DELHI TECHNOLOGICAL UNIVERSITY

NEW DELHI, INDIA

TEAM DELTECH LUNAR EXCAVATORS
Presents
SYSTEM ENGINEERING PAPER
"HANDBOOK OF DLE AARAVYA"

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As the faculty advisors, we would like to express our support to the Lunabotics Mining Project led by Shubham Verma, a final year undergraduate student of Delhi Technological University, India. The team has been religiously working for the last one year on the Research and Development of a Telerobotic Lunar Excavator and is vehement on participating in NASA's fourth annual Lunabotics Mining competition slated to be held from May 20-24, 2013. We have been associated with the team in solving their technical problems and guiding them through this venture to fore claim their vision.

The complete Lunabot has been built under our supervision and the complete System Engineering process design has been verified by us. We are very hopeful about this project and expect the team to do well in the competition.

The project "Aaravya" adds to the legacy of Research and Development that Delhi Technological University (formerly Delhi College of Engineering), India has pioneered over the last seven decades. We are grateful to NASA for providing such opportunity to our student community which will enhance their interest in R & D. We support the team's initiative and wish them all the best.

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Abbreviations

STEM : Science technology engineering math
SOFT : Survival of fittest (trade of tables)
OSIEC :open source integrated electronics circuit
COTS :commercial off the self
POS : project/process objective statement

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1. AGENDA

DelTech Lunar Excavators used the mantra of abstract analysis and practical experimentation to decipher each and every aspect of Aaravya, the Lunabot.

The first step was to understand the competition, its rules and regulations and what NASA is looking in a Lunabot. The team then studied about robotics, particularly excavators and analysed the past participants of the competition to get a fair idea of what the demands of the competition are and made a schedule of work to assign specific tasks for each month and planning was done until the beginning of the competition at Florida in May, 2013.

The team decided to tackle each aspect of the Lunabot independently one at a time. As a result, the Lunabot was divided into 3 main sub-systems as shown in figure 1:

- Excavation
- Chassis and Locomotion
- Dumping

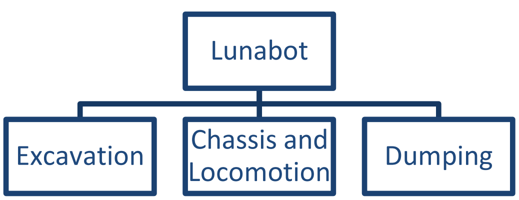


Fig 1: Sub systems of Lunabot

The above systems were further subdivided into Mechanical and Electrical systems to achieve division of labour and efficiency. Understanding the fact that space missions like excavation on the Moon involves lot of funds putting the constraints on payload and energy requirements. It was decided that the aim of the team would be to reduce weight, use economical materials without compromise on quality and use least amount of energy. With the above objectives in mind, the team set out to build a Lunar Excavator that could achieve all the objectives and give fresh new perspectives by enthusiastic undergraduates to a reputed organisation like NASA. Every parameter of the Lunabot along with its interaction with the environment was tested by rigorous experimentation. The results were inferred and used to design our Lunabot.

All possible designs were tested and then these were ranked on various grounds. Weighted point method was used to select the best design which optimizes between simplicity, cost, efficiency and weight. After selection of the final design, the system engineering process laid emphasis on designing each component carefully. Various models were studied to finalise the components of the Lunabot and their interaction with the environment.

The competition is of great importance to not only us but technological manpower all over the world. The team used this platform to promote STEM (Science, technology, Engineering and Mathematics) among young students and undergraduates. The team realised its shared dream of being able to solve real world problems as engineers. The world needs, man to use ,its technological prowess to make the world a better place. Mining resources on the Moon and other celestial bodies will also be very important in the future as the resources on Earth keep on depreciating.

Thus having all these parameters in mind, the team embarked on a mission to showcase its bravura and build an excavator that could, in future, be capable of actually mining regolith on the moon.

2. Project Overview

NASA's “Lunabotics Mining Competition” is an international competition for the University students pursuing a course in the field of science and technology, designed to engage and retain students in science, technology, engineering and mathematics (STEM) and promote a high level of interest in space related activities. In the process of doing so, NASA which has pioneered in space exploration will benefit by possibly finding new concepts and solutions to the difficulties presented by different teams for excavating regolith, which could later be applied in actual lunar missions and can also help in setting up a human base on moon for collecting regolith which can be processed to obtain vital substances such as water and oxygen; therefore, machinery that mines and transports regolith is likely to be an important component of future moon missions.

The various parts of the competition and rules & regulations are:

1. Onsite mining which seeks the young enthusiasts to design and build a wirelessly/autonomously governed robot that can traverse an obstacle area, collect regolith simulant in the mining area, then travel back across the obstacle area and deposit the mined material in a collection bin.
2. Other categories of the competition include team spirit ,outreach project, system engineering paper and slide presentation.

3 System Engineering

3.1 Project Objective Statement

To develop an innovative yet simple and robust Lunabot design adhering to the rules of competition , OSIECs and commercially off the self-parts within budget constraints by workforce of four students in eight months .

3.2 Design Process

3.2.1 Development Life Cycle (DLC)

The Lunabot's design analysis started with the very idea of keeping the level of project adherent with industrial projects which urged the team to complete its objectives using an industrial software model, so that the team can have future insight and track of the project .After requisite research and studying different models i.e V model , Prototype model , Spiral model the team chose the simple waterfall model with main focus on the maintenance and testing as the lunabot's product definition was stable and also the team had no ambiguity about the final design and requirements .

It is a linear sequential life cycle model and in this DLC model each phase is completed before start of next phase ,with identifiable deliveries to the next phase. At the end of each phase, a review takes place to determine if the project is on the right path or not.

This model helped the team in structuring a proper plan as the members used to have team meetings and team review after each phase so errors and future problems were minimized to the extent that the members came across only a few problems in our design's implementation and integration. The team assumed that a detailed documentation from the design phase can significantly reduce the implementation effort. The team was emphatic towards testing, so even before integration phase; testing was started on different modules separately. A detailed diagram, in fig 2, 2
how the process unfolded.

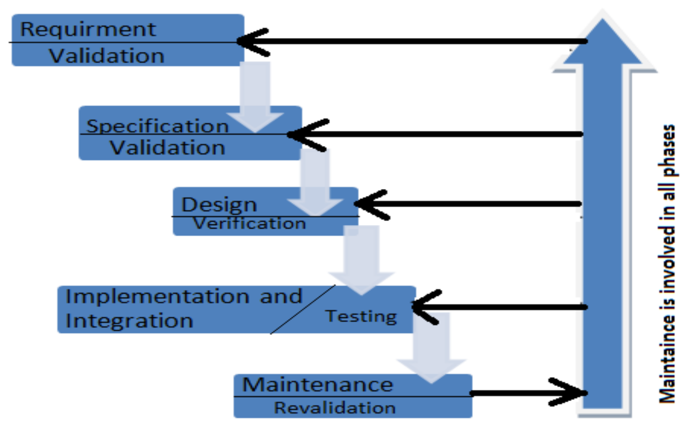


Fig 2. Semantics of Waterfall Model

3.3 Constraints

As given in the NASA's rulebook for the competition the team must adhere to following rules and constraints:

1. Dimension of lunabot: 1.5m X 0.75m X 0.75m, with height must not be more than 0.75 and base and length are interchangeable as per convenience .
2. Weight of Lunabot: it must not exceed 80kg, exclusive of communication part not attached to lunabot and control room part of system.
3. Time limit: 10 minutes for operation and 5 minutes for removal of hardware from lunapit.
4. Emergency Red Button: It must be present to stop all functioning of lunabot at once.
5. Bandwidth: average 5Mbps may be used for all purposes.
6. Wireless: Network communication should abide by 802.11b/g IEEE protocol.

The team tried its best to abide by these rules.

3.4 Deliverables

In order to achieve the Project objective statement, the deliverables are:

1. Fully functional lunabot adherent with competition rules and constraints.
2. Robust and simple design within budget constraints.
3. System engineering paper structured on guidelines provided by NASA's rulebook.
4. A Slide presentation showing the various parameters stated in the rulebook.
5. An Outreach project document showing the team's endeavor to disseminate the ideas of STEM .
6. A Video showing at least one complete cycle of operation.

3.5 Requirement Analysis

3.5.1Functional requirements

1. The lunabot shall be operational for 20 minutes continuously.
2. The lunabot shall excavate the BP-1 (Regolith simulant)
3. The lunabot shall dump the BP-1 into hopper which is at height of 0.75 from ground.
4. The lunabot shall operate from the control room with complete visual and auditory isolation.
5. The lunabot shall navigate through the craters and boiler placed in the obstacle zone.
6. The lunabot shall not throw dust while in operation.
7. The lunabot shall not use any component, technology or process that wouldn't work on lunar surface or that is dependent on gravity .
8. The lunabot shall be self-powered.

3.5.2 Non Functional requirements

Reliability requirement

1. It shall work for 20minutes continuously with battery
2. It shall have proper housing for the circuitry to avoid dust.

Efficiency requirement

1. It shall excavate at least 10 kg of regolith in 10 minutes.
2. It shall use average 5Mbps while in operation.
3. It shall maneuver lunapit obstacle zone without getting toppled or falling in the crater.

