Space Jockey

A Mobile Robot Platform for Spacecraft Exterior Inspection & Maintenance

Conceptual Design Review - Team B
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1. Introduction

Figure 1. Spacecraft launch

The process of space launch and travel is a taxing process for both man and machines. Wear and tear incurred by spacecraft during launch and orbital operations can greatly increase costs by decreasing reliability and reusability. In some cases, even reasonable wear and tear can lead to loss of life if undetected and unrepaired, as evidenced by the Space Shuttle Columbia Disaster in 2003.

Thus, there is a definite need for spacecraft inspection and repair operations in orbit. The best current solution to this problem is met by astronauts performing Extra-Vehicular Activities (EVAs) to perform manual inspections. This solution adds danger to the mission, consumes valuable in-flight resources like power and fuel, and is time-consuming and expensive to operate.

We propose building a small, portable robotic platform capable of traversing the exterior of spacecraft in orbit, and scanning for visual or thermal abnormalities on the hull. This could provide a less expensive and safer option for mission planners.

2. User Needs

The Space Jockey mobile robot is intended for use by organizations owning and maintaining spacecrafts that require may require occasional or regular inspection and maintenance. In particular, the robot shall be used as a safer and more cost-effective solution to hull maintenance than astronaut EVA. In this way, the intended users of such a robot would be astronauts or Earth-based technicians who might otherwise commission an EVA mission to accomplish spacecraft maintenance tasks.

To supplement or supplant entirely the need for astronaut EVA, the robot must be able to:

- Secure itself to a spacecraft hull using a mechanism that functions without the aid of gravity or atmospheric pressure.
- Traverse the hull in such manner that a large proportion of its surface area is reachable.
- Maintain an awareness of its environment, and to avoid collisions with obstacles that could damage either the robot or the craft itself.
- Visually survey the craft for the purposes of inspection either by the robot or a human operator
- Operate tools and manipulate its environment in order to perform repairs or otherwise alter the craft.
- Reliably function for a useful period of time.
- Communicate with astronauts or operators aboard the craft or on Earth.

- Operate in spite of harsh environmental factors including vacuum conditions, intense radiation, and large temperature ranges.

3. Use Case

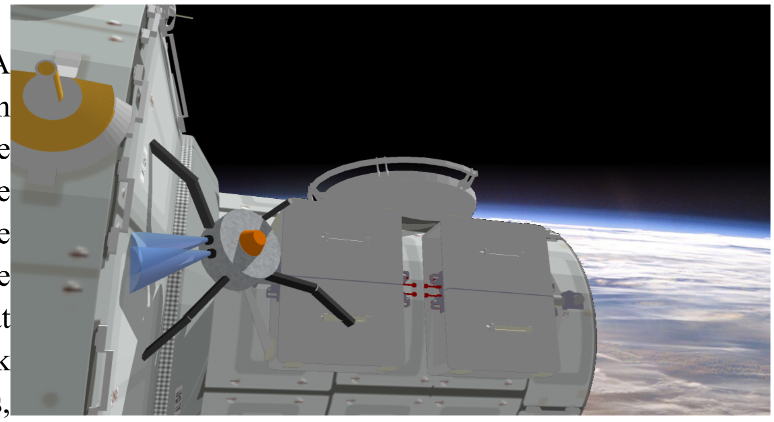


Figure 2. Robot on spacecraft hull

On May 30th, 2018 NASA Mission control registered an atmosphere level warning from the Quest Airlock Module onboard the US side of the International Space Station. Initial assessment of the atmosphere losses indicated that there may be a fault with the airlock control and recycling mechanisms, but additional diagnostics revealed no fault with the equipment. Research into the NASA archives indicated that a communication satellite collision had taken place on a similar inclination in 1978, and it was hypothesized that the ISS may be orbiting in close proximity to the fringes of the debris field resulting from that collision. This evidence led mission controllers to believe that the module may have suffered an impact event with an untraceable 2-3cm piece of debris. The module was immediately sealed to protect the crew's safety.

Mission control began immediately discussing repair options for the module, due to the elevated risk of orbital debris, EVAs to the location would pose a larger danger to crew safety. In addition, the Canadarm2, often used for transporting tools and astronauts during EVAs, was incapable of being retrofit with the necessary inspection and repair equipment from inside the station. It was decided to deploy the newly acquired Space Jockey robot out of the smaller experiment airlock onboard the Japanese Experiment Module "Kibo", quite near the desired inspection site.

