder mount. All coordinate axes are defined in the same direction as the Hubble coordinate system. All GA positioning commands from ground controllers will be in this reference frame.

The absolute axes to be used in orientation calculation are defined relative to the Hubble. The x–axis is parallel to the line joining the Solar Array supports, the y–axis is perpendicular to the x–axis and z-axis is parallel to the cylindrical axis of the HST.

4.2 Communications

4.2.1 Emergency Stop Command

Most communications between the GA and DR is handled through ground control, since most operations are not time critical and transmission lag is not a factor. The only direct communication between the DR and GA computers occurs if the DR detects a possible collision with any element on the HST. In that case, an emergency stop signal is sent directly to the GA Emergency Systems controller that halts GA motion. This will prevent any damage to the HST. Since this is a time critical operation, the signal is sent directly from the DR to the GA, and ground control is later notified when the system has stabilized.

Collision detection on the DR is handled by infrared proximity sensors placed in strategic locations (most likely collision points TBR). Data from the sensors will be assessed by the proximity controller on the DR. This controller has the highest priority along the 1553 bus to the control computer. The 1553 bus controller will be designed to stop all tasks and allow passage for the stop signal. This priority will be maintained through the DR/GA interface to ensure immediate stopping.

4.2.2 From Ground Control to DR/GA

Ground control will be responsible for sending the following signals to the DR or GA

- Start next operation
- Stop all operations (basically a halt command that acts like an emergency stop.)
- Upload new scripts
- Upload software patches
- Tool selection signal

4.2.3 From DR/GA To Ground Control

The DR will send the following information to ground control

- Self check results

- Operation successfully completed (containing operation description)
- Error report (containing the process and system/component where the error occurred)
- Up-to-date coordinates as calculated by LCS (DR) or Kinematics Modeler (GA).
- Video Feeds
- Force/torque sensor data

4.2.4 DR Ground Control to GA Ground Control

The DR ground controllers communicate the following information to GA ground controllers.

- Position Data (when move required) - This will be sent as coordinates to which the origin needs to be shifted relative to the current position of the origin. See Coordinate system for details.
- Orientation data – This will include final orientation indicating the angles each axis has to make with the absolute fixed axes. See coordinate system for details.
- Volume data – volume of space occupied by the DR or DR/payload combination to calculate trajectory and prevent bumping into the HST.

4.2.5 GA Ground Control to DR Ground Control

The GA ground controllers communicate the following information to DR ground controllers.

- Successful capture before startup.
- Move command carried out successfully, DR task can begin.

Communication protocol will require that the data will be communicated to GA ground control by the computer. The receipt of the data is acknowledged before the next operation can follow. Verbal communication may be added for redundancy purposes to ensure nothing is missed.