Safety requirements

1. The lunabot shall have emergency red button to halt all operation and 5cm in diameter.
2. The robot shall not use any explosives or dangerous part

3.6 Configuration management (CM)

Configuration Management is an integral part of today's industry system engineering process and is used for establishing and maintaining consistency of a product's performance, functional and physical attributes with its requirements, design and operational information throughout its life for the lunabot project. Massive file work and documentation in initial phase of the project lead the team to rethink the strategy and to create proper system and indexing for better and efficient use of resources and parts of repository at the team's disposal. Firstly for documentation and paper work the team created google group with mailing list and separate thread for each subsystem and scheduled deadlines. Proper documentation was created regarding indexes, naming files, managing parts and repository of components.

4. BUDGET

The varied parameter of the lunabot design that was considered exhaustibly for better scheduling of budget:

i. Open Source Integrated Electronic Circuits (OSIECs)

ii. Motors, sharing the largest part of the budget, were used motors

iii. Worm gear were designed on milling machine

iv. Cheapest alloy of Aluminium was considered.

Estimated Budget	4545$
Actual Investment	1540$

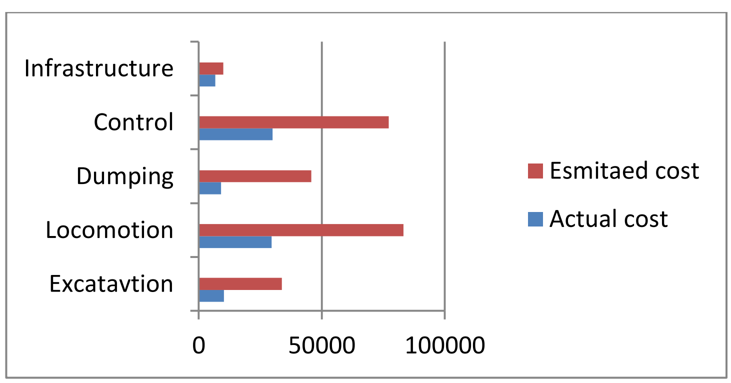


Fig 4: Budget comparator

The detailed budget is provided in Appendix 2

5. Project Planning

In its advent of following the sequential mode(waterfall model) , the team created a detailed and tentative work plan from start to finish .The team tried their best to stick to the work plan and was successful in meeting the deadlines . Fig 5 given below is the work plan which the team created in beginning of project .It was divided in the five phases .The schedule for each phase was developed only after completion of the previous phase.

Given below is the work plan developed one phase at a time.

Pre-phase A: (10/8/2012 to 30/8/2012)

Studied the rules and regulations of the competition → Referred to videos and papers of the previous year teams → Contoured the basic design of the robot.

Phase A: (31/8/2012 to 10/9/2012)

Dealt with anatomy of the various proclaimed designs of the bot. → Procured knowledge of the various hardwares used in bots. → Procured knowledge of various softwares required.

Phase B: (11/9/2012 to 30/9/2012)

Produced a detailed design of hardware requirements and technology → Produced a detailed design of software requirements and interfaces. → Sorted the most suitable and robust design.

Pre-phase C: (10/10/2012 to 20/11/2012)

Solid works design and analysis. → Formed a basic prototype of chassis. → Structured a model of container and bucket.

Pre-phase C cont:

Approached faculty for lab procurement. → Encryption of a formal proposal.

Phase C: (15/11/2012 to 10/1/2013)

Purchasing , manufacturing parts of chassis → Purchasing , manufacture parts of ladder system → Purchasing manufacure of dumping system parts

Phase D: (17/1/2013 to 25/3/2013)

Assembling the various parts of locomotion system → Assembling the various parts of dumping system → Assembling the various parts of ladder system

Phase E: (16/3/2013 to 10/5/2013)

Assembling all module of lunabot . → Testing the Lunabot for funtionality and Extrapolation of results. → completion of system engineering paper , outreach project,slide ppt.

Fig 5: Work plan

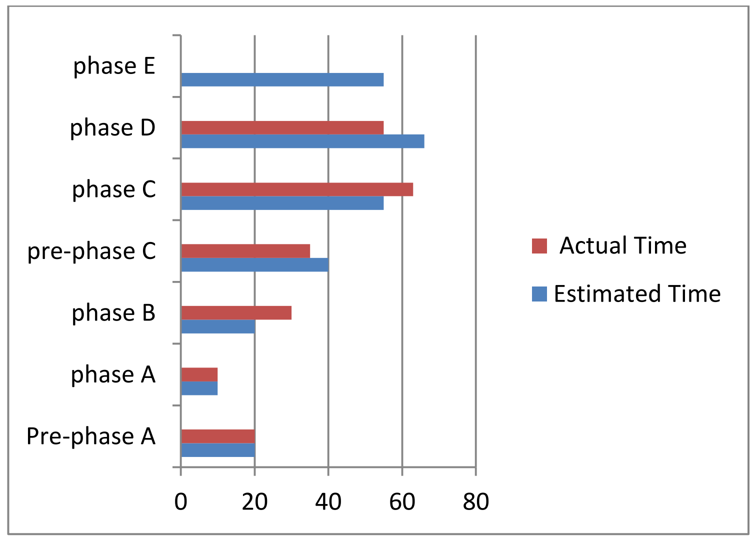


Fig 6. Planner comparator

In the above figure we have drawn a bar graph showing the variation between time estimated for a phase before start and the actual time it took to complete the phase .

X-axis shows the number of days and Y-axis shows the phases completed. Looking at the statistics we missed two deadlines and were ahead of time in meeting two deadline so the total estimated time till completion of phase D was approximately 210 days and actual time till completion of phase D is 203 so percentage efficiency of our estimation prediction was 98.59% .phase E is not considered in the calculation as it is in progress .

6. Evolution of Design of Lunabot

6.1 Primitive Design

The team structured with a primitive design based on its initial research as shown in Fig 7

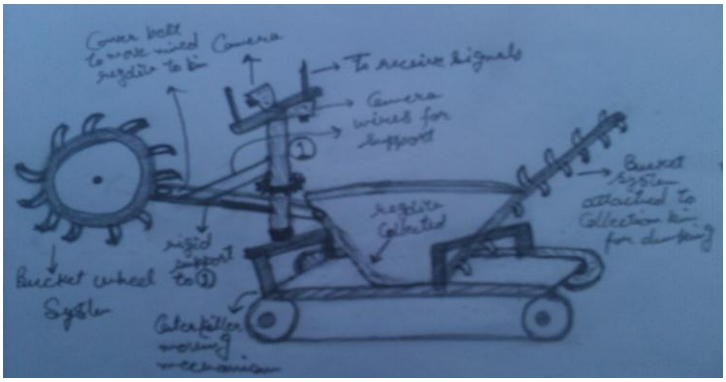


Fig. 7 Primitive Design

Bucket wheel is chosen as digging mechanism. The idea behind this selection was to get a continuous and quick digging mechanism. Regolith collected from bucket wheel was emptied into the container by taking the wheel above the container and rotating it in opposite direction. This made mechanism complex and the process involves a lot of dust generation. Tracked wheels are used for locomotion. For dumping the collected regolith into the NASA's collection bin a smaller bucket ladder is attached and vibrators provided at the bottom for empting the container.

The system seemed complex with multiple degrees of freedom and the stability of lunabot is questionable.

6.2 Second Design

This design was an amalgam of two different design mechanism used in tandem.

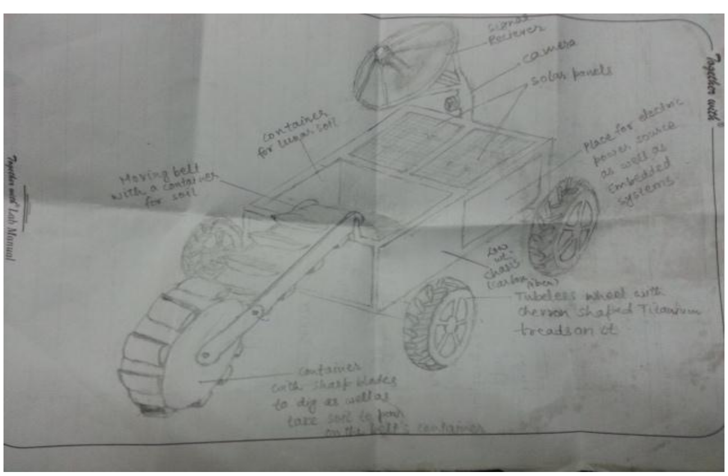


Fig 8 Second Design

Bucket wheel was again chosen as digging mechanism with a slight m 4 ıde of tr 5 regolith to container. Regolith excavated by wheel was transferred to a small bucket ladder which in turn dumps it into collection bin. The process was continuous and dust free. A four wheel differential drive mechanism is chosen for locomotion. Dumping of regolith is done using crane/winch mechanism and tilting the container to dump all the regolith in NASA's bin. This saved a lot of time especially while digging and dumping. The digging system entails high degree of synchronization between bucket wheel and bucket ladder. Dumping system was not rugged and stable.