Mission Cmdr. Jebediah Kerman and his twin brother Bob were immediately tasked to unpack the robot from its storage module, and fitted it with a temporary hull sealing device (which used expanding foam to fill the voids between layers of the hull shielding and create a temporary seal). The roughly ½ meter cubed unit was then prepped, powered up and tested, before being deployed through the undersized experiment airlock aboard Kibo. A path was planned for Space Jockey by the station's onboard computer and wirelessly transmitted to the robot's computer, enabling it to navigate to the Quest Airlock Module.

After about two hours of teleoperated inspection tasks, the operating crew identified a small impactor had indeed punctured the prograde side of the airlock module, adjacent to the crew lock. Visual inspection revealed that a 3-inch hole had been torn through the hull's outer shielding plates, and thermal imaging revealed that a hairline fracture had punctured the inner pressure vessel leading to the loss of atmosphere from that module. The Space jockey robot deployed sealing foam to the area as a temporary measure, restoring the module to provisional operating status. A return path was transmitted to the robot, allowing it to return to Kibo's experimental airlock for retrieval and storage by the crew members.

After the robot's intervention, the crew was able to apply hull sealant to the interior of the pressure vessel, permanently sealing the leak. To complete repairs, replacement shielding plates for the module were included in the next station service mission, and an EVA scheduled for external repairs to mitigate future impact dangers in the area. The use of the space jockey robot provided a critical first step in the repair process, and allowed the station to be fully repaired with a minimum level of danger to the crew.

4. System-Level Requirements

Requirements for the Space Jockey system are listed in the following sections per-subsystem: Robot and Command Center.

4.1. Robot

The robot will have to be operated wirelessly through command center. The requirements for the robot will be divided into 3 parts: Mobility, Peripheral, Manipulation

4.1.1.Mobility

ATTACH	Attachment Mechanism
Description	The robot shall be able to attach to the spacecraft hull using a mechanism that works without gravity or atmospheric pressure.
Priority	High
TPM	Maintain a stable attachment to the test surface regardless of the surface's orientation (upright, vertical, upside-down)
Units	--
Rationale	The robot must remain attached to the spacecraft in order to perform inspection and maintenance and not float away into space.

BATT	Battery Life
Description	The robot shall have a battery life sufficient to accomplish its desired function, without frequent interruption for recharging.
Priority	Medium
TPM	At least 45 minutes of battery life doing repairing tasks

Units	minutes
Rationale	Operators need the robot to be operable for a long enough time to complete its tasks quickly and reliably.

TRAV	Traversal
Description	The robot shall be able to traverse the surface it's attached to at a pace suitable to completing tasks in a reasonable period of time.
Priority	High
TPM	At least 10 times of the size of the robot's body within one hour.
Units	Meters
Rationale	To be maximally useful, the robot should be able to access as large an area as possible of the craft, and move from any location to any other in a reasonable period of time.

MOBILE	Mobility on the hull surface
Description	The robot shall be capable full planar mobility on the craft, capable of moving forward, backward, and rotating along the axis normal to the surface.
Priority	High
TPM	Has 3 degrees of freedom
Units	DOF
Rationale	Maximum mobility improves both the robots total task space on the surface, as well as its ability to reach a desired location quickly and efficiently.

4.1.2. Peripherals

CAM	Stereo Camera Vision
Description	The robot's capacity to take in visual information using two stereo cameras mounted to the chassis.
Priority	High
TPM	The cameras shall capture at least a 45^{o} field of view
Units	Degrees
Rationale	A wide field of vision assists the robot's capacity to localize, identify obstacles and (potentially) foothold, and to provide the human operator with useful information on which to base directives.

TEMP	Thermal Imaging Sensor
Description	The robot shall employ thermal imaging to further identify abnormal conditions of the hull
Priority	Low
TPM	Accurate sensing of thermal variation within 1^{o} Celsius
Units	Degrees Celsius
Rationale	Some potential hull defects, such as electrical problems or gas leakage may have accompanying thermal phenomenon not captured by a standard vision camera.

FOOT	Foothold Detection
Description	The robot should be able to visually identify and keep track of footholds in its vicinity.
Priority	Conditional on Attachment Method
TPM	Accurate sensing of foothold
Units	--
Rationale	Should the robot depend on them for attachment, knowledge of footholds is essential to planning a traversal path. Additionally, such knowledge may also aid global localization by anchoring the kinematic model to known locations on the hull.