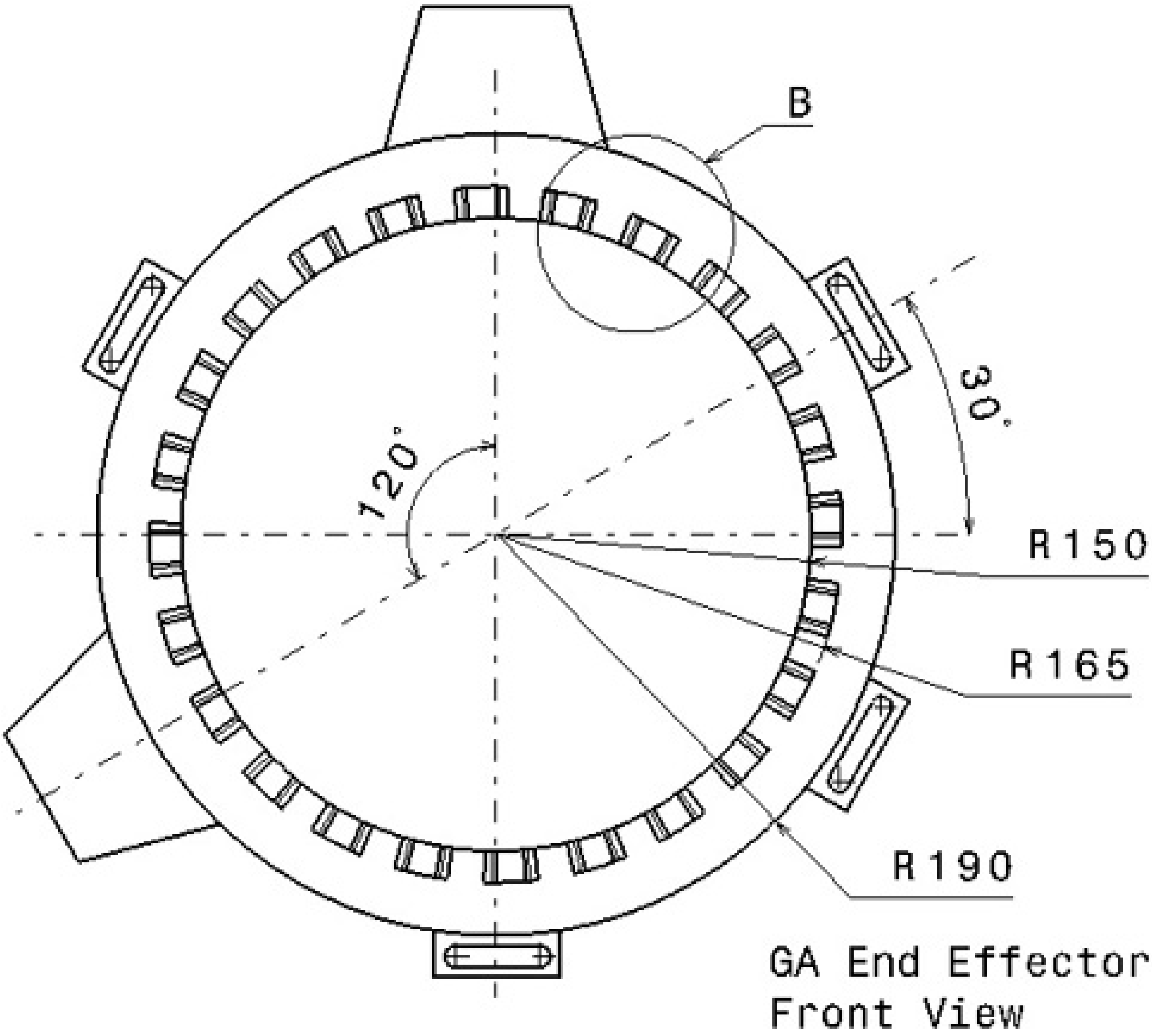
5 ICD References

[1] Space Mission Analysis and Design – 3rd Edition, James R. Wertz and Wiley J Larson.
[2] Engineering Fundamentals, www.efunda.com.
[3] Electrical, Mechanical and Software Assignments, HERO, 2004.
[4] Electrical, Mechanical and Software Assignments, Frontier Robotics, 2004.
[5] ICD, FRGF_cor14ASTS, Ch 14, AER 407 Supplemental Notes, 2004