6.3 Third Design

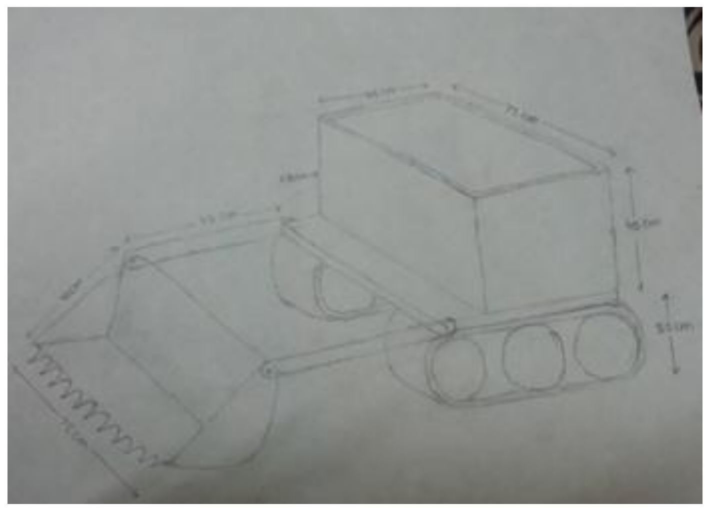


Fig 9. Third Design

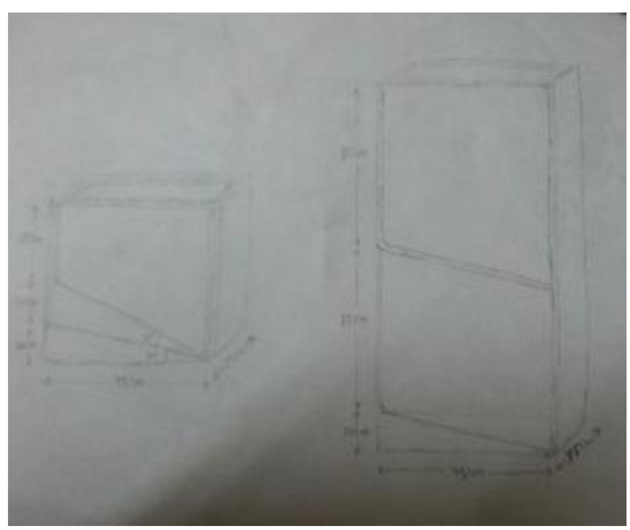


Fig 10. Container side views

A simple scooping mechanism was chosen for digging. The scoop dumps the regolith into the container. Collection bin was the forte of this design. The system had two containers placed co-axially. Scoop filled the inner container first and this moved up with the help of linear actuators. Scoop filled the outer container now, thereby almost doubling the collection capacity of lunabot. Tracks were used for locomotion as the payload is high. The inner and outer containers finally dump the collected regolith into NASA's bin with linear actuators and screw jack respectively.

The digging mechanism required high degree of freedom. Lunabot has to travel a lot of distance with the elevated containers. This shifted the centre of gravity upwards making it more prone to tipping over in the obstacle area. The designs were analysed by a weighted point method as shown in S.O.F.T 1.

Parameters	Design 1	Design 2	Design 3
Simplicity	6	5	7
Cost Effectiveness	4	7	6
Stability	8	6	5
Novelty	5	6	8
Efficiency	7	5	6
Total	30	29	32

S.O.F.T 1: scores of all design on various parameters scale(1-10)

7. Evolution of Electronics systems

The evolution of the hardware in the mechanical section synchronously plays an influential role in the design and implementation of the electronics, control and software domain. The team had a firm urge to research and develop their own hardware and interface with all of them at brisk pace (PWM frequency). Different circuits were tested and implemented. The scrutinising parameters that led to design evolution were adherence to rules, stability, simplicity, robustness, budget constraints, mobility and innovative design.

The team had stretched sessions on different proposed designs with consideration of above laid scrutinising parameters and its operational behaviour like performing mechanical operations (refer to fig 21). The team inferred that the design is not a linear process, and that iteration and backtracking are likely to occur between stages.

In the realm of control analysis, the team started with selection of DC motors, power source, embedded platform, communication setups, camera and each analysis presented the team a more refined analogy for the selection.

7.1 Selection of Motors

The actuators are the muscles of the lunabot and thus full FBD analysis stretching to rotational, kinematics and kinetics were analysed to come up with the varied selection of motors to give Aaravya a robust actuation.

Types of motors	**PMDC**	**Servo**	**Stepper**
Gear ratio	3	3	1
Cost	3	1	2
Torque	3	3	2
Power	3	3	2
Speed	3	2	1
Complexity	3	1	3
Feedback	1	3	1
Accessibility	3	1	2
Total	**22**	16	14

S.O.F.T 2: selection of motors

The electrical and mechanical response of the motors were analysed by torque and no load criteria.

a) The stall torque, τ at which the torque is a maximum, but the shaft is not rotating. Current drawn by motor is maximum in this case. $\tau = ilBd$

$$\boxed{\tau \ \alpha \ i \ \text{(Current drawn)}}$$

b) The no load speed, ω, is the maximum output speed of the motor ; $\omega = V/ (lBd)$

$$\boxed{\omega \ \alpha \ V \ \text{(Voltage Applied)}}$$

However these two characteristics are inversely proportional to each other for a motor. Therefore appropriate value is chosen to have maximum power.

7.2 Power Source

The selection was mainly weighed on the weight of the battery system and availability, as weight marked a specific consideration of points allocation in the competition. Potential Battery Types that we consider as viable power sources are: Valve Regulated Lead Acid (VRLA) , Nickel Cadmium (NiCad), Nickel Metal Hydride (NiMH) ,Lithium Polymer (LiPo). During the selection among different types of battery , the parameters that we considered are – Specific Energy, High Discharge Power, Self Discharge Rate , Weight & Cost.

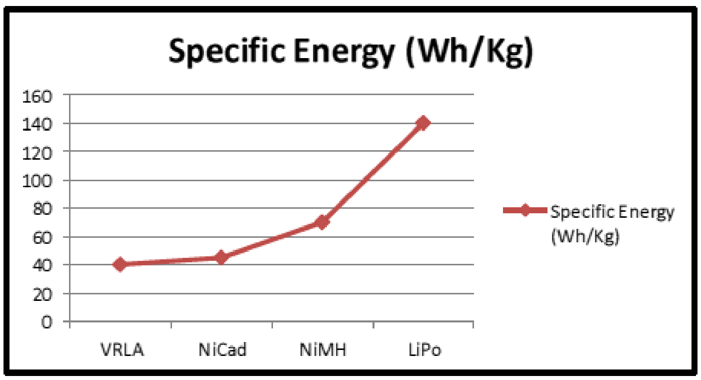


Fig 11: comparison of Batteries on Wh/Kg

Parameters	**VRLA**	**NiCad**	**NiMH**	**LiPo**
Specific Energy	1	1	2	4
High Power Capability	5	5	5	5
Low Self Discharge	3	3	3	4
Weight of 100 A-h	1	2	1	4
Low Cost	5	3	3	1
Total	15	14	14	**17**

S.O.F.T 3: selection of battery

Hence LiPo battery was selected.

7.3 Open Source Integrated Electronic Circuits(OSIECs)

OSIECs were designed by the team inline with the endeavor to learn by implementing things of their own. The requirements were analysed by searching problem statements on forums and developing the used circuit with its further evolution by testing. During the development of lunabot the team tried to develop the systems and circuits indigenously. The team understands not only the implementation of various systems and sub-systems used in fabrication but also its functionality, this helps in better debugging and improves productivity.

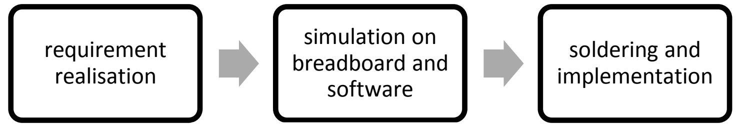
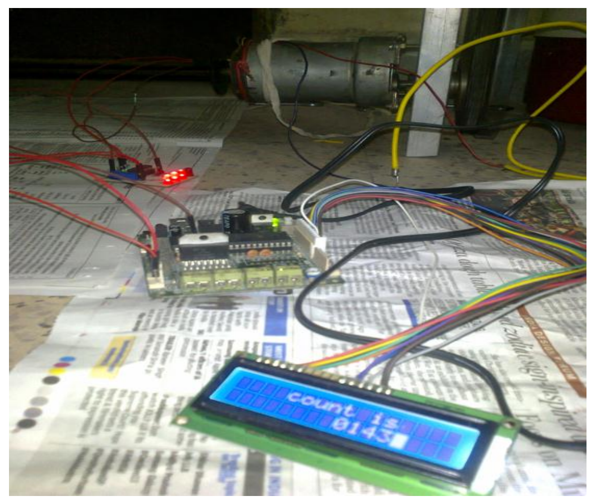


Fig 12: circuit design methodology

7.4 Embedded Platform

The team started working with Atmega32 in the platform of AVR Studio 5 . Interfacing of motors using serial data transmission and through Infrared Remote control were done to analyse the behavior of motors speed with PWM & wireless control. The resultant circuit for serial communication utilizing Max232 IC was built, soldered and used.



