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Team 516: NASA Human Lander Self-Leveling System

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Abstract

Team 516 is working with NASA to create a leveling platform for the new Artemis missions. On these new missions, NASA plans on returning to the Moon with a human lander in search of water deposits. NASA plans to land near the Moon's south pole where they know the ground is uneven. This creates an uneven working environment inside the lander which is unsafe for the astronauts onboard. This project focuses on the design of a self-leveling platform that can level the lander capsule with the astronauts inside. The goals for the project include a design that is lightweight, reusable, and levels in less than one hour.

The design separates the lander's capsule and legs. This location blocks dust and harsh temperatures. The design takes in the angular readings from the onboard sensor. With these readings, electronically controlled rods level the lander cabin. These rods will perform a series of movements to adjust the lander cabin position from inside the leg base. The software for the design allows the rods to move quickly and accurately by using a two-axis plane. This plane exists from the union of two opposing rods. These rods will move in pairs until they reach a level state. The project relies on both the hardware and software equally.

The leveling section is independent from a specific lander design. This gives the design a wide variety of lander setups. The simplicity of this design allows for easy maintenance and a low mission impact. The design fits two key goals of being both reusable and lightweight. Another key goal for the project is a quick leveling speed, which this design achieves. Overall, the self-leveling module orients the lander cabin within the design constraints and ensures the cabin interior is suitable for the astronauts.

Acknowledgement

Team 516 would like to take time and recognize the many people who have helped our vision become a reality. First and foremost, the team would like to offer special thanks to the NASA Marshal Space Flight center for offering us the exciting objective of designing and prototyping a self-leveling system for a lunar lander. In particular, we would like to thank our project sponsor Rachel McCauley for providing us with constructive feedback and putting us in contact with other employees that helped us along the way. One of those employees in particular, Richard Knochelmann, has been there to help us and provide critiques that helped steer us in a better direction for our project. Aside from NASA employees, our team would not have been able to excel without the aid of our senior design coordinator and professor, Dr. Shayne McConomy. Dr. McConomy provided our team with priceless advice and feedback and sacrificed so much to see us succeed. From several semesters knowing Dr. McConomy as a teacher, it has always been obvious that he goes above and beyond what is required to prepare us for our future careers and life, and for that we are thankful. Dr. Dorr Campbell also served an important role in our project and offered us guidance on our material selection and environmental challenges that helped improve the reusability of our design. Throughout both our design and prototyping phases, the FAMU-FSU College of Engineering machine shop helped to guide us in the technical aspects of manufacturing a prototype. With this guidance, we were successfully able to produce a prototype and test our design to the fullest. We also would like to extend our gratitude to Neil Coker for assisting our team by helping us place our part orders in a timely, professional, and pleasant manner. Finally, the team would like to acknowledge the FAMU-FSU College of Engineering and all of the staff that helped to prepare us for this journey.

Our time spent here was full of ups and downs, but we genuinely believe that we are stronger and more prepared for any obstacle the world may throw our way due to the lessons learned and connections made in this program.

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Notation

NASA	National Aeronautical and Space Administration
MSFC	Marshall Space Flight Center
ACO	Advanced Concept Office
CLPS	Commercial Lunar Payload Services
LVLS	Local Vertical Leveling System
IMU	Inertial Measurement Unit

Chapter One: EML 4551C

1.1 Project Scope

Project Description

Last time NASA landed on the moon, the plan was for the Apollo mission to land on the lunar plains to provide the most stable environment for landing and takeoff. The next mission to the moon, anticipated to be in 2024, is projecting a lunar landing on the South Pole in search of water deposits. Due to the uneven terrain on this part of the moon's surface, a self-leveling capability is needed for the legs of the lander to ensure the most solid foundation for the next landing and takeoff. The self-leveling legs are to be designed to handle this uneven terrain, which is expected to have a slope, be rough and dusty, and have extreme temperatures.

Key Goals

The key goals for this project are to develop and prototype a system that allows the NASA lunar lander to land on uneven terrain. The system will account for basic environmental factors such as temperature, low-gravity, and friction. Surface temperatures of the moon can vary between -170℃ and 120℃, rendering most electronics ineffective. The low gravity of the moon will require modifications of basic kinematic calculations.

The desired landing location of the moon is the southern hemisphere in search of water. Because of this, the legs will need to account for the dusty, uneven conditions and the possibility of water. Additionally, the team will strive for a lightweight design that can operate with as little energy consumption as possible. The goal is to define a versatile system that meets the previous constraints.

Primary Markets

The Human Lander Program at NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) would be the primary market for the project. The team there is interested in a new self-leveling leg design and components for the Artemis missions to the lunar surface in 2024, as well as to Mars for future Artemis missions.

Another primary market could be for different commercial space exploration companies, such as SpaceX, Blue Origin, Virgin Galactic, and others. These companies work with NASA as partners on the Artemis missions to make the landers. They will be able to use the self-leveling legs on their own projects in their missions to space as well.

Secondary Markets

The secondary markets for this system would include anything where self-leveling is a desired feature. This includes RV’s, cruise ships, or construction machines, such as cranes. This system would apply to each of these markets because uneven terrain is a problem for each. If parked on a large slope or going over large waves, this technology could be repurposed to keep tables, beds, or appliances flat. This is also applicable to the construction industry where crews are at the mercy of their environment which may have uneven terrain, making it difficult to see and operate large, heavy machinery.

Assumptions

Team 516 is only responsible for the design of self-leveling legs for a human lander; they are not responsible for the application of the legs into various human landers. The team will test the prototype under Earth's conditions on a terrain like the lunar landing site. The team will then process the test results while considering the lunar impacts. The team will not be responsible for the mapping of the terrain prior to landing. The lander will contact the lunar surface and then adjust accordingly. To account for the effects of space and the lunar atmosphere, specialized software will be used to design and simulate the lander in various situations. The team will aim to create an energy efficient design but will not be responsible for the energy production.

Stakeholders

The stakeholders for this project include the NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO), the companies NASA has enlisted in the Commercial Lunar Payload Services (CLPS), the FAMU-FSU College of Engineering, the senior design coordinator Dr. Shayne McConomy, and the team advisor Dr. Dorr Campbell. NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) is the main stakeholder in that it has provided the team with the task at hand and will provide the funding necessary for this project to be completed.

Other stakeholders for this project include the companies NASA have enlisted in the Commercial Lunar Payload Services (CLPS). This project will have a direct impact for these companies in aiding them to develop future lunar technologies. The FAMU-FSU College of Engineering is a stakeholder as it is the main bridge between NASA and the engineering team working on the project. Dr. Shayne McConomy is a stakeholder because he oversees all the mechanical engineering senior design projects and must ensure the success of each, including this one. Lastly, our faculty advisor Dr. Dorr Campbell is a stakeholder due to the knowledge and support he provides to the team.

1.2 Customer Needs

Introduction

Customer needs data represents the customer's wants and desires for what the product is to achieve. This data helps in narrowing down the specific functions of what the design and prototype are to accomplish. To obtain this data, the team created a list of questions to outline the overall functions of the intended design.