4.1.3.Manipulation

ARM	Manipulator Arm
Description	Use of one or more legs as a manipulator in addition to their locomotive function.
Priority	Medium
TPM	Given a fixed support-leg positioning, the end effector of a leg can act on an area on the hull surface at least 0.2 square meters in dimension.
Units	Square Meters
Rationale	To quickly perform a task on the craft surface, the robot's manipulator should be capable of acting upon a reasonably large area without repositioning its supporting legs.

TOOL	Screw driving tool
Description	The robot shall be capable of precisely driving the screw
Priority	Low
TPM	Locate the tip of a screw, drive it using a rotary screwdriver, and disengage when the screw is

	sufficiently tightened, all within 10 minutes.
Units	Minutes
Rationale	Screwdriving is a common rotary tool use, useful for demonstrating the general capability of rotary tool use.

4.2. Command Center (CC)

Operators will operate the robot manually and wirelessly from this command center.

4.2.1. Communication

BAUD	Wireless Communication Speed
Description	The command center shall be able to communicate to the robot wirelessly in a sufficient bandwidth
Priority	Medium
TPM	At least the robot shall be able to communicate in 50 kbps speed
Units	Kbps
Rationale	Wireless communication obviates the need for a data tether, which may tangle or otherwise interfere with the robot's operation.

DELAY	Communication without noticeable delay
Description	CC shall communicate with the robot without noticeable delay
Priority	High
TPM	Max latency less than or equal to 5s
Units	seconds
Rationale	Swift communication makes teleoperation more responsive for human operators and speeds up task completion.

RANGE	Operable range
Description	Command Center shall be able to maintain a wireless link with the root to a sufficient distance.
Priority	Low
TPM	Reliable communication with the robot within a distance of 50 meters.
Units	Meters
Rationale	The operable range of the robot must be large enough to ensure operators do not lose contact mid-mission, and maximize the area of the spacecraft accessible for the robot.

VIDEO	Video streaming from the robot
Description	Command Center shall stream video feeds from the robot at a sufficiently high frame rate.
Priority	High
TPM	Video streaming at least 5 frames per second
Units	Hertz
Rationale	Stable, reactive video feed will provide the human operators with responsive feedback as they direct the robot.

4.2.2. Control

LOCAL	Localization
Description	Localization of the robot's position and configuration.
Priority	High
TPM	The location of the robot's center of mass can be tracked within 10 cm and joint angles known within 0.1 degrees.
Units	Centimeters and Degrees
Rationale	Localization is crucial both for the human operator's knowledge of the situation as well as the path planner's capacity to generate useful joint trajectories.

PATH	Path planning
Description	Build a path planning for the robot to move to certain position
Priority	High
TPM	An executable path between any two locations in the task space, spaced 10 or fewer meters apart, can be generated accurately within 5 minutes
Units	Minutes
Rationale	Path planning is crucial for the robot so that the robot knows its most efficient path to achieve certain position

5. Trade Studies

5.1 Mobility Study

The chief challenge to be tackled in our robot design is the question of mobility. Providing a reliable, stable platform for tooling and inspection equipment in a zero gravity and hard vacuum is a difficult problem. Many approaches to this have been explored in the past by the space industry, and recent advances in dry adhesive technology have opened up new possibilities.

5.2 Mobility Design Options

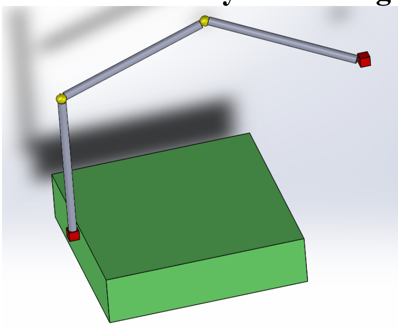


Figure 3. Dextrous Arm

Dextrous arm with external spacecraft attachment hardpoints

This option is very similar to the currently deployed Canadarm 2[1] onboard the ISS. A large remote manipulator is fitted to the exterior of the craft and may "walk" from point to point along the outside of the craft.

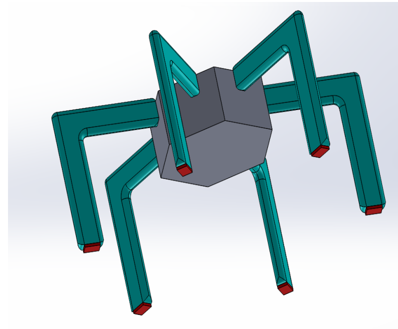


Figure 4. Multilegged robot with adhesive feet

Multi-legged robot with adhesive feet

The option is similar to the AWIMR[2] project and relies on new advancements in conformant materials/dry-adhesives to connect to the spacecraft exterior.