6 ICD Appendices

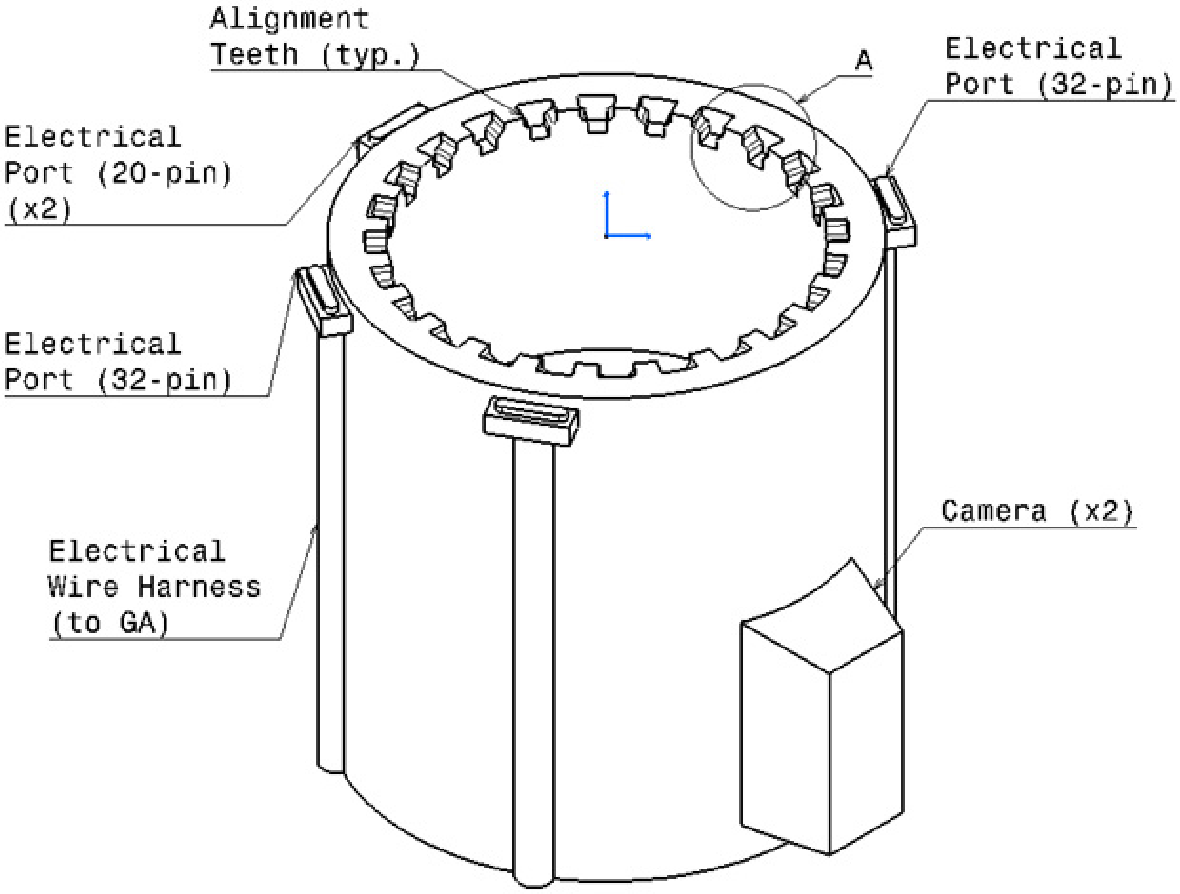
6.1 GA End Effector

6.1.1 Front View



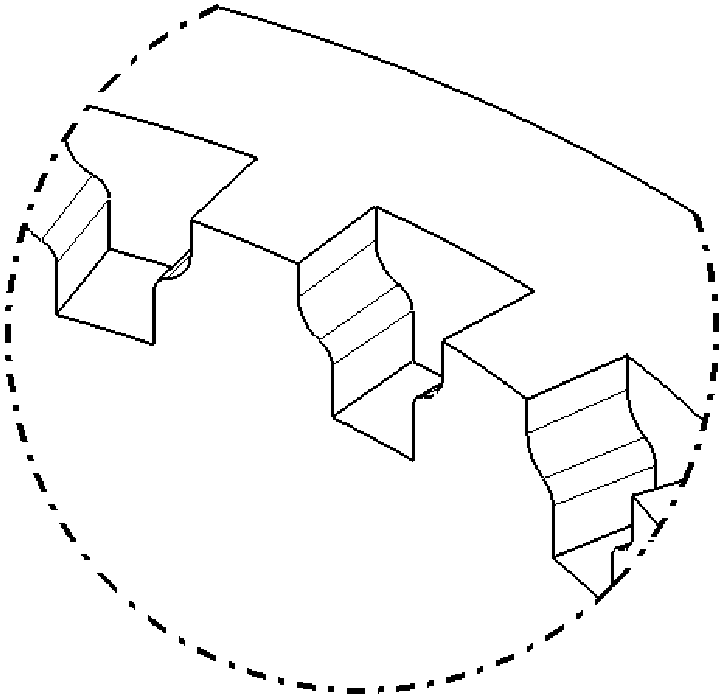
GA End Effector
Front View

6.1.2 Isometric View