Questions and Interpreted Needs

Questions	**Response**	**Interpretation**
1. What do you like about the current lander leg systems?	We like the stability and weight.	The design needs to keep the stability and weight of previous lander legs in mind.
2. What do you dislike about the current lander leg systems?	It does not self-level.	The design is to have self-leveling capabilities.
3. What part of the landing mechanism is our team responsible for?	We planned on you designing the legs and ground contact points.	The team is to design the legs and contact point with the landing surface.
4. Are we limited to a certain material?	No, however the materials used must have X specific properties.	The team is to select a material that meets specified properties.

5. What is the maximum mass that the legs will be supporting?	15,000 kg in earth's gravity (weight of the Apollo moon lander)	The legs are to support a maximum weight of 15,000 kg on Earth.
6. What scale are we designing to?	The model should be parametric which allows for variable scale.	The CAD will be done parametrically.
7. What software should our team simulate in?	Industry friendly that allows for easy sharing.	The team will use the software of their choice.
8. How detailed would you like the simulation to be? Fully/Partially Animated etc.	The function of the self-leveling system must be fully animated but other parts can be partially animated.	The team is responsible for a detailed simulation of the self-leveling system.
9. What lander platform should we be designing for?	The system should be able to be applied onto various lander models.	The self-leveling system needs to be able to be applied to different lander models.
10. Do the legs need to be stored away while not in operation? Do they need to be secured?	No.	The legs can be rigidly attached to the lander.
11. What will the system be powered by?	It will have a common power source with the rest of the lander.	The team is not responsible for designing a power system.
12. Do we need to be worried about the time it takes for the legs to level?	Yes, a good time goal to have is about an hour.	The legs are to level the lander within one hour of landing.
13. Do we need to be worried about clearance under the lander?	Yes, there need to be at least 1 meter of clearance.	There is to be a minimum clearance of 1 meter above the landing surface.

14. Does the leveling need to occur upon landing or during approach?	The leveling process will start upon landing.	The self-leveling process is to begin upon landing.

Table 1: Customer Needs Data

Table 1 displays the questions posed to the customer, their responses, and the interpreted needs from each statement. The questions above were created by Team 516 to focus in on the customer needs for the project. The basis of these questions came from the preliminary knowledge the team had of the project, as well as from initial research. Since the team has not been in contact with the NASA sponsor, the responses to the questions were created with the help of Dr. McConomy, research, and educated assumptions. From the responses, the interpreted needs were determined from the customer statements. One of the main needs of the customer is for the design to have self-leveling capabilities, and for this to be well modeled, through a prototype and simulation. Other needs include the self-leveling system to be able to be applied to different lander models, the leveling to take place once the lander touches down, and that the leveling takes place within two minutes of landing. Also, an important customer need for the team to note is that they do not have to design a power supply.

Even though the responses and interpreted needs listed above may not be directly from our NASA sponsor, the team believes that they will set a good baseline to move forward with the project until that initial connection is made. The idea is to generalize the design as much as possible so that it can be applicable to different lander designs and be able to be altered if necessary.

1.3 Functional Decomposition

Introduction

Progressing from the customer needs, Team 516 created a functional decomposition for the self-leveling lunar lander system. By understanding what the system needed to be successful, the goals and needs were broken down into smaller and more achievable functions. Each of the smaller functions also fell under at least one major function, showing how the functions relate to one another. This step allows the team to decompose the larger objective into smaller portions and will therefore allow for creative approaches to solve the problem.

Discussion of the Data Generation

To generate data for the functional decomposition, the team had to break down the overall project system into major and minor functions. Once the major functions were determined, they were broken down into minor functions, which resulted in the most basic functions of the overall system.

The team determined that the major functions of the project were motion, power, sense, and lander. These four major functions breakdown the overall system into four distinct parts. The idea behind this is to have areas of focus for the design, without specifying any technologies or potential solutions. The first of these major functions is motion. The team decided that no matter what the design eventually entails, motion will be the primary factor for how the leveling of the lander takes place. From motion, the next major function is power. Power is important because it will be the primary source of energy that will allow the lander to move and become level. From the interpreted needs, it was determined that the system only needs to receive and use power, not store, or create its own to operate. Following power is the major function of sense. Sense will be an important characteristic of the system because it will determine how much motion will need to occur to level out the lander. The idea is for the system to sense the need to level upon landing and use the power supply to inhibit the motion of the system. Finally, the last major function covered by the team is the lander itself. Since the actual system is the self-leveling itself, the team thought it best to include the lander as a major function of the project. The overall success of the project will mainly be determined by how well the lander is leveled and stabilized once it contacts the surface.

Introduction to Graphics

With the customer responses in mind, the needs were determined and broken down into basic functions. In the cross-reference table below, the determined functions are in the first column and the following columns are the determined major functions.

Functional Decomposition: Cross-Reference Table				
Function	**Motion**	**Power**	**Sense**	**Lander**
Angle	X		x	
Transform Electricity into Mechanical Motion	X	X		X
Identify Angle Offset	X		X	X
Translate				
Translate Power	X	X		
Receive Power		X		X
Recognize Signal			X	
Identify Signal			X	
Detect Signal			X	
Process Signal			X	
Output Power		X		
Stabilize	X		X	X
Halt Mechanical Motion	X			X
Level	X		X	X

Table 2: Cross-Reference Table

Once the cross-reference table was completed, a functional decomposition hierarchy chart was constructed. At the top of the chart represents the overall system and it then splits into the various major functions determined by the team. The major functions were then broken down into the most basic functions of each to determine the most basic functions of the project.

Concept Selection

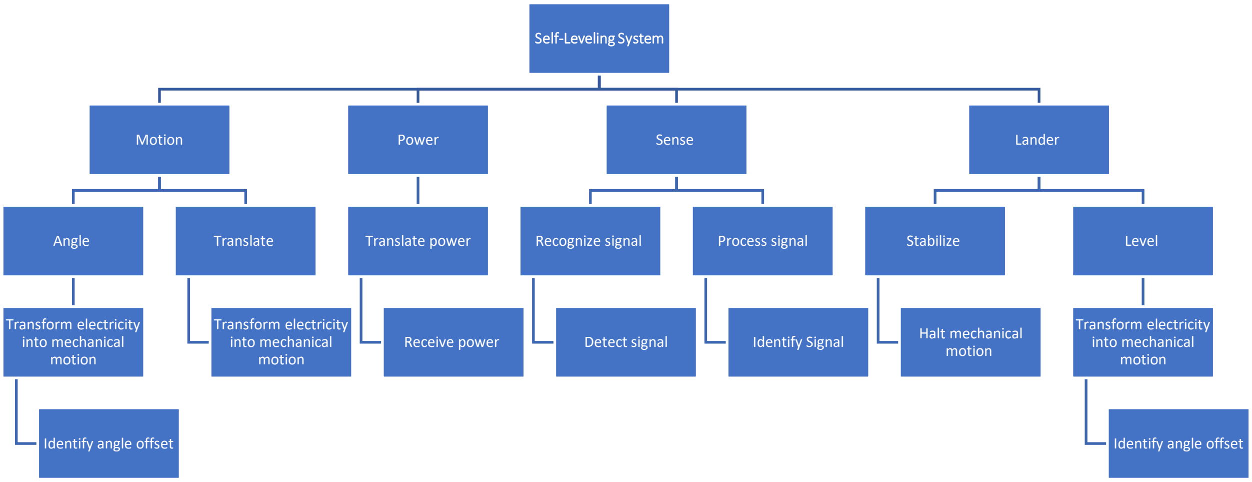


Figure 1: Functional Decomposition Hierarchy Chart

Determining Minor Factors

To determine the major functions of the system, the team needed to create minor functions the system had to accomplish. Those minor functions were then connected through the functional decomposition hierarchy chart to their respective major functions.