. Fig 13: circuit measuring RPM count of motor from encoder,atmega32

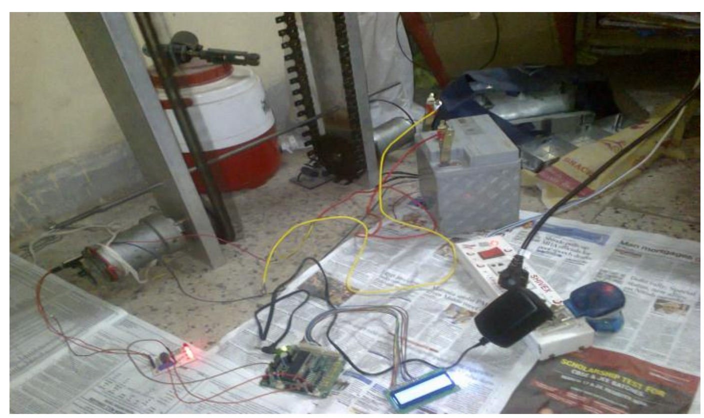


Fig 14: circuit setup of RPM measurement of motor

7.5 Communication Setup

The rules stated to control the lunabot either through a wireless channel or design it with autonomous credibility. The team decided to implement the design with wireless features. The lunabot needed to be in compliant with 802.11b/g IEEE protocol.

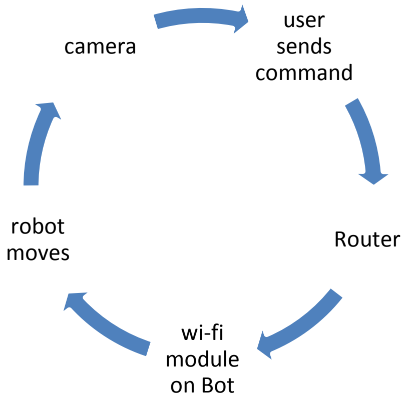


Fig 15: Communication setups

Communication channels involved:

1. Wireless medium :router to wi-fi and camera to control room
2. Serial communication: wi-fi module to robot

7.6 Camera

As our lunabot is visually and auditory isolated from control room so we are depending on the camera's video output to control our lunabot. We will be using IP camera, as it reduces the number of processes handled by the microprocessor. Wireless ip camera provides its own web server where image captured by the camera can be view from any computer with internet access. 10BASE-T Ethernet signals provide transmission speeds upto 10 Mbps. Devices are connected to the cable and compete for access using a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol.

7.7 Control Engineering

Control is a very important parameter that needs to be adhered to for better functionality of the lunabot. The team learnt that it is very difficult to realize a linear system. A finer blend of feedback and linear system analysis was procured for a finer control. The **telerobotic system** is a typical hybrid system that contains both continuous time and discrete event dynamics as example the robot can be considered as a continuous time system modeled customarily by differential equations or difference equation, and the human operator whose function is to generate the commands for the robot located in the remote side, however, can be modeled as discrete event dynamics.

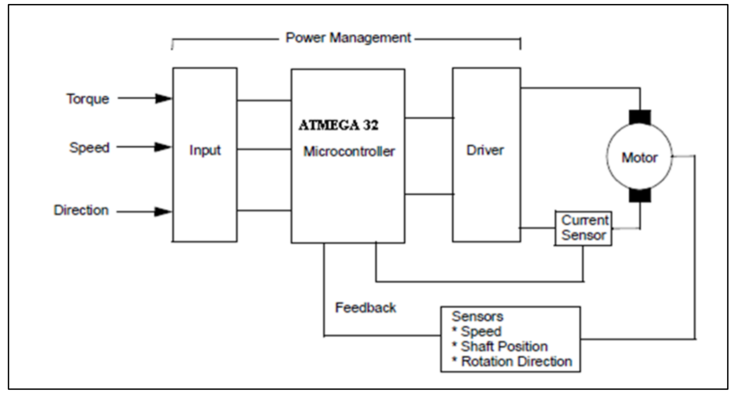


Fig 16: feedback from motor to atmega32

A basic mathematical modeling of the lunabot system was studied and analysed. The most nonlinear element in the model is the DC motor. Its behavior on application of load shows nonlinear characteristics that further are reciprocated in the non-linearity of the lunabot. The team, thus, decided to improve linearity by using encoders and PID algorithm in lunabot design.

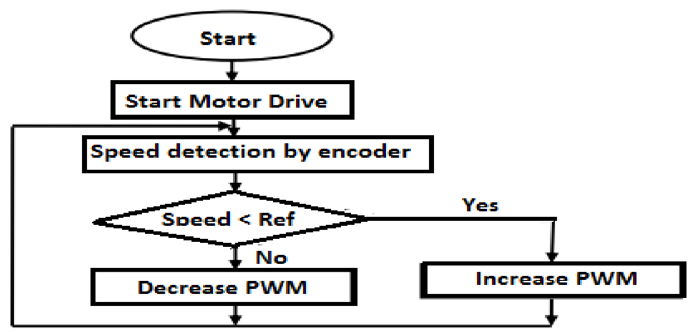


Fig 17: Motor control algorithm

8. Final Design of the Lunabot

8.1. Chassis/Drivetrain

4130 alloy steel square tubing is used. A part of chassis for installing bucket ladder inclined at 54.34 deg. Drivetrain has four wheels with two rear drive train motors. Timing belt is chosen as inferred by following:

Characteristics	Flat belt	V - Belt	Triplex Chain	Timing Belt
Slipping	2	5	8	8
Load Capacity	3	7	9	7
Weight	9	8	1	8
Max permissible tension	5	6	9	7
Total	19	26	27	30

S.O.F.T 4: various possible drivetrains

8.2. Bucket ladder system

70 cm tall single-chain bucket ladder which articulates up and down through the use of a link and was powered by a motor.

The tip of the bucket ladder moves downward and directly over the collection bucket to avoid dust generation.

The bucket ladder will move up and out of the way of the collection bucket when the collection bucket is raised for dumping.

The Bucket Ladder system had following advantages :

- Requires less power and force.
- Multiple excavation buckets adds continuity ,hence less time consumption which makes excavation process reliable.
- The mass of the bucket ladder is more uniformly distributed than a front-end loader.

8.3. Elevator dumping system

• Dumping mechanism is having a collection bin, which would move up and down along two screws to a given height.

Screw arrangement driven by a motor to move the bin to and fro.

Stopping of bin was achieved by switching off the motor. Rear face of the container was brought down using an actuator to let the regolith flow out of it.

SPECIFICATION OF MOTORS

After analysis of the lunabot design the team chose motors with following specifications. (refer appendix A for calculation of specs.)

Motors	Operating Voltage (V)	RPM	Torque (Nm)
Caterpillar	18	100	70
Bucket Ladder	18	80	35
Dumping	18	65	70
	18	75	15

Fig 18: specifications of motor used

8.4 OSIECs

The team tried to exploit the knowledge in open source realizing the various interfacing circuits for the project. The algorithm used is as depicted in fig 9 .

H bridge: A lot of design analysis was carried on in coming up with its circuit. The approach that led to design of the circuit:

i. Testing the motors for their stall current.

The tests presented a remarkable insight in deciding on to the power systems, electrical interfacing and switching components selection. The team used a basic series testing circuit of which the details and observations are presented in APPENDIX 3. Stall condition of the motor was sensed as one of the worst case guideline, a part of Risk Management, and thus circuit is designed with a factor of safety of 5.

ii. Trade off analysis of switching elements

The design involved as its first level of selecting the switching elements. The parameters considered are price, speed, threshold voltage(V_t),Max power dissipation(P_{max}),V_{gs}/V_{be} on the scale of 5. Packaging is considered thoroughly for it needed to be good for PCB soldering, TO-220 or TO-92 thus wee considered, further TO-220 for its embedded heat sink.

Elements	Price	Speed	V_t	P_{max}	V_{be}/V_{gs}
BJTs	2	1	4	2	1
MOSFETs	4	5	1	4	3

S.O.F.T 5 Switching components selection

Inference: MOSFETs are considered as switching element with 17 points.

iii. **Selection of components**

The Power MOSFETs were chosen to design the circuit. The NMOS inverter and CMOS inverter were analysed with different parameters.

Parameters	CMOS	NMOS
Switching Action	4	2
Power dissipation(& R_{ds})	2	4
Complexity	5	2
Price	3	4
Availability (Free samples)	4	2
Total	**18**	14

S.O.F.T :6 CMOS v/s NMOS H bridge

Inference: This led to the decision of choosing the CMOS circuit to be implemented in our lunabot.

Specification of mosfets chosen for the implementation of NMOS inverter were as follows:

Part Number	$V_{operating}$	I_{output}	P_{max}
1. PMOS (IRF4905)	-55V	-74A	200W
2. NMOS (IRFP064N)	55V	110A	200W
3.NMOS(P55NF06)	60V	50A	110W
4.PMOS(SUM11P08)	-80V	-110A	125W

Fig 19: MOSFETs specifications

The mosfet used has some gate capacitance which is to be charged and discharged for en efficient switching action. These were driven by Mosfet drivers. The required output current provided by mosfet drivers can be calculated as follows:

The output current depends upon the gate capacitance of the mosfets and voltage applied across the gate and source of the mosfet.