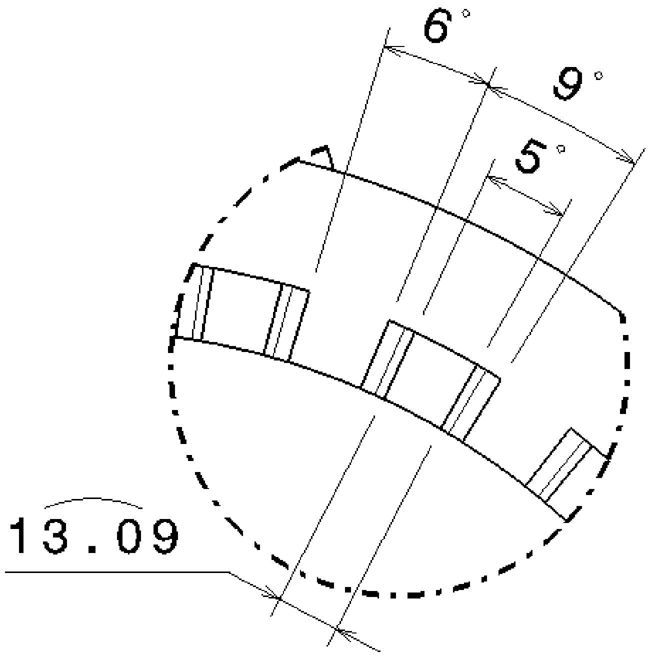


GA End Effector Isometric View

6.1.3 Interface Teeth Detail

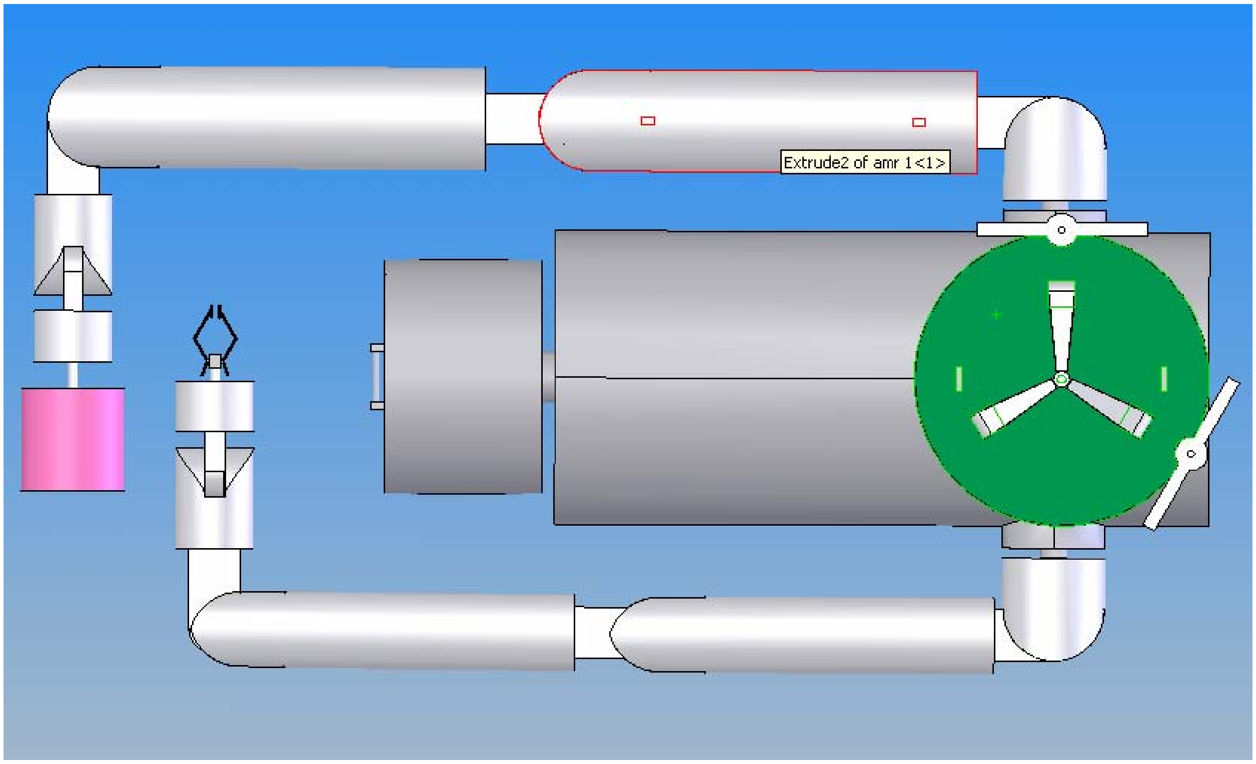


Detail A
Teeth Profile

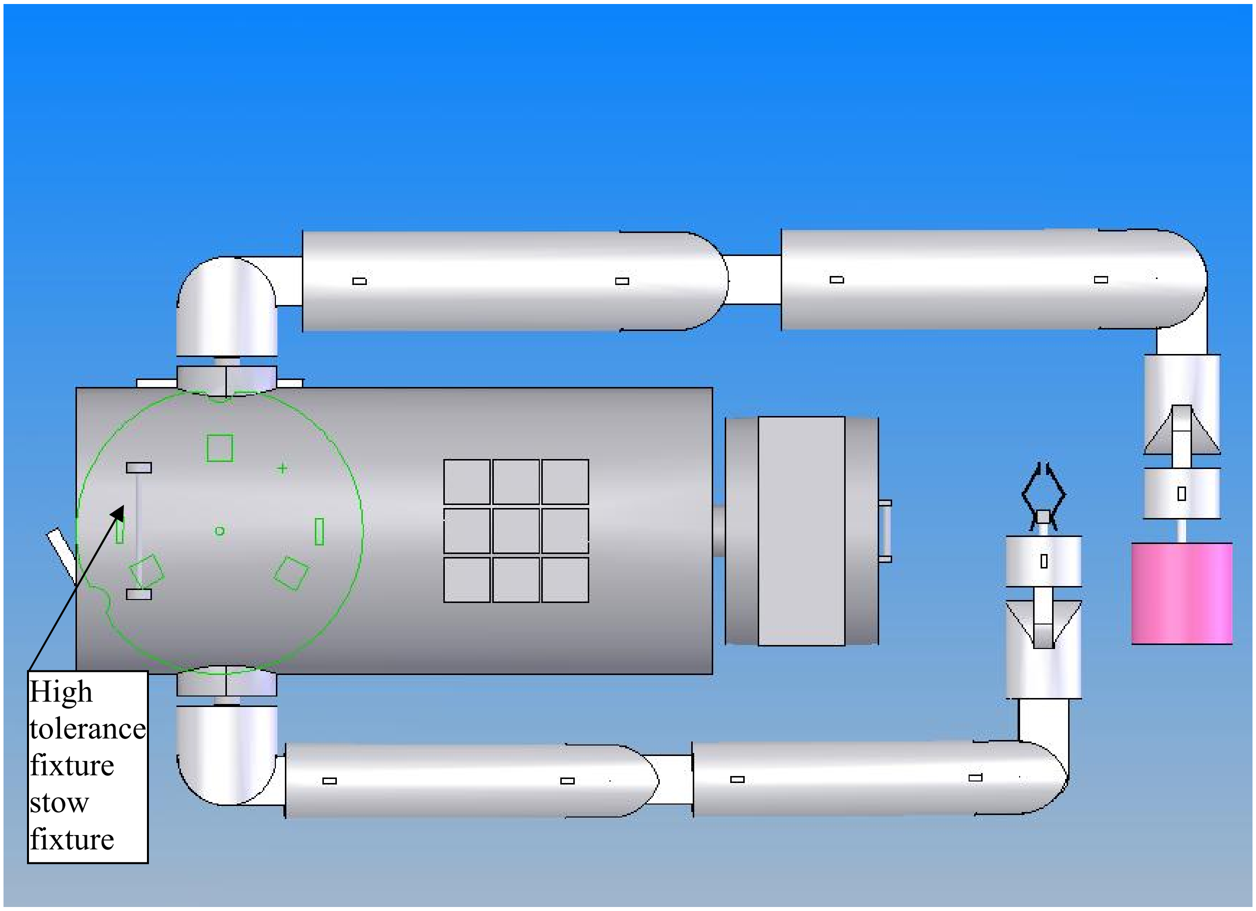