The first major function of the system, motion, needs to be able to do two things: angle and translate. This is because whatever solution to the problem the team chooses, the overall goal of being level depends on the angle the lander is at the start of landing and at the level position. To get to the level position, the mechanism needs to be able to move, which means translation is an important part of the motion function as well. Since both functions need to be able to translate the electrical power from the lander into mechanical motion, the angle needs to be able to sense and deliver the power into the mechanism to be able to translate it to a level position. However, the angle also needs to be able to identify the angle offset before it can move into the correct position.

The next major function, power, only has one minor function and that is because to translate the power to the mechanism, it needs to be able to receive power from the lander itself. Since the mechanism does not have to store power or use its own power supply, the lander will provide the power to be able to translate the power among the different components of the design.

The third major function, sense, has three minor functions within. The mechanism must be able to recognize the correct signal and to be able to recognize a signal, it has to be able to detect if a signal is there in the first place. Once the signal has been recognized, the mechanism must be able to process the signal. This is to ensure that the correctly identified signal is being used in the correct operations, such as motion of the mechanism. The function then has to be able to distribute that signal amongst the different parts of the mechanism to ensure translation.

The fourth major function, lander, was created so that the team can meet the goal of creating a level platform that the astronauts can stand, work, and walk on. To meet this goal, this function has the minor functions of stabilization and level. The level function translates electrical power into mechanical motion, identifying the angle offset as it moves toward the specified angle from the sensors. The stabilize function was created to be able to halt the motion of the level function so that it is not moving while the astronauts are working around on the platform.

Function Relations

After analyzing the cross-reference table and comparing each function, it becomes clear that no component is independent but rather, a complex web of relationships. The most widely shared minor functions are transforming electricity into mechanical power, identifying the angle offset, stabilizing the lander, and leveling the lander. These minor functions are shared by three of the main functions. Furthermore, the angle, translating power, and receiving power are minor functions shared by two of the main functions. This determines that most components are going to rely on multiple shared functions to complete the task. The team determined that the most important function of the design will be sensing the environment. This contains the greatest number of minor functions proving that this is most critical to a functional, holistic design.

1.4 Target Summary

Introduction

Progressing through key goals and the functional decomposition, Team 516 created the targets and corresponding metrics for the leveling system. The targets show the numerical value that the team has deemed necessary for mission success. A metric has been paired with each target to describe how the team plans to validate each function. Also included is the method of validation for each target and metric to show how the targets will be assessed and ultimately confirm that each target is met. Together, the targets and metrics will allow the team to move forward accurately and with strong intent on mission success and safety.

How Target Values and Metrics were Determined

After completing the functional decomposition and diving deeper into research, the team established the targets and metrics for the project. The metrics for the project are how the team plans to validate the functions and were found by providing a base unit of measure for each function. For example, time was determined to be the metric to validate the functions pertaining to signal processing. Assuming signal processing will occur, the time it takes to recognize, detect, identify, and process will impact the project and its effectiveness. Each of the metrics for the project are deemed as either performance measures or objective measures, where they can be directly quantified.

The targets of the project are intended to expand on the functions and metrics with more specificity and provide target values to achieve for each. These targets were based on the metrics created for the project, as well as some other important design considerations uncovered through research. When determining values for the targets, the team chose the approach of selecting values that would be the worst-case scenario. This was done to ensure that expectations are exceeded, and the design is built to be as effective as possible. Since the team has not determined the scaling for the prototype, targets for force and work involving gravity were calculated for both the conditions on Earth and the moon. Other targets involving angle, level, and the time to level were determined from discussions with the NASA sponsor and data received from the Apollo missions.

Detailed Description of Targets

The values for the targets are for the full-sized leveling system, not the scaled model. All the values in the table can be taken with plus or minus five percent of the target, unless stated otherwise.

The full-scale leveling system needs to be energy efficient, yet still level in a reasonable amount of time. Upon speaking to one the team's NASA contacts Andrew Wayne, he confirmed the maximum amount of time the system can take to level as one hour. This was then subdivided into the mechanical motion portion "time to level" with 55 minutes, and the "halt mechanical motion" portion with 5 minutes.

The work required for motion was determined using work is equal to force times distance. The distance traversed will be different for every leg, but these numbers were calculated for maximum distance traversed. The maximum distance the legs can elevate is three meters and the lander has an assumed mass of 16,000 kg.

The amount of power required was determined from the calculated work required. It was calculated using power is equal to work overtime. The time used was the 55 minutes converted to seconds from the "time to level" portion.

Recognize, Detect, Process, and Identify a signal were decided by using a standard 16MHz oscillating crystal clock that processors use. This allows for the initial angular reading to occur in under 4ms.

The target for identifying the angle offset was found by trying to locate the steepest slope on the moon. That angle was determined to be plus or minus 45 degrees which occurs on the walls of lunar craters; this was discovered using the Lunar Orbiter Laser Altimeter (Kreslavsky, M. A., & Head, J. W., 2016). The angle offset of the lander after touchdown with the lunar surface directly impacts the leveling angle. The leveling angle is defined as the angle that is acceptable for the lander to be considered level. The range for this was determined to be zero plus or minus five degrees based upon speaking to Andrew Wayne at NASA. The target for factor safety was determined by using NASA's standard of 1.4 for spacecraft.

Detailed Description of Metrics

Metrics are the standard of measurement for the different functions and attributes of our design. The metrics were chosen based on the level of validation we needed to meet the targets for the different attributes of design. The metrics the team has used are: Angle, Power, Time, Stress Ratio, and Work. The angle metric has been used for identifying the angle offset and the leveling angle. Angle is the standard measurement that was chosen because it was the most concise and clear standard for designing a level system.

The power metric was chosen for transforming electricity into mechanical motion, receiving power, and translating power. The power metric was chosen specifically for the metric system units of power (N*m or kN*m) since the weight requirement was given in metric tons (1000 kg = 1 metric ton). The power metric is needed because of the range of motion and the weight the project must support.

Time was chosen for recognizing a signal, detecting a signal, processing a signal identifying a signal, halting mechanical motion, and the time it takes to level. All the functions that must deal with the different signal inputs have time as their metric because having a fast response time will reduce the time it takes the system to do calculations and begin leveling. Halting mechanical motion's metric is time for the astronauts to begin their work. The time it takes to level is measured in minutes which is a time measurement.