If ΔQ_{gs} is saturation charge which can be stored across the gate and source terminals of the mosfet. It must be charged and discharged in time Δt which is switching time of the mosfet, which further is decided by the $\Delta Q_{gs} = C_g \times \Delta V_{gs}$,where C_g is the gate capacitance of the mosfet. So the current provided by the driver must be equal to

$I_o = \Delta Q_{gs}/\Delta t = C_g .\Delta V_{gs}/\Delta t$

Putting the values form datasheet, the required current came out as 2Amp , and then the type of mosfet drivers are chosen using following table.

Parameters	Driver ICs	Transistor
Switching speed	5	3
Cost	2	5
Current	4	3
Complexity	2	5
Safety	3	2
Total	16	**18**

S.O.F.T :7: selection of MOSFET Drivers

According to above table, **Transistors** having higher points were considered.

Following transistors were chosen according to purpose and have following specification.

Parameters	TIP122	CDIL2N6107
V_{be}	5V	5V
V_t	2.5V	1.5V
I_c	5A	10A
Packaging	TO-220	TO-220
$P_{dissipation}$	65W	40W

Fig 20: MOSFET driver specification

9. System Hierarchy

The team vision for the systematic hierarchical model of the lunabot was divided not on the engineering backgrounds but on the aspects of operation. Thereby the team focused upon the various parameters that were provided as the guidelines (rulebook) that led to the decision to implement the bot at the very level of functionality. The execution process was more systematic and defined as the team had better interfacing with various functional characteristics and behavior of the lunabot. Aaravya was divided into basic operational characteristics as Excavation, Drivetrain and Dumping which were further classified on the engineering grounds so as to understand the basic needs of the system at more adept level.

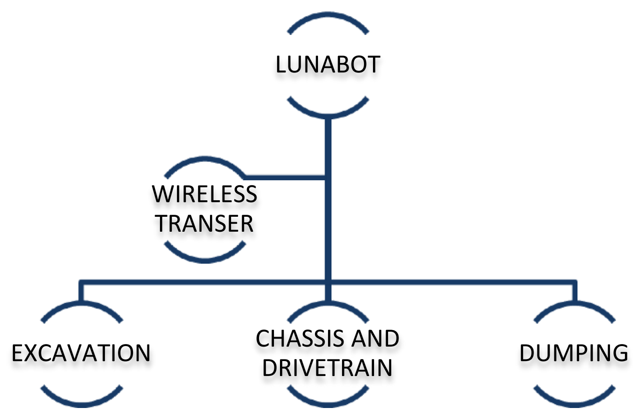
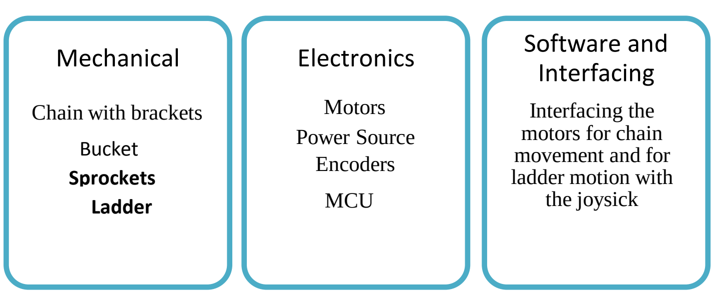


Fig 21. Main Hierarchical model

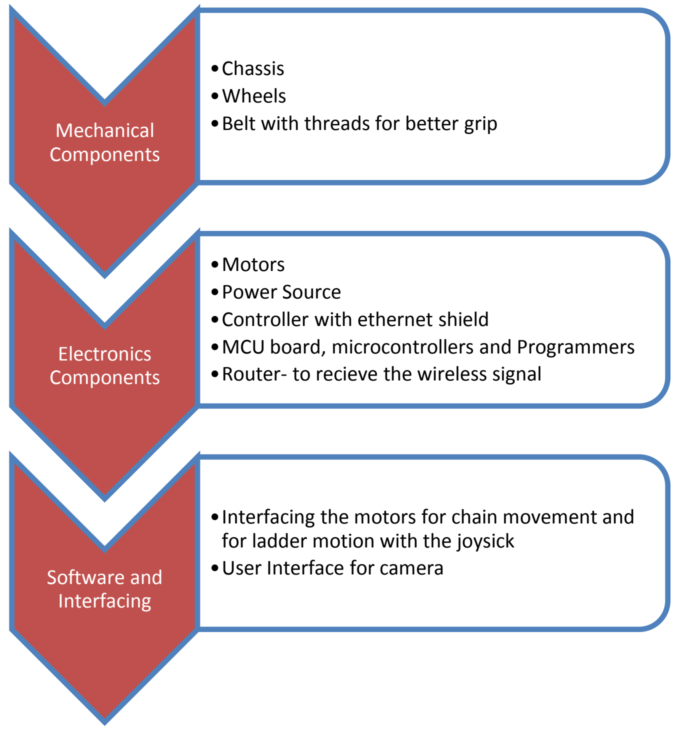
The sub-division of each operational feature was on the following parameter:

- Mechanical
- Electronics
- Electrical and Control
- Software

9.1 Excavation Hardware

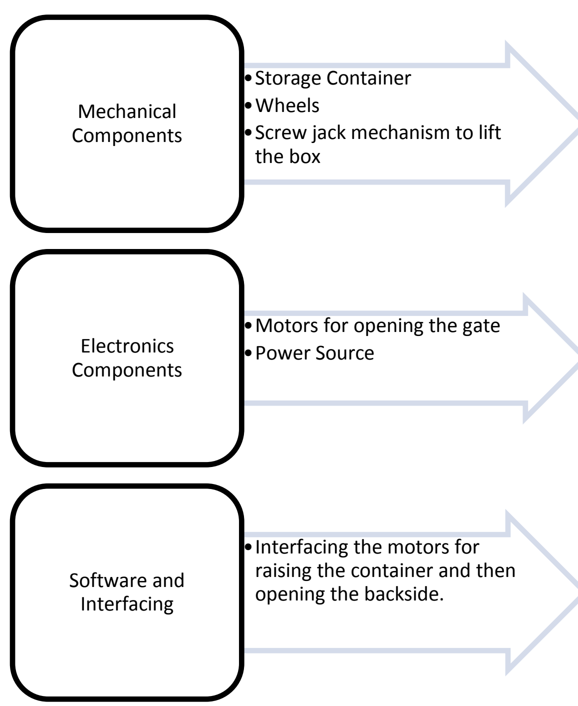


9.2 Chassis and Drive train



The Power Source which was being used is a 6 cell battery 22.9V, Ah, 20C. The controller being used is the arduino due board and WRT 54GL router was used to receive and broadcast signals.

9.3 Dumping



10. Concept of Operations

The Con-Ops of the system can be explained by stating the required tasks that has to be done along with the technical know-how, that the end-used will need to complete the required job.

Lunabot at its highest level can be divided into three subsystems under two categories as follows:

- Mechanical Subsystem
- Electronics Subsystem
- Software Subsystem

These three subsystems are interfaced by the engineering principles to each other as shown in figure:

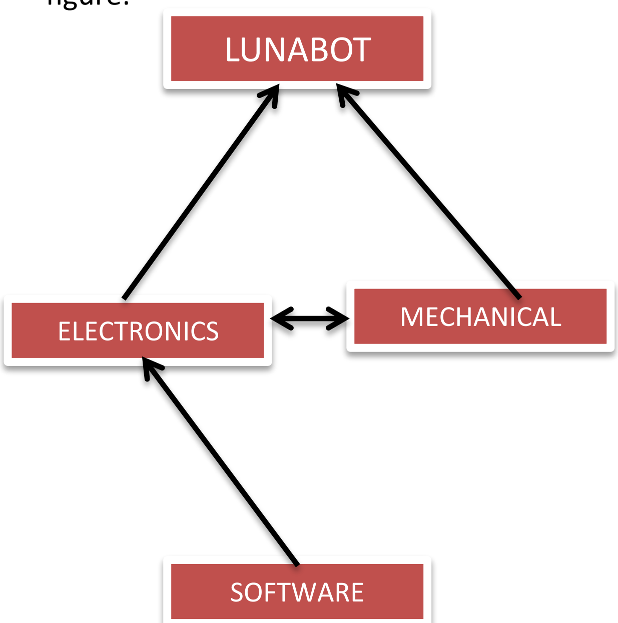


Fig22: operational model of lunabot

System Structure

Lunabot was interfaced with its environment through various sensors and actuators. Rotary encoders return feedback to the microcontrollers which control the locomotion speed. Feedback from camera gives end user the valuable visual feedback from which he can send the necessary control signal via the router from the control room.