Detail B
Teeth Top View

6.2 DR Stow Configuration

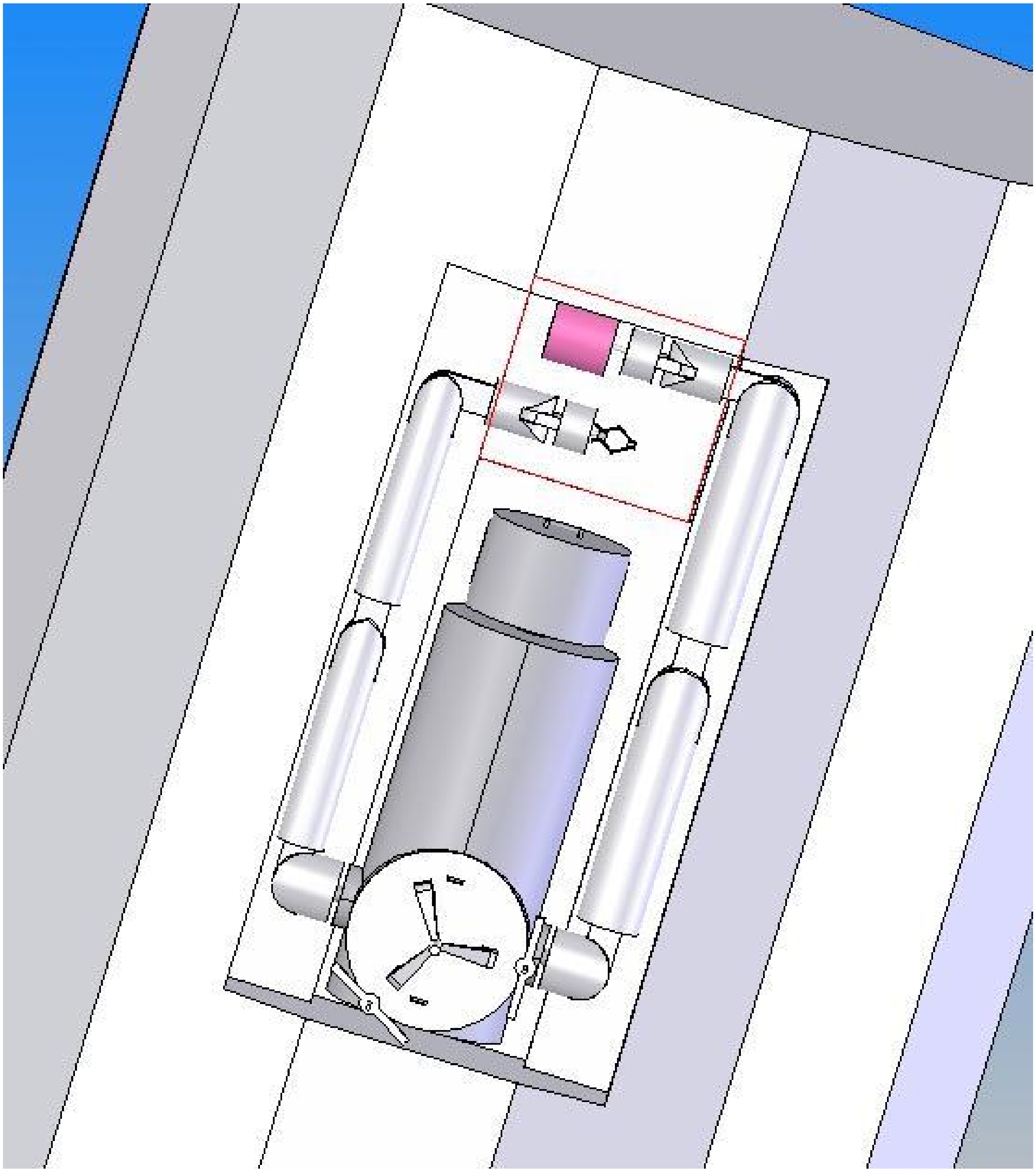


In this picture we see the back of the DR. It gives us a view of the grapple fixture with which we are going to interface with the GA. As specified by the GA team we have tracking fixtures at 120 degrees to each other. It also identifies the location of the power/data connector.