Stress ratio was chosen as a metric for the function of factor of safety since it is determined by the ultimate stress divided by the working stress of the project. This was chosen because the team needs to consider factors of safety when it comes to working with NASA and their human landers system.

The last metric is work; this was chosen for the work required for motion. As stated above the range of motion and weight of the project creates forces and to overcome those forces work needs to be done to achieve the goal of a level working environment for the astronauts.

Critical Targets and Metrics

Attributes of Design	Target	Metric	Method of Validation
Identify Angle Offset	0° ± 45° Degrees	Angle	Inertial Measurement Unit (IMU), used to measure physical orientation attributes
Leveling angle	0° ± 5°	Angle	Inertial Measurement Unit (IMU), used to measure physical orientation attributes
Transform Electricity into Mechanical Motion	130.8 kW to 470.88 kNm (Earth)	Power	Observe if the motors run when voltage is sent through the system.

	21.6 kW to 77.76 kNm (Moon)		
Time to level	55 minutes	Time	Stopwatch

Table 3: Critical Targets and Metrics

The mission critical elements of this design are in the table above and consist of transforming electricity into mechanical motion, leveling angle, time to level, and identifying the angle offset. Transforming electricity into mechanical motion is considered a critical function because it has the most overlap between functions. It is shared between the main functions of motion, power, and lander making it an extremely important aspect of the project. If this fails it will affect multiple other main functions and will cause the system to fail. Leveling angle is critical because the main objective of the project is to obtain a level environment for the astronauts. If the cabin is not level, then the mission is deemed a failure. Time to level is considered critical because of NASA's con-ops. Con-ops are the timeline of events for the astronauts with an effort on maximizing efficiency. If the design takes too long to level it will affect the rest of the mission which will ultimately shorten the time the astronauts have to complete their tasks on the lunar surface, potentially leaving no time at all. If this were to occur, the mission would be deemed a failure. Finally, identifying the angle offset of the lunar module is critical because of the need to know the module's orientation to accurately adjust. If the design cannot correctly identify the original angle offset from level, the design will not function properly causing mission failure. The team assessed every attribute in the first column of the above table and concluded that these four were the most important functions and failure to complete any would result in total mission failure.

Method of Validation

To test the leveling angle and identify the angle offset the team will use an IMU (inertial measurement unit) to measure the orientation of the module. This value will then be compared to the local vertical. If the leveling angle is within plus/minus 5 degrees of 0 degrees, this is ruled a success. The IMU will be used similarly to calculate the orientation of the module prior to leveling. This value will then be compared to the local vertical so the system will know how to alter the module. To validate the mechanical motion, the team will simply observe the system. Once power is supplied and an angle offset is identified, if there is no mechanical motion, the team will know there is failure. If the team can cause some mechanical motion, they will count this function as a success. Finally, to validate the time to level a stopwatch will be used. If the system does not accurately level the module within 55 minutes, this target will be a failure.

1.5 Concept Generation

Concept Generation Tools

For concept generation, coming up with 100 concepts is no easy task. When thinking about various concepts, often there are barriers to creative thinking, such as mental and perceptual blocks. To combat these, the use of concept generation tools can be helpful. Regarding this project, the tools of biomimicry, crap shoot, and a morphological chart were used.

Biomimicry is an approach to concept generation that looks at nature to solve the problem at hand. Since this project involves the leveling of a lunar lander that has legs, the team thought of the legs of a spider. Whether the design will have eight legs or not, the concept of how a spider’s legs can move to stabilize a spider’s body is where the value lies. The idea of legs that can bend at multiple joints, independent of each other, is where the team was able to draw some concept ideas from. The team played around with the number of legs needed for the design and the driver of motion, but the concept was generally the same.

Number of Legs	Mode of Motion	System Orientation
4	Pneumatic	In-line with Gears
6	Mechanical	External on Legs
8	Electromagnetic	External on Body

Table 4: Morphological Chart

Above is a morphological chart that was used to create concepts. With this chart, concepts were created varying the number of legs, mode of motion, and the system orientation. Besides the number of legs, the modes of motion were included as recommendations from one of the team’s NASA contacts. Also included from this contact were the different system orientations possible. The system orientation of the concepts will determine if the system will be in-line with the gears, requiring collaboration with the shock absorber team, or either on the body or legs where no collaboration will be necessary. This chart was used by choosing an option in the first row, then an option in the second row, and another option in the third row to create a concept. This process was repeated multiple times to create different concepts by varying these three categories.

The third concept generation tool used was crap shoot, which was thinking of random, out of the box concepts to solve the problem. This tool was used to create a few different concepts based on ideas that would not typically be thought of. Some of the concepts created using crap shoot were out there, such as using one leg for the lander, stabilized by a large gyroscope. Even those these concepts were strange, they led to other more realistic concepts that could be viable.

Selected Concepts

Out of all 100 concepts, the following eight concepts were chosen. These concepts vary in their design, but ultimately seemed like the most realistic and usable out of all 100. It was decided that among the concepts chosen, the sensing method will remain constant. This was done to normalize the concepts and compare them by focusing on more variant characteristics. The team deemed varying sensing an unfair to give one concept an advantage or disadvantage over another because of sensing characteristics. Also, the team decided to assume that the lander will perovide enough power for each of the concepts.

High fidelity

Concept 1.

Mechanically actuated linear rods that placed between the legs and lander base that extend and retract to level the capsule.

This concept will use four actuating linear rods placed at four points between the lander base and legs that will be mechanically raised and lowered until level is achieved. The idea behind this concept is that the rods will only have to level the lander capsule and not the entire lander. It will use the onboard sensors of the lander to detect the need to level and will be able to easily level in the amount of time required. One of the strengths of this concept is that it will be housed inside the lander body and safe from the lunar environment. Reusability is also a strength of this concept as the rods would just need to be calibrated on Earth, or not at all depending on how much they needed to level for the prior landing.