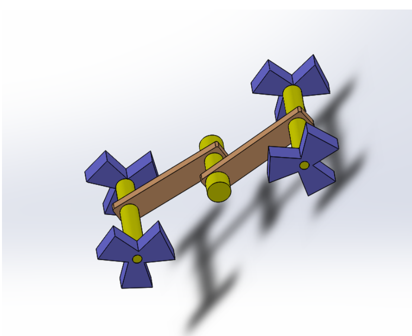


Figure 5. wheeled robot with adhesive pads

Wheeled robot with adhesive pads

This is similar in form to the Waalbot, developed here at CMU[3], this mobility option uses wheels as the basis for mobility. The wheels themselves would be composed of discrete pads of dry-adhesive material to adhere to the surface, and would employ a passive mechanism to "peel" pads away from the surface as it travelled.

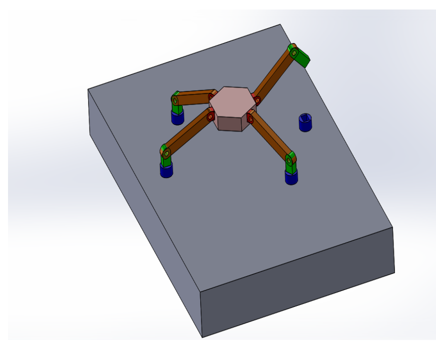
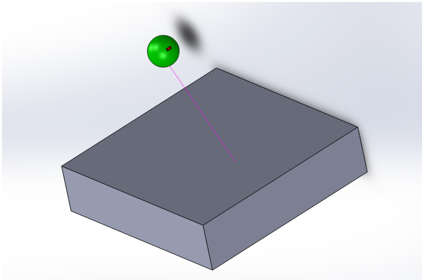
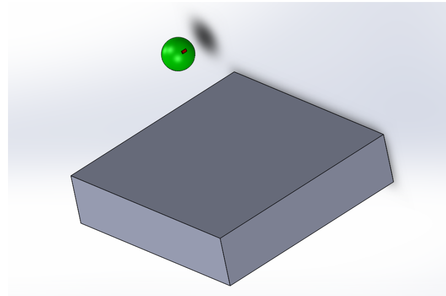


Figure 6. multi legged robot with atachment hardpoints

Multi-legged robot with attachment hardpoints.

Combining elements of the first and second options, this robot would navigate the hull surface using external hardpoints to anchor itself. This approach has much in common with the discontinued LemurIIb[4] design developed by the JPL in 2006.

 **Figure 7. Tethered robot** **Tethered Robot** A robot is attached to the craft using a tether and surveys the craft from a distance, being held at a distance by centripetal forces with the possibility of retracting/extending the tether and "wrapping" around the craft to get close enough to perform maintenance. Some research has been done into tethered Satellite deployment[5]. This approach would leverage that work for inspection applications.	 **Figure 8. Free flying robot** **Free Flying Robot** A robot flies at a distance from the craft, achieving attitude control and translation using a reaction control thruster system. Visual inspection would be performed at a distance, and the craft would have to translate itself to the hull in order to perform any kind of maintenance. Prior investigation into this type of vehicle has been performed by NASA's JSC in their aerCAM project[6].

5.3 Selection Criteria

Table 1. Selection Criteria

Criteria	Weight	Description
Mobility	**20%**	This metric tracks the relative speed and ease with which each design option is able to reach its inspection goals.
Fuel / Power requirements	**5%**	Keeping the overall robot as light and as simple as possible is a virtue in the design of space systems. Large batteries and other consumables add complexity and weight, and limiting deployment duration and reliability of the robot.
Safety systems / Fallback	**10%**	This metric evaluates the relative danger of the robot damaging the spacecraft or being lost in case of a control failure.
Infrastructure Requirements	**10%**	Requirements for handholds, power stations, tethers, or other devices to be affixed to the spacecraft hull increases the cost of deployment of our system.
Platform stability	**10%**	As one of our desired tasks for our robot long term is tool usage, the ability of the robot to provide a rigid platform for manipulation tasks is weighed in this metric. This is also used to track the relative reliability of the craft attachment mechanism.
Complexity	**15%**	As we are limited in time and scope for this project, the relative complexity of the design task must be weighed to guarantee

		feasibility within the time constraints.
Testing Feasibility	**20%**	Since we do not have access to a zero-g testing facility, the relative ease of earthbound verification testing of our system is evaluated by this metric.
Proven Technology	**10%**	This metric weighs the reliance of each design on untested or not readily available technology. Reliance on difficult to acquire parts or pieces could jeopardize the success of the project.