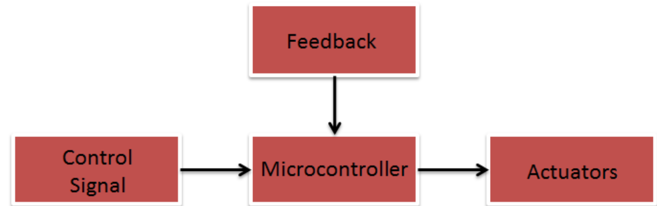


Fig 23: Signal Flow

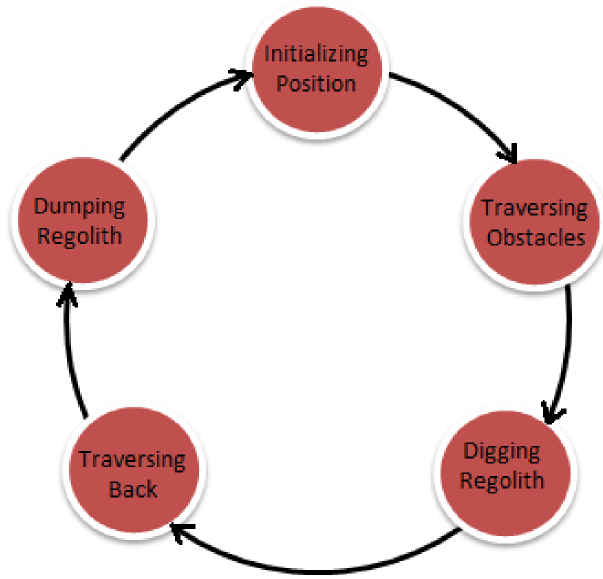


Fig 24: Mechanical Con-ops

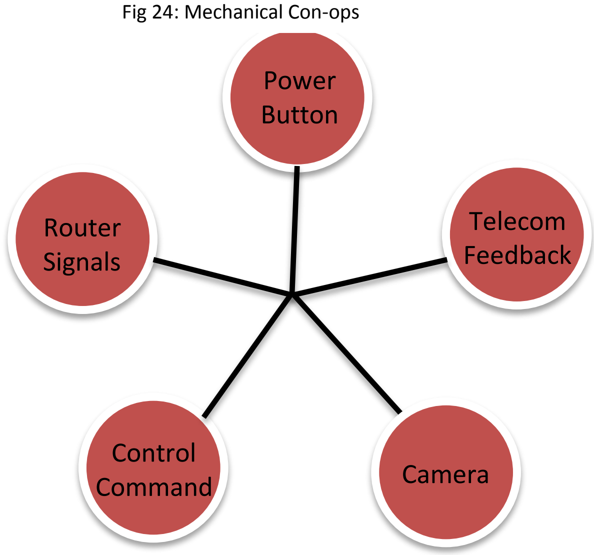


Fig 25 Electrical Con-Ops

11.1 EXCAVATION MECHANISM

POS: to collect maximum regolith in minimum time interval with weight being as light as possible.

The chosen method was the bucket ladder mechanism. A chain attached with 8 buckets rotates to continuously dig regolith and simultaneously dumps it into the container of the Lunabot

Parameters	Bucket Wheel	Bucket Ladder	Conveyor belt	Collector Arm
Weight	6	5	6.5	8
Simplicity	8	7	8	4
Cost	5	8	7	3
Digging Time	6	7.5	5	5.5
Total	25	**27.5**	26.5	20.5

S.O.F.T 8: different excavation mechanisms

Inference: bucket ladder mechanism was selected

11.1.1 SPECIFICATIONS OF COMPONENTS

- Steel roller chain(0.5 inch pitch) with attachments
- 2 Sprockets (27 teeth, 0.5 inch pitch) attached with motors to rotate the chain.
- 8 Sheet metal buckets (25X5X4 cm^3) which are slightly wedged for a better shear angle.
- Aluminium Extrusion (4 inch X 1 Inch cross-section)
- Lightweight Nylon wheels (diameter) to mount the sprockets.

11.1.2 FEATURES OF LADDER

The ladder has 2 Aluminium extrusions joined by 2 mild steel rods. Each extrusion has 2 attached sprockets that have a chain (with attachments) running over it. DC motors are attached to the sprockets. 8 buckets are added on the attachments over the chain.

The ladder is kept at an angle of 53.5 degrees to the surface and controlled by linear actuators that set it on or off the ground.

As the motor starts, the chain starts rotating forcing the buckets into the regolith and thus the buckets start collecting the regolith. As the buckets come up, they dump the regolith into the container. This mechanism offers several advantages. The numerous buckets and consistent rotation help to mine a large amount of regolith in a very short time interval thus saving a lot of time for locomotion and dumping.

Figure 26: Bucket Ladder

11.2. LOCOMOTION

POS: To minimize weight, maximize stability. Optimum ground clearance and achieve a speed of about 1.0 m/s.

A caterpillar type drivetrain mechanism has been used. A timing belt goes over the 4 wheels for locomotion of the chassis. The chassis is a parellelopiped structure made of hollow Aluminium pipes.

Parameters	4 Wheel	Caterpillar
Weight	6	7
Simplicity	8	5
Cost	7	7.5
Stability	5	8.5
Speed	8	7
Total	34	35

S.O.F.T 9: various locomotion mechanisms

Inference : caterpillar mechanism was selected.

11.2.1 SPECIFICATIONS OF COMPONENTS

- 16 Square cross sectional (1.5 X 1.5 inch^2) hollow Aluminium pipes of thickness 2 mm.
- Sheet metal L clamps to join the pipes.
- 4 Aluminium wheels of diameter 10 cm.
- Two 27 teeth worm gears of diameter-?
- Metal shafts to rotate the wheels attached to motors.
- 450mm L rubber timming belt of width 10 cm with V-shaped rubber treads.

Aluminium is light as well as strong and hollowness provides great weight reduction. The chassis has a rear wheel drive standing on 4 Aluminium wheels with worm gears provided for gear reduction. Attached motors drive the wheels. A rubber belt with treads has been put over the 2 wheel sets to implement the extremely stable moving track locomotion mechanism.

The Lunapit surface provided by NASA is irregular, bumpy and has craters. Stability of the Lunabot becomes very important in this scenario. The caterpillar mechanism with the large contact area provided by the belt with treads gives that extra stability and prevents slipping or toppling.

The hollow parellopiped structure provides extreme weight reduction and gives considerable amount of ground clearance so that the small craters and boulders can be easily traversed without having to realign the Lunabot.

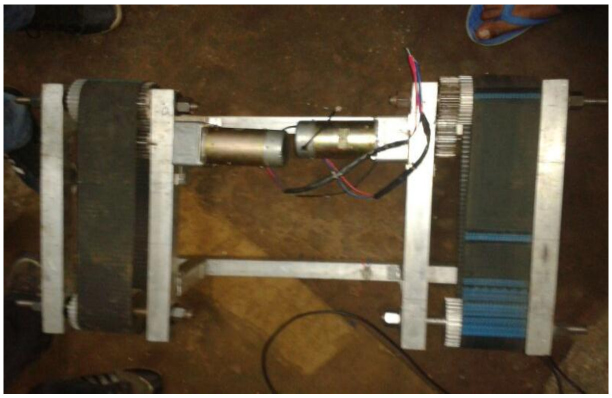


Figure 27: Chassis with caterpillar track mechanism

11.3 DUMPING

POS: To store as much regolith as possible and dump the regolith smoothly and quickly.

The method chosen is one of a raked container which is lifted by two screw jacks to the required height and as the container opens from one side, the regolith flows along the rake to the bin.

Parameters	Pulley and Rails lifting mechanism	Screw jack Lifting mechanism	Conveyor belt Dumping mechanism
Weight	5	7	8
Simplicity	4	6.5	6
Cost	8	8	4
Lifting Stability	3	7	8
Time Taken	6	6	5
Total	26	34.5	31

S.O.F.T 10: various dumping mechanisms

Inference : screw jack mechanism was selected.

11.3.1 SPECIFICATIONS OF CONTAINER

- A 40X37X40 cm^3 sheet metal container.
- Metal angular stand with a rake angle of 10 degrees.
- An 18 gauge metal sheet attached at the base of the container giving a rake angle of 25 degrees.

Figure28: Top view of the container

11.3.2 FEATURES OF CONTAINER

The container is provided with an internal slope so that the regolith can flow easily out of it if one of the sides of the container is opened. This is the best way to dump from stability point of view as there will not be any angular moment and so the toppling risk is minimised. Strength is given to the container by providing supports and double layer of sheet at those areas where factor of safety is less.

After due experimentation, it was decided that a total of 35 degrees rake angle will be given as it optimizes between container capacity and regolith flow. The angular stand reduces the rake required in container thereby increasing capacity and also gives additional strength and support.

For the smooth raising and emptying of container, a screw jack mechanism has been used. In this, 2 lead screws of 450 mm length and 25mm diameter are attached at the sides of the container and nut is fixed to the container via an “L” clamp. The nut is fixed in its position in the clamp by an LN bolt. Motors are fixed to the bottom of the screws.

Figure 30: Highlighted region shows the ‘L’ Clamp

For dumping of regolith after attaining the desired height, two DC motors and four bar crank mechanism is used.

Figure31: Highlighted region shows the 4 bar mechanism.

The motor shaft is connected to the crank of the 4 bar linkage. So rotation of motor shaft leads to the opening and closing of the gate. For the gradual and smooth flow of regolith from the container, the slope of the opening gate should be equal to the slope provided in the container which is done by a chain that determines the exact opening position of the gate.