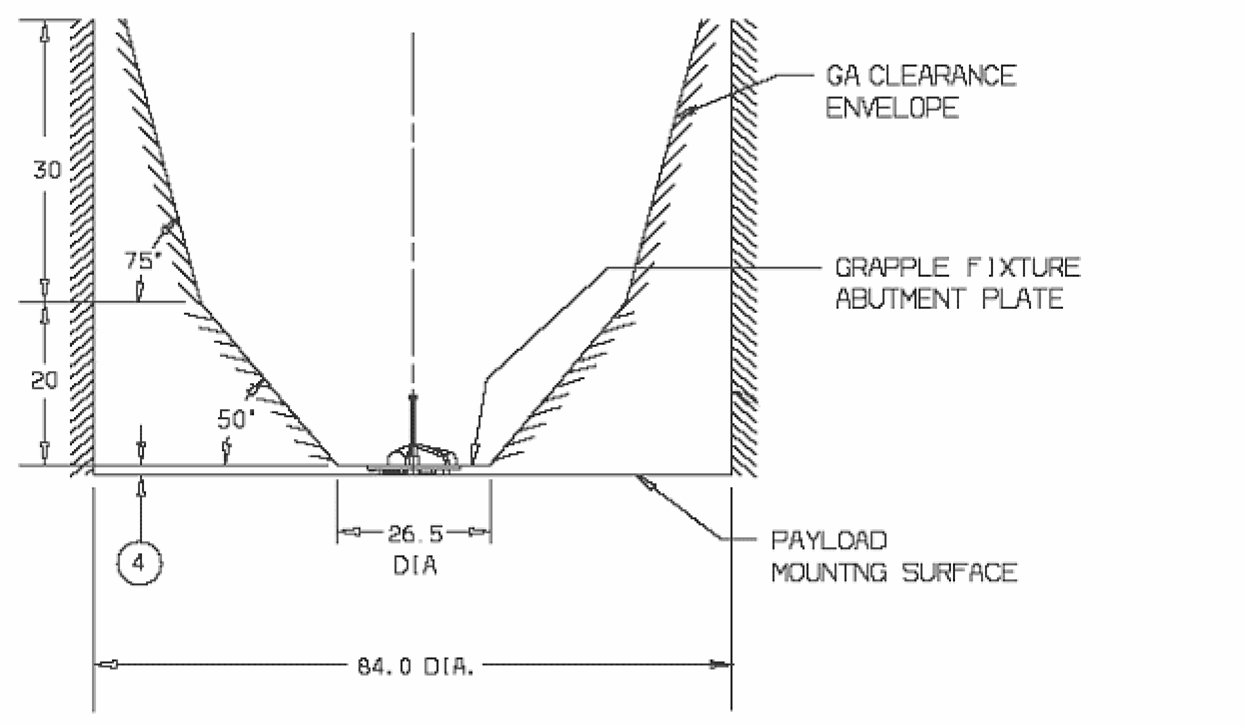
Here we see the front view and the stow fixtures to be used for stowing in the EM. The high tolerance stow fixture designed to maximize capture envelope is to allow the GA to put us in the EM with imposing extra requirements on their GA. Once the high tolerance fixture is in position it will be clamped down and positioned tightly and accurately and the other fixtures can then be locked in position.

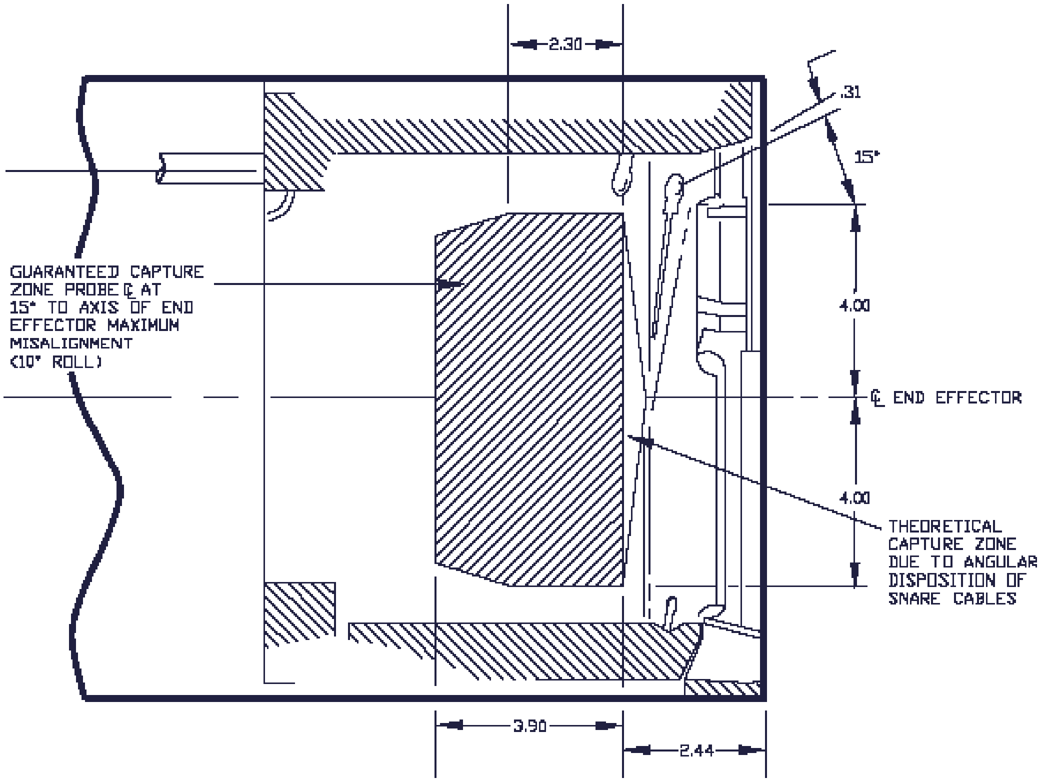
There are 12 stow fixtures in total; five support each arm, one on the head and the high tolerance stow fixture at the base of the GF.