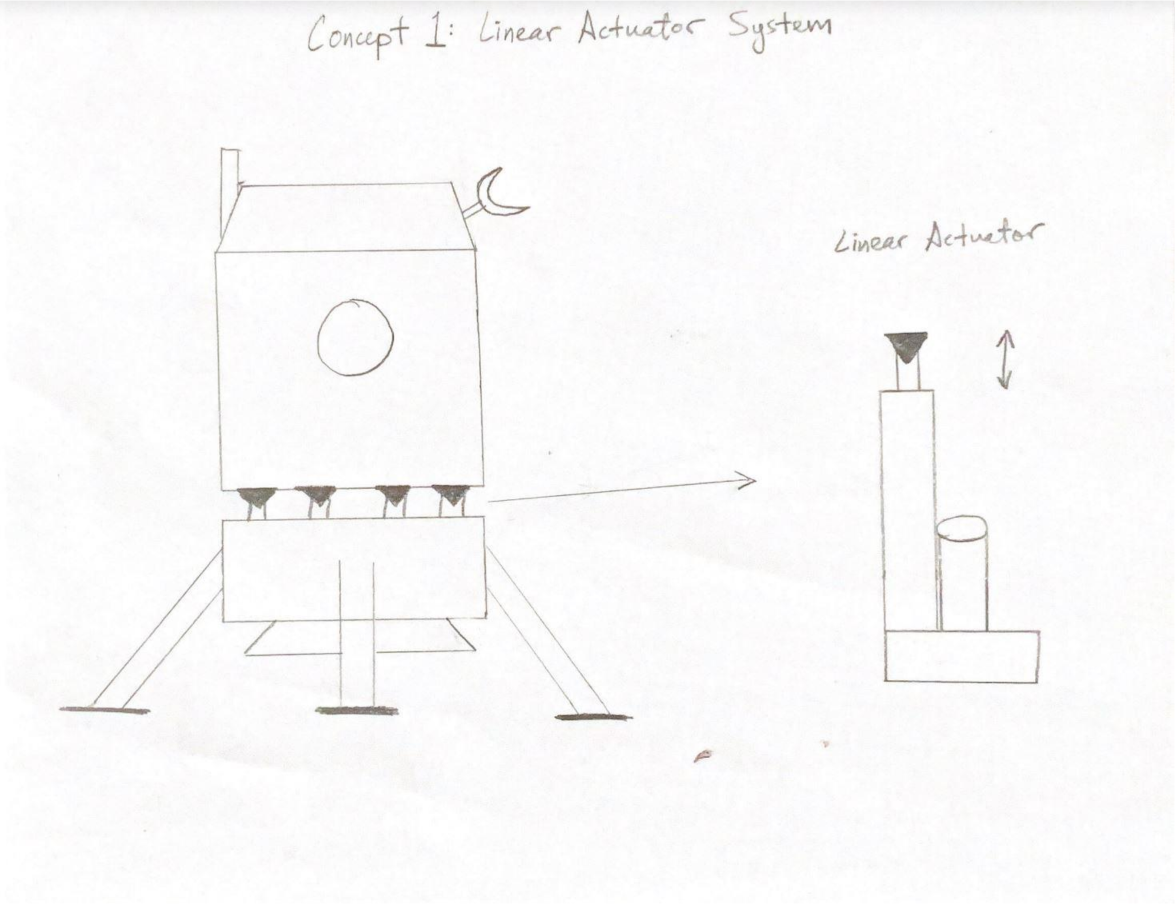


Figure 2: Concept 1

Concept 2.

Telescopic leg modules that are separate from the lander's legs and are attached to the side of the lander that extend after landing and lock in place mechanically.

This concept will have telescopic legs on the sides of the lander in between pairs of the lander legs. These legs will be secondary and not used for landing purposes. The idea is that they will deploy as necessary depending on the need to level. They will be made of a specialized material that can be exposed to the lunar environment. The legs will mechanically deploy and lower from housing built into the outside of the lander. The lander will be leveled by the legs pushing into the lunar surface until level. The motors to extend the legs will be included in the housings and there will be a brush like bottom to the housing to dust off the regolith from the legs once they contract. This concept will use the onboard sensors of the lander to detect the need to level and will be able to easily level in the amount of time required.

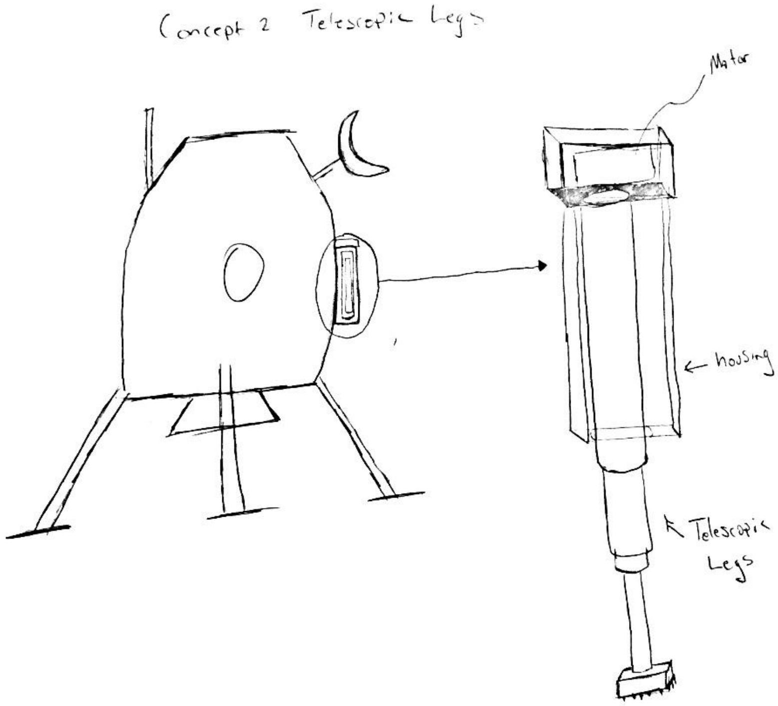


Figure 3: Concept 2

Concept 3.

Spring system between the lander base and legs like a 3d printer bed.

This concept would be designed from the way a 3D printer bed operates for leveling. Four springs would be placed between the lander base and legs and would be fully extended in this space. This concept will use the onboard sensors of the lander to detect the need to level and the springs will be mechanically tightened using individual motors until the lander is level. This is another concept where the system will be safe from the outside environment and will not be fighting the forces of gravity the lander weight to lower. The springs may also provide an added benefit for force dampening upon landing. Reusability for this design is also good because ideally the springs will be able to be extended or contracted if necessary so they motor can reset the springs after loading.

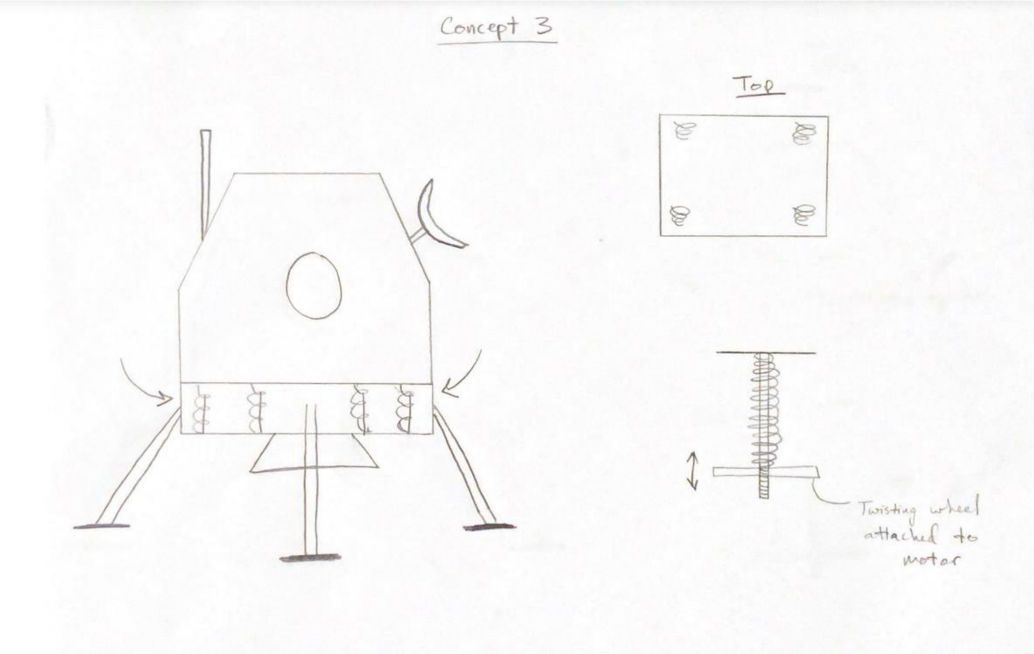


Figure 4: Concept 3

Medium Fidelity

Concept 4.