5.4 Study Scoring Matrix

Table 2. Study Scoring matrix

Dextrous Arm	Legged Hardpoint	Legged Adhesive feet	Wheeled Adhesive Pads	Free Floating	Tethered	Criteria	Weight
6	6	9	7	10	3	Mobility	20%
10	8	6	7	3	10	Power	5%
8	8	6	6	3	1	Safety	10%
4	2	8	8	10	4	Infra-structure	10%
8	10	8	6	0	0	Stability	10%
7	7	8	10	1	3	Complexity	15%
8	10	10	10	1	1	Test Feasibility	20%
10	10	3	3	8	5	Proven Technology	10%
7.35	7.65	7.8	7.55	4.6	2.75	Totals	100%

5.5 Results

Based on the results of our trade study, we have chosen to pursue the legged design with adhesive feet. However, a key issue that is alluded to in the "Proven Technology" criterion is that we are unsure at this time of just how applicable dry-adhesive surfaces will be to common spacecraft surface materials. In the event that they're found unfeasible, either because of cost, availability, poor adhesion, or a high potential of damage, our fallback strategy is to use the legged design with hardpoints. This will allow us to complete the project with only a minor redesign of the foot mechanisms, and an added hardpoint component necessary.

6. System Architecture

6.1 Functional Architecture *(See Diagram on following page)*

Main functions of Space Jockey are partitioned into two parts: Robot(1,2,3, 14,15,16,17) and Command Center(4-13) .

The robot captures the images and sensor data from the camera (1) and the sensors (2) and then transfer this data through the wireless communication (3). Command Center receives that then processes it (4,6) and also display the images to user (5). From the thermal data and images from camera, Command center detects if there is any visual and thermal flaws on the hull (7), and notifies the user if there is any (8). Command Center also updates the internal hull map (9) and track its position based on the foothold(8).

If the user gives command to go to certain position or to do repair tasks, command center receives that input command (11) and then processes the path planning based on the map generated and the robot's current position(12). After the path is generated, command center sends the data through wireless communication to the robot (13). This data will drive the motors either for movement (14&16) or for driving the rotary tools (15). The result of the repairing tasks or movement will be sensed again and the whole processes are repeated until the mission is completed.