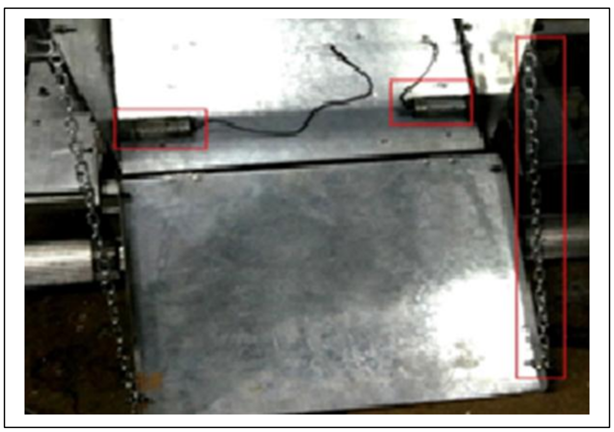


Fig 32: marked sections showing motors and chains of container

12. Interfacing of Various Systems

The interfacing plays a crucial part as there are a lot of peripherals and sub systems that need to be working in a linear relationship for stable, robust and continuous operation.

a. Lunarena ⟺ Lunabot

The most challenging aspect in the designing of the Lunabot was its interaction with the environment provided in the Lunarena by NASA. First it had to cope with all the dust that it will be surrounded by in the Lunapit. The body of the Lunabot was manufactured keeping in mind the dust tolerance. The components were designed in such a way that they can be operational even in dust ridden atmosphere and the sensitive components were cased in dust resistant materials. The second interaction was between the excavation buckets and the regolith. Zeng and Mckey models were studied to get an idea about the force and stress required that will be sufficient for excavation.

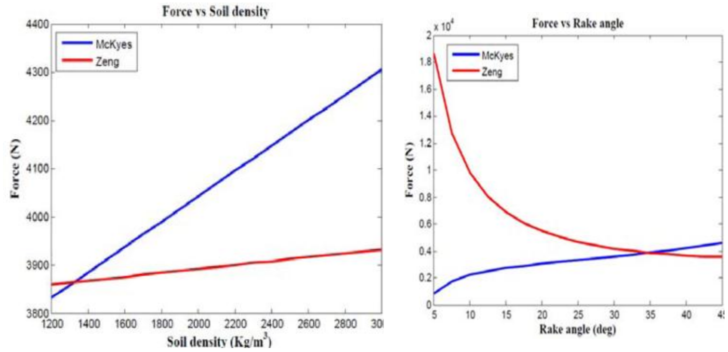


Fig 33: Rake angle and solid density curves

b. Electronics ⟺ Lunabot

The heart of the control and decision making is taken care by the Micro-controller. The team is using the Arduino Due, the ARM Cortex M-3 version board from Arduino with ATSAM3X8E processor. The board is decided on the parameters like processing speed, no of GPIOs, no of PWM channels, easier programming interface and price. The board interfaces with:

i. Due with Arena

The feedback from the arena in terms of positional control of the motors is fetched by the encoder attached to the motors' rear shaft. This shaft encoder with a disc gives the controller the decisive inputs to control the speed and hence its traversal through the arena.

ii. Due with wireless data

Arduino Wifi shield is attached to the arduino due board which is being used for serial communication with the router established near the arena. The shield and board both coupled together is used to control the lunabot from the control room by the team members using the joystick. Here is how wifi communication during competition works:

Fig 34: wireless setup

iii. Due with electrical system

All the devices of electrical system like the emergency button, ladder motors ,mining motors, locomotive system's motors and the electronic components like the H-bridge circuit which controls theses motors are connected to the arduino due board either directly to the circuit or through external wiring. The board receives power from the external batter power source.

Due is also helping to control the speed of overall 7 motors through PWM (Pulse Width Modulation) technique as with PWM we are actually varying the voltage being applied to each motor individually as per the written code and the given control signals and so their rpm get changed as a result we are implementing the gear mechanisms to control the speed of the motors with the help of the Arduino Due board.

iv. Due with the mechanical system

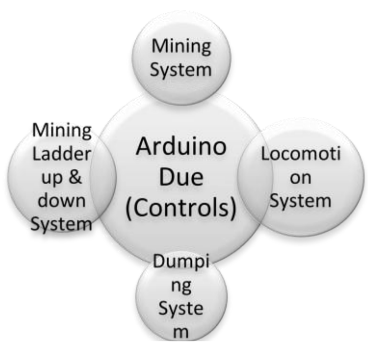


Fig 35: Arduino interfacing with mechanical

Due is controlling every aspect of the whole mechanical system of the lunabot like the mining system, dumping system, caterpillar locomotion system and the system which makes the mining ladder go up and down.

Signals to control and infer movement in a particular part of the lunabot is sent from the control room which goes through the router and finally it communicates with the wifi shield attached to the due the board further processes the signals and as per the written code in it's flash memory it makes the motion or movement to the concerned part of the bot.

c. Wireless ⟺ Lunabot

The consideration of robust and adept methods to control Aaravya was trickled down from the guidelines and rules designed for the competition. The selection of the router WRT 54gl was made on account of: one reason was price and other was the firm adherence of the team to learn from experimenting also the selected router is more hack-able. WRT 54GL V1.1 has a Broadcom BCM 5352 processor @200MHz with a 16 MB CPU and a 4 MB RAM, it is fast enough to decode the received signals. The preloaded firmware allows the user to upload 4 MB firmware image. It is fully supported by Tomato, OpenWrt and DD-WRT.

The Wireless interfacing includes sending the signals to the lunabot from the control room wirelessly. We tried to hack the router both in terms of software and hardware, Hardware hacking would have directly provided us with the serial signal directly and thereby we could have saved on the cost of a Ethernet to serial converter since it would have provided us with 3.3V TTL signal and the processor works at 3.3V so it will be easier to interface them.

The use of arduino based shield would provide us with the WIFI connectivity (802.11b/g connectivity). It uses SPI for host communication and features an on board PCB antenna along with a low power usage and supports both infrastructure and ad hoc wireless networks.
The router on receiving the signals via the Ethernet cable sends the signals wirelessly to another router hosted on the bot which decodes the signal and feeds the arduino board with the serial input of the instruction.

d. Power ⟺ Lunabot

The high power components in the Lunabot are all interfaced with 3mm thick having ampacity as high as 250 amperes. When selecting the appropriate wire we consider a number of important factors including: ease of assembly (solderability), temperature survival (materials and plating), bend and flex fatigue (stranding, alloy wire size), tensile load (alloy and wire size), system loss and voltage requirements (gauge and material type), ductility ease of motion (hardness, stranding and material) etc. Tests followed by analysis makes us to choose above specified cable.

The key element of the cable network is the smart interfacing of electronics components with mechanical parts which makes the cable network easy to maintain and results in least power loss during transmission. The schematic circuit of components with the electrical circuit of lunabot is shown in figure below.

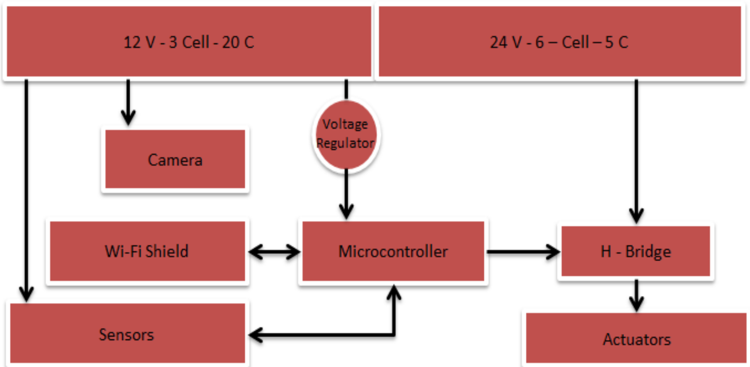


Fig 36: Power interfacing

Power system in the lunabot consists of two batteries: 24-V 6 cell LiPo and a 12-V 3 cell LiPo. The former is responsible for running actuators that draws heavy amount of current resulting locomotion, excavation and dumping. About 90 % power requirement will be met by this battery. The latter will be responsible for supplying power to microcontroller, camera & wifi shield.

e. Software ⟺ Lunabot

The software model is designed as forth:

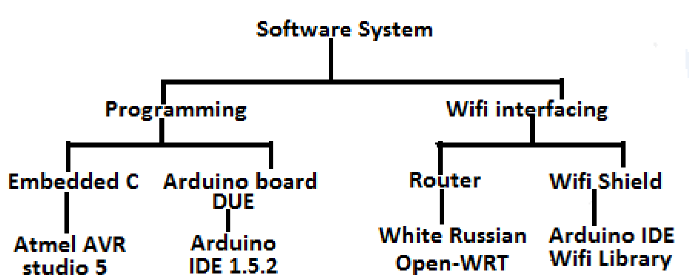


Fig 37: Software model

13. Regolith Analysis

POS : To test various parameters of lunar soil simulant prepared by team.

Lunar regolith stimulants :

Lunar soil simulants are JSC-1A,NU-LHT-2M,CHENOBI and BP-1. From all of the above simulants BP-1 behaves best like lunar regolith. BP-1 behaves best because of it's particle size and shape.BP-1 is prepared by crushing BLACK POINT LAVA.