Three-legged mechanical extending in-line with gear to act as a tripod.

This concept would be a total leg design for the lander. Three legs would be designed to act as a tripod to support the lander. In line with the gear of each leg, there will be rods that can be mechanically actuated to extend to level the lander. These rods will most likely be housed inside the legs along with the motors. This concept will use the onboard sensors of the lander to detect the need to level and the springs will be mechanically tightened using individual motors until the lander is level. The need for legs will save weight for the lander and can allow the legs to be robust to support the lander weight.

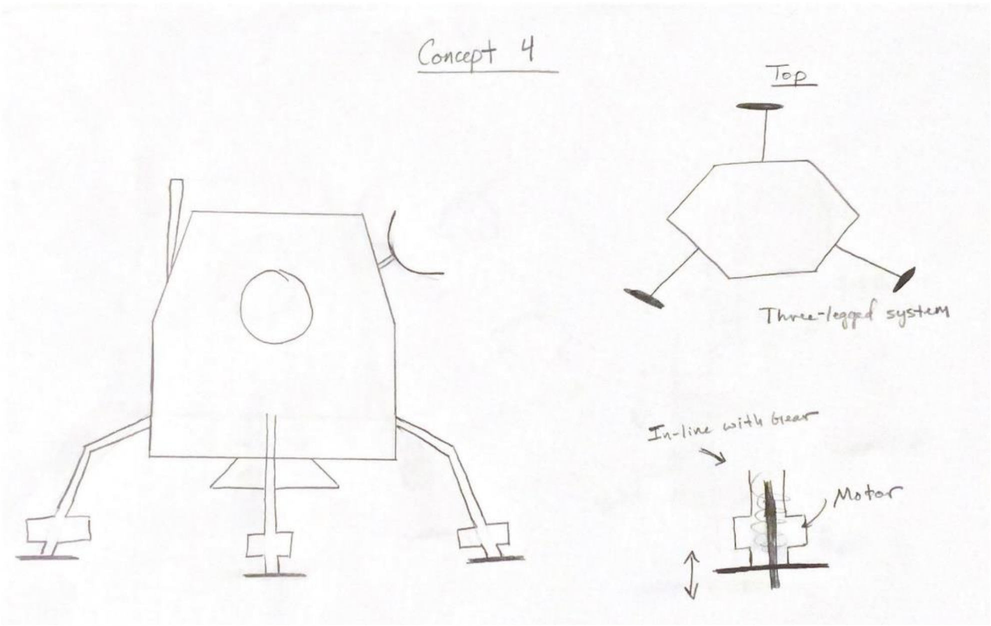


Figure 5: Concept 4

Concept 5.

Gas chambers that release gas at four points to level itself.

The idea behind this concept is to use gas chamber like pistons located at the base of the legs of the lander. There will be a high-pressure gas chamber with a piston to move when gas is released. When the onboard sensors sense the need to level, the gas would be slowly released until the lander is level. The biggest drawback of this design is that the high pressure of the gas chambers has the potential to explode if something were to go wrong. This provides an added danger to the system and needs to be heavily considered. This design would be filled with the chosen gas so that gas is only required to be released through a mechanical valve.

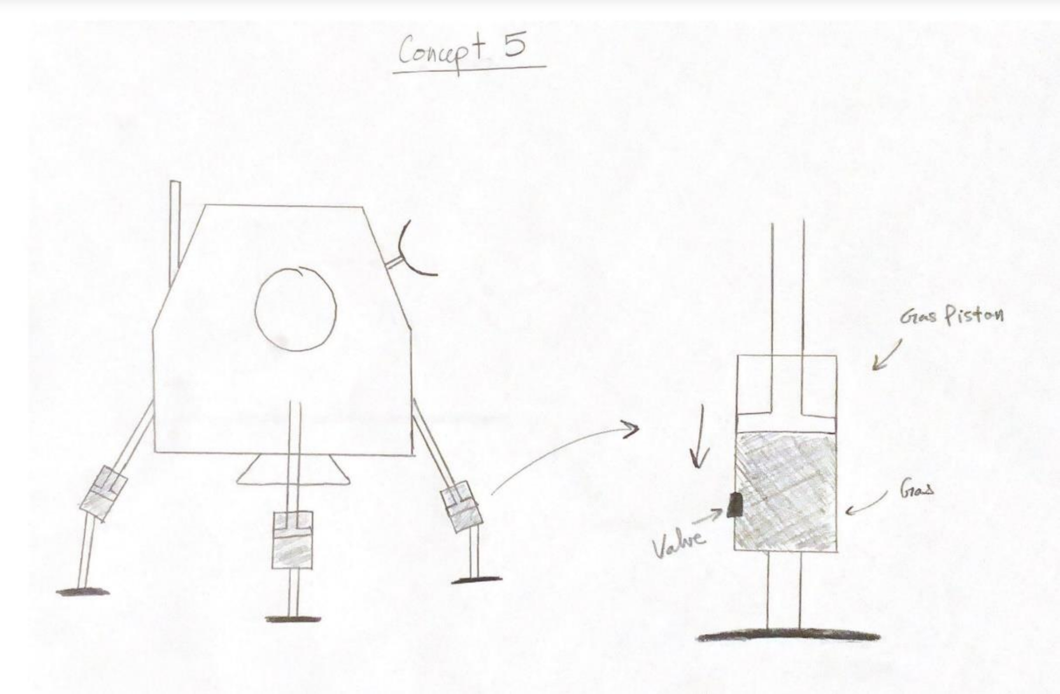


Figure 6: Concept 5

Concept 6.

Slider system between the legs and lander base to move the center of gravity until level.

This concept would have a four-way slider system between the lander base and legs that would be able to move the lander body to move the center of mass until level is achieved. The idea is that moving the center of mass would balance out the static forces acting on the lander to get to level. Once the lander body slides into place it would stay there until take off, where it would move back to its original location. Being a connection between the lander base and the legs, this concept will be protected from the lunar environment and be reusable, as it is just a mechanical slider. This concept would use the on-board sensors and draw power from the lander's power supply.