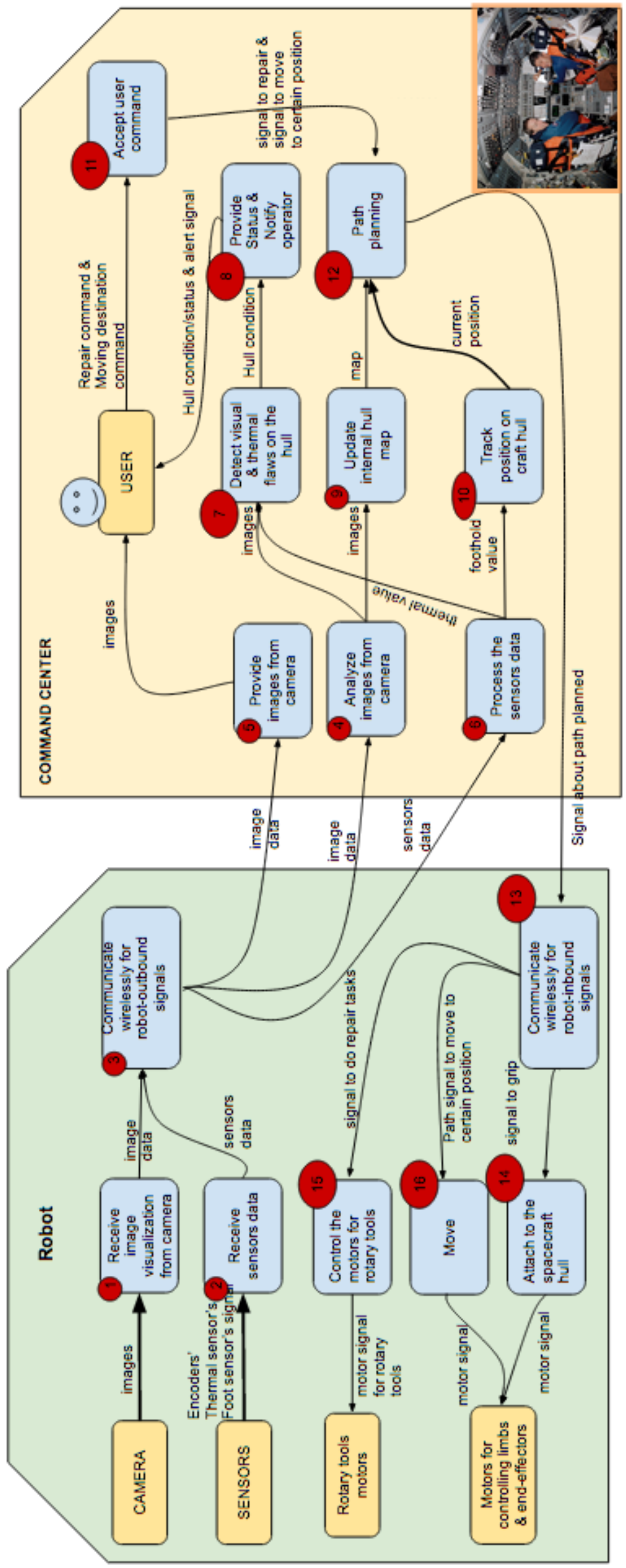


Figure 9. Functional Architecture

6.2 Physical Architecture

The Space Jockey consists of two main systems: Command Center and Robot. Each system is connected using 2.4GHz connection. The robot will have Arduino Due board to control motors via motor controller and gathering data from camera and sensors using its IO pins. This board will communicate through wireless serial communication the command center. A PC (Linux/windows based) will be used as the command center to process the sensor data, build path planning and receive input from the users using keyboard / joystick.

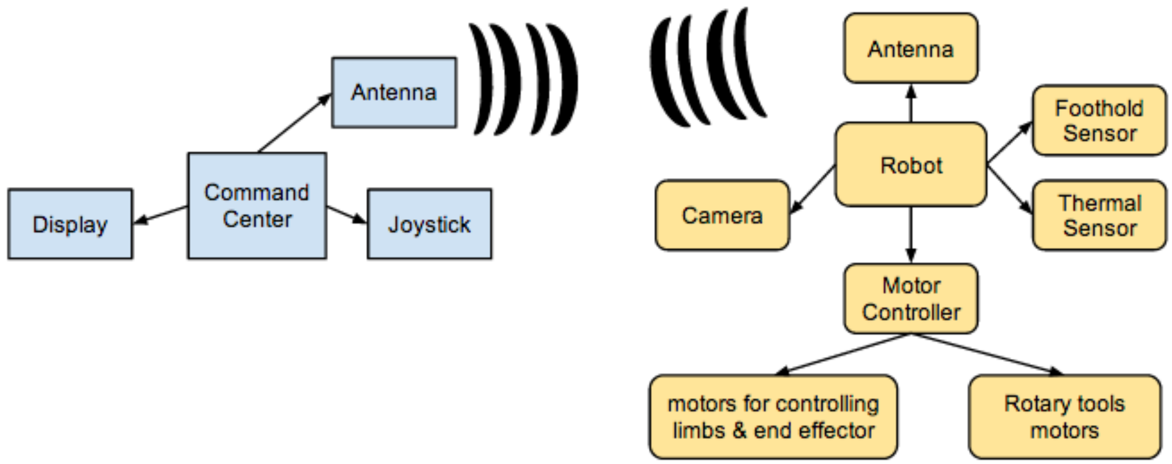


Figure 10. Physical Architecture

7. Major Subsystems

7.1 Sensing

The Sensing subsystem includes cameras and any other sensors used to gather raw data about the robot and its surroundings. The highest bandwidth component will be the vision data gathered from the stereo camera set. Other sensors will include joint encoders, internal heat monitors, voltage monitors, and potentially force-feedback and a thermal imaging peripheral if rotary tool use and thermal sensing fall within time and cost constraints.