Finally, this is the configuration in which the DR is going to be stowed in its bay on the EM.

6.3 Capture Envelope





6.4 Load Calculations

Loads on the GA/DR fixture during extreme cases

Stopping 1000lb	w/ FOS		**Equivalent Load on fixt**		
Linear Force case:	99.3			w/ FOS	
Distance from force to centre of fixture			Force	99.3	N
			Torque	**288.0**	**Nm**
Torque case:	37.8				
Distance from torque centre to centre fixture			Force	125.9	N
			Torque	37.8	Nm
Applying a 50-ftlb Torque					
Torque	67.8		Force	**226.0**	**N**
Distance from torque centre to centre fixture			Torque	67.8	Nm

6.5 Cable Mass Calculations

32 wire bundle through the GA

density Cu 8960 kg/m^3

	Wires										
	# of wires			**current required at interface**	**circuit length (m)**	**wire gage**	**wire current**	**bundle current**	**wire diameter (mm)**	**bundle diameter (mm)**	**bundle mass (kg)**
	there	**return**	**total**								
high power	5	5	10	1.92							
low power	4	4	8	0.87							
data 1553	2	2	4								
video	2	2	4								
data RS 232	2	2	4								
data RS 422	1	1	2								
			32	1.92	10	22	4.5	2.25	0.64262	7.9	0.93

	Shielding		
	thickness (m)	**surface area (m^2)**	**mass (kg)**
high power			
low power			
data 1553			
video			
data RS 232			
data RS 422			
	0.000254	0.2	0.56

Connectors		
number of connectors	**mass per connector (kg)**	**mass (kg)**
2	0.1	0.2

Total mass 1.69 kg ** for one 32 wire bundle

Total mass of cables through GA
3.39 kg

6.6 Electrical Interface Requirements

6.6.1 Power Interface

	Number needed for requirement
ARM 1 TCS 115V Primary	2 (includes return line)
ARM 1 TCS 115V Backup	2 (includes return line)
ARM 1 115V Primary	2 (includes return line)
ARM 1 115V Backup	2 (includes return line)
ARM 1 24V Primary 1	2 (includes return line)
ARM 1 24V Backup1	2 (includes return line)
ARM 1 24V Primary 2	2 (includes return line)
ARM 1 24V Backup2	2 (includes return line)
LCS 24V Primary	2 (includes return line)
ARM 2 TCS 115V Primary	2 (includes return line)
ARM 2 TCS 115V Backup	2 (includes return line)
ARM 2 115V Primary	2 (includes return line)
ARM 2 115V Backup	2 (includes return line)
ARM 2 24V Primary 1	2 (includes return line)
ARM 2 24V Backup1	2 (includes return line)
ARM 2 24V Primary 2	2 (includes return line)
ARM 2 24V Backup2	2 (includes return line)
LCS 24V Backup	2 (includes return line)

Connection Interface Power Requirements

Power line	**Number of connectors for power line**
Low Power 115 V	16
High Power 24 V	20
Total	**36**

The power lines will need 18 pins for primary power system and another 18 pins for a completely redundant back up power system.

6.6.2 Data Interface

	Number needed for requirement
ARM 1 1553 Primary	2 (includes return line)
ARM 1 1553 Backup	2 (includes return line)
ARM 1 Video Primary	2 (includes return line)
ARM 1 Video Backup	2 (includes return line)
ARM 1 Sensors RS232 Primary	2 (includes return line)
ARM 1 Sensors RS232 Backup	2 (includes return line)
RS 422 (LCS) Primary	2 (includes return line)
ARM 2 1553 Primary	2 (includes return line)
ARM 2 1553 Backup	2 (includes return line)
ARM 2 Video Primary	2 (includes return line)
ARM 2 Video Backup	2 (includes return line)
ARM 2 Sensors RS232 Primary	2 (includes return line)

ARM 2 Sensors RS232 Backup	2 (includes return line)
RS 422 (LCS) Backup	2 (includes return line)

Connector Interface Data Requirements

Data Line	Number of connectors for data line
1553 Data Bus	8
Video Line	8
Sensors RS232	8
LCS RS422	4
Total	**28**

The data lines will need 14 pins for the primary data line and another 14 pins for a completely redundant back up data line system.

Appendix 11 Class Photo

University of Toronto Spacecraft Design Class (AER 407), Fall 2004