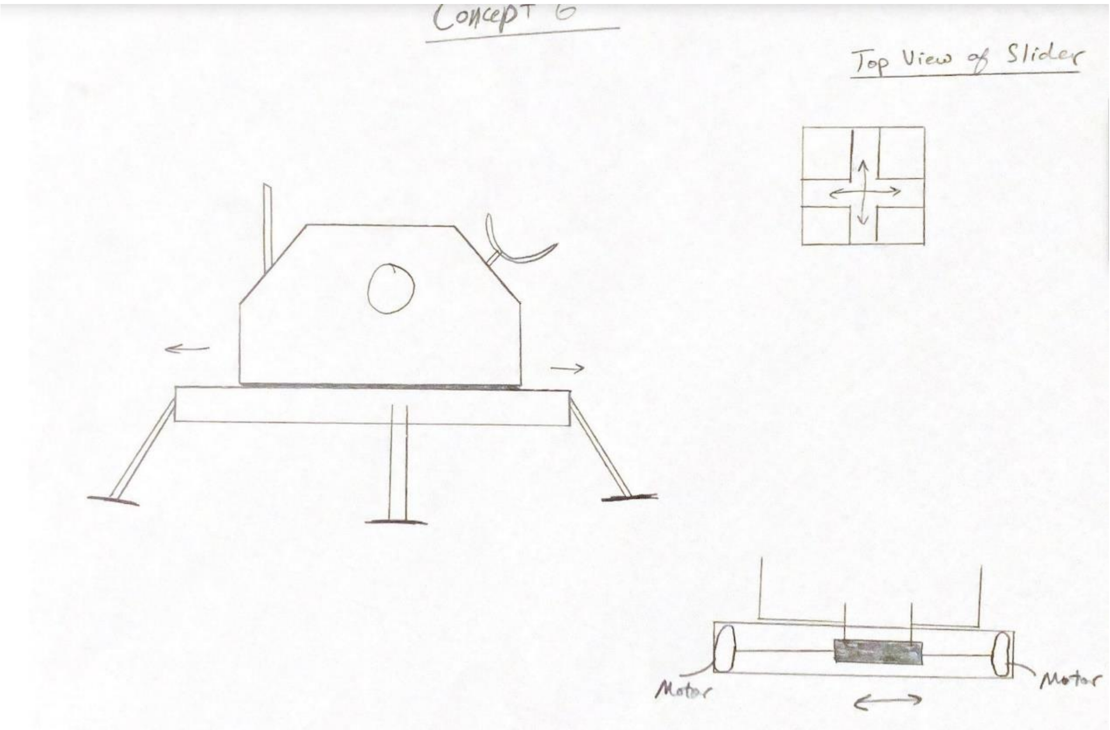


Figure 7: Concept 6

Concept 7.

Secondary landing gear (not used for impact) with three independently controlled arms that can be adjusted to level.

This concept would have secondary arms not used during landing that would deploy to level the lander. These would be stored on the sides of the lander and extend outwards. This concept would use the on-board sensors of the lander and draw from the lander's power supply. One of the drawbacks of this design is that the secondary legs will be constantly exposed to the outside lunar environment. This could lead to extra material needs that can increase the complexity of the concept. The legs would extend out and lift the lander until it reaches level, and then they would lock in place and hold that position. Reusability of this design depends on the capabilities of the materials used to withstand the lunar environment.

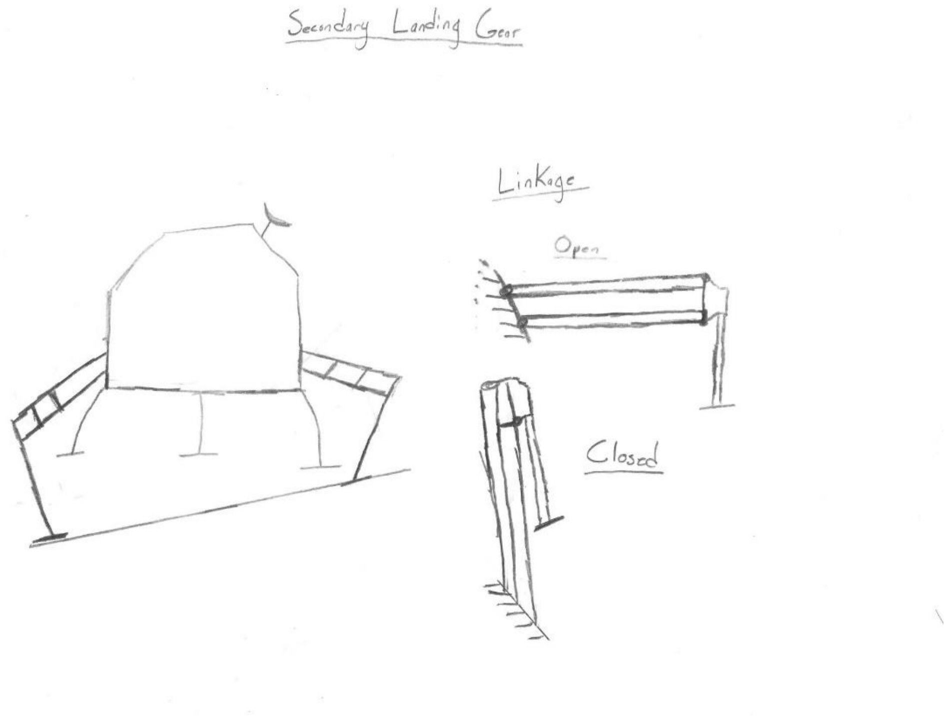


Figure 8: Concept 7

Concept 8.

Gear and track on legs to extend/shorten legs to level.

This concept would have a gear and track system on the legs that would extend and shorten the legs until necessary. One of the benefits of this design is that it would be able to expand and contract from the beginning, allowing for small adjustments on the legs to achieve level. The downside to this design is the potential damage that can be done to the gears from the highly abrasive regolith. This concept would again use the lander sensors for leveling and would draw from the lander’s power supply.

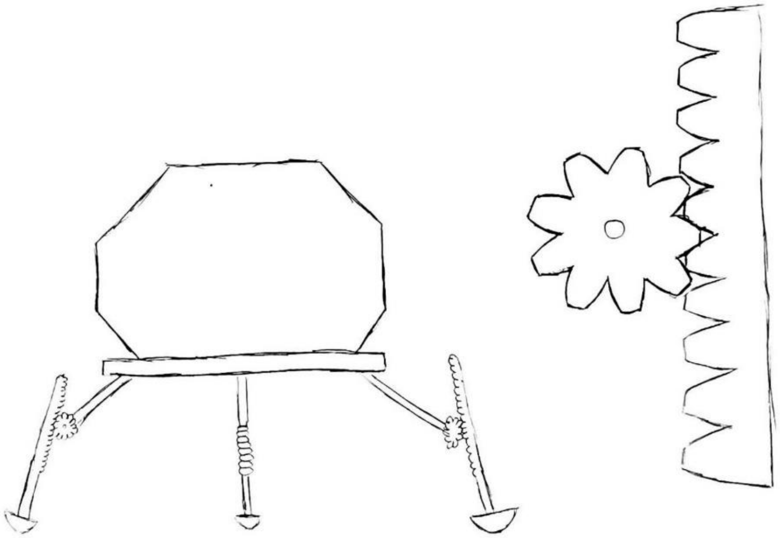


Figure 9: Concept 8

1.6 Concept Selection

Binary Pairwise Comparison

	1	2	3	4	5	6	7	Total
1. Sub-hour Level Time	-	1	0	0	0	0	1	2
2. Lightweight	0	-	0	0	0	0	1	1
3. Stability	1	1	-	0	1	0	0	3
4. Reusability	1	1	1	-	1	1	0	5
5. Safety Factor	1	1	0	0	-	1	0	3
6. No/Low Maintenance	1	1	1	0	0	-	0	3
7. Manual Override	0	0	1	1	1	1	-	4
Total	4	5	3	1	3	3	2	21