7.2 Perception

The Perception subsystem synthesizes raw sensor data and from them derives information useful for populating models of the robot and its environment. Key processes here will include the fusion of data from cameras and any range-finding sensors to detect obstacles and characterize the terrain ahead of the robot. Additionally, encoder feedback from joints will be used to update the kinematic model of the robot used in its control subsystem. If these are insufficient, it may be necessary to source information from visual processing to further refine knowledge of the robot's configuration.

7.3 Mechanical

The Mechanical subsystem comprises the physical form of the robot and its mechanisms that enable mobility and manipulation. The robot will consist of a central chassis with legs extending outward in radial symmetry. Each leg will have four degrees of freedom: 2 at the shoulder, 1 at the elbow, and 1 at the wrist. An additional motor may be used in one or more legs should the time and cost budget accommodate the development of rotary tool operation. The alternative space in this subsystem primarily concerns the choice of degrees of freedom in the leg joints (e.g. whether the elbow and wrist joints will provide pitch or yaw variation). For the feet of the legs, our first choice is dry-adhesive padding, with hardpoint-grasping as a fallback.

7.4 User Interface

The User Interface subsystem comprises the graphical user interface and underlying software that enable a human operator to visualize and interpret information coming from the robot, as well as direct the robot to navigate within and manipulate its environment. This will run on the command center console and provide the human operator with a video feed, a simulated state of the robot based on joint encoder feedback, some representation of the robot's immediate environment, and information on any pending directives or path-executions-in-progress.

7.5 Planning & Control

The Planning and Control subsystem is responsible for simulating and planning the operations of the robot in response to its environment as well as directives provided by the human operator. This software subsystem will maintain a map of the robot's surroundings, and a kinematic representation of its statement. Using this information, it will compute paths for the robot to follow and in turn generate joint trajectories to be sent to the robot's onboard computing facilities for execution.

8. System Validation Experiments

System validation experiments will be demonstrated in December and May to show requirements have been met. December demos will focus on proving subsystems, while May will demonstrate the finished system operating fulfilling our described system objectives.

8.1 Fall Semester 2013

We will have finished our first original prototype at the end of this fall semester. The prototype will demonstrate mechanical stability, functioning electrical subsystems, an operational user interface, and basic control features. The planned validation tests are as follows:

1. **User Interface**: The user interface will be comprised of a GUI linked with the robot. It will demonstrate live video feed from the robot, a kinematic model informed by the joint motor encoders, and other basic information about the system such as temperature and electrical systems status.
2. **Sensing**: Evidenced through the user interface, all sensors will be operational and in (wired) communication with the command center console and show live feedback. Accuracy of sensors such as joint encoders and temperature sensors will be corroborated by external measurement.
3. **Perception**: The command center will be shown, through the user interface, to be maintaining a basic kinematic model of the robot based on joint encoder feedback that is accurate on a joint-by-joint basis within 1 degree.
4. **Mechanical:** The robot will be shown to be in a mechanically stable condition even while in motion, and able to support its own weight while standing and walking. Additionally, it will demonstrate stable attachment to surfaces in upright, vertical, and upside-down orientations.
5. **Control:** The robot will demonstrate basic control features by assuming resting and standing positions with three and four legs grounded. At least one stand quadrupedal gait will be demonstrated in four cardinal directions.

8.2 Spring Semester 2014

At the end of spring semester, we will have a surface crawling prototype robot. It will be tested by traversing, the underside of a suspended spacecraft surface analogue (Ceiling or Duct Pipe) while sending video and sensor feedback to a human operator. The robot's destinations will be directed by operator, and the command console will generate paths for the robot, which it will then transmit to the robot for execution. The total distance travelled will be equal or greater to 10 times the robot's length with legs fully extended. Additional subsystem tests will be performed as necessary to demonstrate the meeting of all HIGH-priority system-level requirements described in Section 4. If within the final scope of the project, we will also demonstrate use of a rotary tool and/or thermal imaging.