Properties of lunar regolith

1. Low cohesiveness
2. May exist in bulk range of densities
3. Very high friction angle

Our attempts for making lunar like regolith

1. 50% cement and 50% silt
2. Desert soil mixed with burned wood ash
3. Beach soil mixed with clay powder
4. Desert soil mixed chalk powder and a small amount of cement

Selected sample :

50% Desert soil ,5% Cement, 25% Chalk powder,20% parting soil

Mechanical testing of regolith sample

While designing a digging machine we have to consider many of the mechanical properties of soil which the machine have to dig. So it is very important to study different mechanical properties of regolith we have prepared.

Important properties of soil

- Shear strength
- Density variation at different pressures
- Friction angle
- Cohesiveness

Among above properties shear strength is most important for us. Shear strength of our sample should be comparable to BP-1 soil .

Different instruments to test shear strength of soil

- Pocket vane shear tester
- Pocket penetrometer
- Geovane shear strength tester
- Laboratory vane shear tester

Instrument used by us :

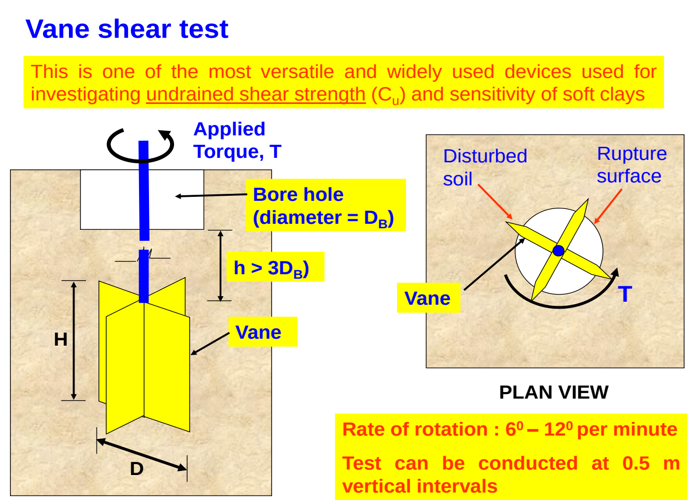


Fig 38: Van Shear Test

Laboratory pics of vane shear test :

Fig 39: lab test of regolith sample

Calculation of shear strength:
Formula used:

$$K = (\pi/10^6) \times (D^2H/2) \times [1 + D/3H)]$$

$$T = s \times K$$

D: Diameter of vane blade H: Height of vane blade
K: Constant depending on dimensions of vane shear tester s: shear strength of soil   T:Torque applied

Conclusion : Experimental data inferences the shear strength is 16 kPa and the actual value is approx 10kPa.

14. Risk Management

Every system has its mitigation strategy so does Team DLE Lunabot. The that would be followed during any malfunctioning situation are as:

Hazardous scenario: If the lunabot gets out of control from operators reach and capable of damaging the surrounding and itself "Emergency Button" will be used which will cut-off the supply power from the main source i.e. Battery.

Uncontrolled Current: Excess current can form an extremely dangerous situation and lunabot may build current as high as 300 Ampere if not properly dealt.
Fuses are placed in appropriate places of the circuit to avoid this condition to happen.

High Temperature: No doubt the arena temperature is 25 C, but lunabot components can warm itself to as high as 100 C during its working condition which is way higher than the components threshold temperature. To avoid this damaging situation to happen high temperature shunts are plugged in appropriate places.

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Appendix 1

Track Velocity Calculation:

For 100 Rpm Motor:

$V = r\dot{\omega}$

V=velocity , r=radius, $\dot{\omega}$ =angular velocity

V= (.1* 100*2*3.14)/60

V=1.046m/s

Torque Calculation:

Total weight at full load: Robot Weight + regolith Weight = 60+60= 120kg

Considering uniform distribution of weight on each wheel= 30kg

Coefficient of friction ų=.8

Friction force Fs=24g N

Torque τ = Fs*r= 24g*.1= 2.4g Nm

Bucket Ladder Calculation:

Size of bucket: 25*5*5=625cm^3

Density of regolith=1.5g/ cm^3

Weight in 1 Bucket= 625*1.5=0.9375kg

Weight in 8 buckets=8*.9375=7.5kg

RPM of ladder system=60

Belt Length=1.54 m

$V = r\dot{\omega}$= (.06*2*3.14*60)/60=0 .3768m/s

Time t= Belt length/ Velocity = 1.54/0.3768=4.08s

To get 60 kg of regolith, Time taken “T” = (60*4.08)/7.5= 32.64s

Considering 40% efficiency, T=54.4s

For 1 round:

From start to dig area: 25s

To set for digging: 25s

Digging 60 kg regolith: 60s

To go back to pit: 40s

Set for dump: 30s

Dumping time: 50s

Total time: 230s

Result

Total given time = 600s

So two rounds will be possible.

Total regolith collected = 120kg.

APPENDIX 2

Budget

Excavation system :

category	Sub category components	Actual price	Estimated price
Motors	Used Brushed PMDC	5625	20000
Motor driver	H bridge IRF4905, IRFZ44n, P55NF06, SUM110P08	320 88 60 0	2*5000 10000
	H bridge driver: IR2110 , FAN7392, TIP122, 2N6107	160 160 40 24	
Ladder	Sprocket &chain	2709	2500
	Bearings	840	1000
Infrastructure	PCB boards, Wires, Solder, Wires, Solder, Heat sinks	200	200

Control System

category	Sub Category	Actual price	Estimate price
Embedded control	MCU Board: Atmega 32, Arduino Due, Raspberry Pi, TMS470M	1250 3044 3090 sample	2000 5000 4500 6000
	Microcontrollers: atmega 328, atmega 32, AT91SAM7XC512	sample 200 sample	600 250 1500
	Programmer: Atmega 32 ISP	375	500
	LCD, cables, adapter	300+ 100+30 0	400+200 + 500
Wireless control	Linksys wrt54gl	3825	15000
	IP Camera	5625	4500
	Wi-fi shield	6138	4300
Power	Lead Acid Battery	2000	6000
	Battery LiPo 6cell+charger	7100	25000
	Charger LiPo	2500	1000

Locomotion system :

category	Sub category	Actual price	Estimated price
Motors	Used Brushed PMDC with encoder	6750	50000
Chassis	Al extrusions and sections	3285	3500
	Timing Belt & pulley	12390	13000
	Spur gears		
	w/l Rod MS , VCP bearing	2730	3000
	bracket & bearing	3535	3500
Motor driver	H bridge: IRF4905, P55NF06, IRFPO64n, IRFPO64n, SUM110P08	320 60 300 0	2*5000 10000
	H bridge driver : TIP122, 2N6107	40 24	
Infrastructure	PCB boards, Wires, Solder, Heat sinks	200	200

Dumping System :

category	Sub category	Actual price	Estimated price
Motors	Used Brushed PMDC	5625	24500 for 1 pc
	Used PMDC in opening flap	1125	10000
Motor driver	H bridge for screw jack: IRFPO64n, SUM110P08	300 0	2*5000 10000
	H bridge for motors in gate IRF4905, IRFZ44n	320 88	2*2500
	H bridge driver: TIP122, 2N6107	40 24	5000
Encoders	Sensors: Photo interrupter +disc	300	5000
	Comparator : LM324n 4channel	90	
Infrastructure	PCB ,Heat sinks	200	200

Infrastructure:

Sub category	Actual price	Estimate Price
Adaptors	900	1750
Ammeter ,	1070	2800
Techometer,	850	1000
LCD ,	300	300
Breadboard ,	500	500
Multimeter	320	450
Wires ,cables	370	660
Resistors , Capacitors diodes	400	500
Soldering iron Stand , wire	380	500
Solder wire	100	100
Lock for lab	192	200
File Hackshaw	200	250
Printing and binding	1075	1000

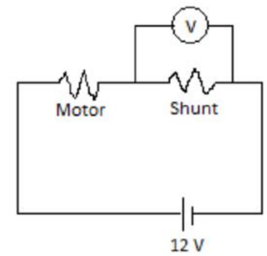
APPENDIX 3

Aim : Analysis of stall current of screw jack and ladder motors for E&E systems interfacing .

Individual Current Series Circuit

Motor	No Load Current (A)	Free Ladder Current (A)	Stall Current (A)
Left Ladder	0.6	0.8	9.3
Right Ladder	0.6	0.7	9.8
Left ScrewJack	0.3	0.8	13.0
Right Screw Jack	0.4	0.8	9.2

Schematic Circuit



Calculation of RPM

Time of 7028 (sec)	Laps	Time of Germany (sec)
4.19	1	3.67
4.26	2	4.02
4.30	3	3.92
4.22	4	3.92
4.19	5	3.94
4.24	6	3.75
4.27	7	3.98
4.30	8	3.97
4.08	9	3.78
4.28	10	3.86
4.25	11	4.03
4.24	12	3.87
4.34	13	3.83
Average - 4.24		3.89
RPM - 58.82		64.11

Where RPM : (60)(Chain Length)/ (Average Time)(Radius)(2π)