9 Work Breakdown Structure

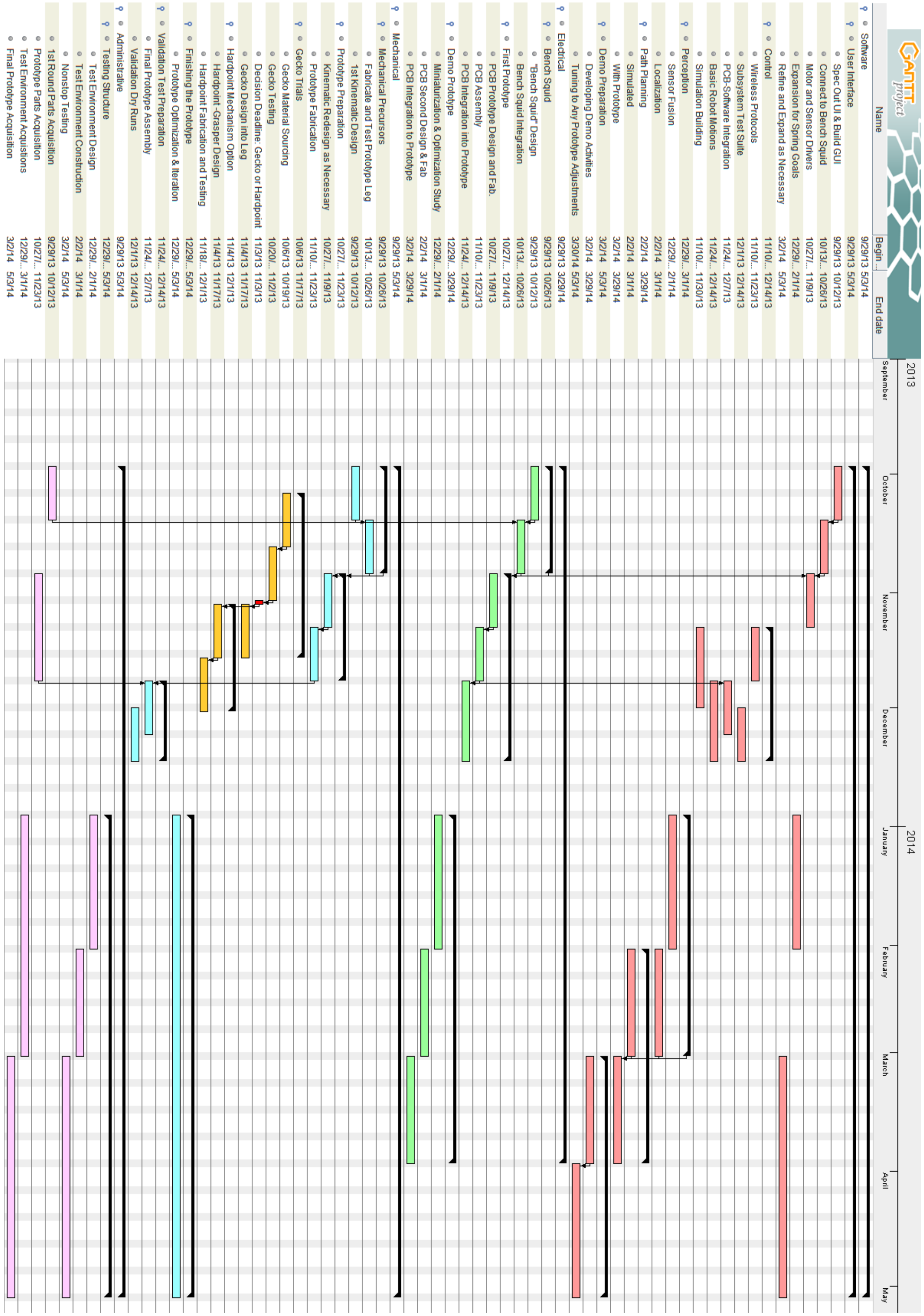


Figure 11. Work breakdown structure

10 Preliminary Parts Budget

Part	Price	Qty	Total Cost
Microcontrollers	$100	2	$200
Radio Modules	$100	2	$200
Servo Motors	$40	20	$800
Motor Controllers	$20	2	$40
I.M.U	$150	1	$150
Batteries	$40	2	$80
Camera	$200	2	$400
Metal Material	$30	2	$60
Acrylic	$20	3	$60
Testing Equipment	$200	N/A	$200
Misc. Hardware	$1000	N/A	$1000
Total			$2990

11 Team Responsibilities

Responsibilities have been divided into four domains, which each team member assuming one primary and one supporting role. Software responsibilities will be roughly divided according to which will be concentrated on the robotic platform (Control) and the user-operated computer (U.I./Simulation). Primary roles correspond to the background disciplines of each teammate. Secondary roles have been assigned according to a combination of interest and capability.

Domain	Mechanical	Electronics	Controls	UI/Simulation
Primary	Songjie	Dipta	Nathaniel	Brian
Secondary	Nathaniel	Songjie	Brian	Dipta

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