Table 5: Binary Pairwise Comparison

The above chart is a binary pairwise comparison between the customer requirements to obtain the far-right column, which are the importance weight factors. The chart has the customer requirements in the left column, along with their corresponding numbers in the top row. In the chart, it was determined if the row beats the column, if so, a 1 would be placed in the corresponding box. For instance, if row 2 beats column 1, a 1 is placed in the box. Now the pairwise portion of the chart relates to the box opposite the diagonal getting the opposite value.

So, if box (2,1) gets a 1, box (1,2) gets a 0. This process was carried out until all the boxes were filled.

The far-right column is the important part of the chart and represents the importance weight factors. The numbers were added up across each row to determine which customer requirements have the most precedence. From the chart, it was noted that reusability was the most important customer requirement and received a weight factor of 5. This was carried out for each customer requirement to determine all seven importance weight factors. These weight factors are then used in the House of Quality.

House of Quality

For the engineering characteristics in the House of Quality, the team decided to bundle similar functions into one overarching characteristic. This led to recognizing, detecting, processing, and identifying signals to be encompassed in signal processing, identifying angle offset and leveling angle becoming angle resolution, and transforming electricity into mechanical motion, receiving, and translating power to be power requirements. The decision to combine these characteristics was because they were all similar enough that the units and improvement directions were all the same.

House of Quality									
		Engineering Characteristics							
Improvement Direction		↑	↓		↓	↓	↑	↑	↓
Units		Degrees (°)	Time (ms)	Power (kW)	Time (minutes)	Time (minutes)	Stress Ratio	Deterioration Rate*	kNm
Customer Requirements	Importance Weight Factor	Angle Resolution	Signal Processing	Power Requirements	Halt Mechanical Motion	Time to Level	Factor of Saftey	Enviromental Resistance	Work
Sub-Hour Level Time	2	**3**	**9**	**3**	**9**	**9**	**3**		**3**
Lightweight	1				**6**	**9**	**6**	**3**	**6**
Stability	3	**3**	**6**		**6**	**3**	**9**	**6**	
Reusability	5	**3**	**3**	**3**	**3**	**3**	**3**	**9**	**3**
Safety Factor	3						**9**	**9**	
No/Low Maintenance	3						**6**	**9**	
Manual Overide	4		**9**	**3**	**9**	**9**	**9**		
* Deterioration rate includes: corosion rate, electrical resistivity, Coefficient of Thermal Expansion,	Raw Score (618)	**30**	**87**	**39**	**93**	**87**	**135**	**120**	**27**
	Relative Weight (%)	**4.85%**	**14.07%**	**6.31%**	**15.04%**	**14.07%**	**21.84%**	**19.41%**	**4.36%**
	Rank Order	**6**	**4**	**5**	**3**	**4**	**1**	**2**	**7**

Table 6: House of Quality

Above is the House of Quality, where the importance weight factors from the binary pairwise comparison are factored into the engineering characteristics. Depending on how important each engineering characteristic was to a customer requirement, it received a score of either three, six, or nine. These numbers were then multiplied by the importance weight factor and summed downwards to get a total. All the totals were then added up to get a raw score. Each sum was then divided by the raw score and got a relative weight percentage. Based on the weight percentages, each engineering characteristic was ranked. If a tie between characteristics was found, each one received the same rank.

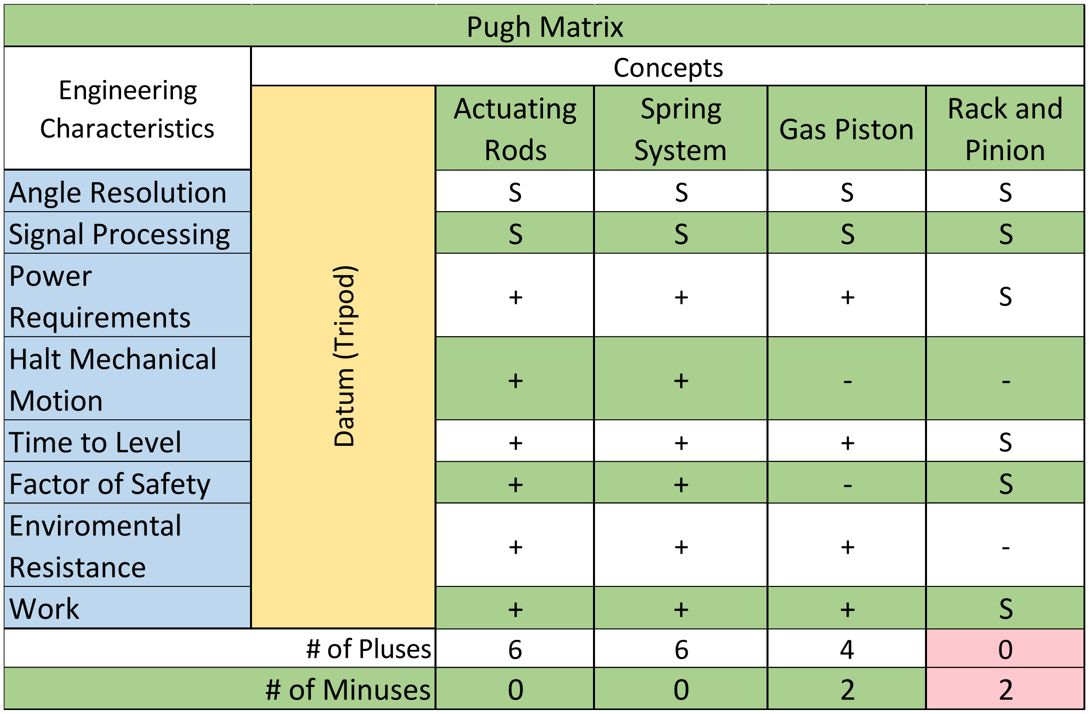
Pugh Matrices

Pugh Matrix									
Engineering Characteristics	Concepts								
	Datum (RV Automatic Leveling System)	Actuating Rods	Telescopic Legs	Spring System	Tripod	Gas Piston	Slider	Secondary Landing Gear	Rack and Pinion
Angle Resolution		+	+	+	+	+	+	+	+
Signal Processing		+	+	+	+	+	+	+	+
Power Requirements		+	+	+	+	+	+	+	+
Halt Mechanical Motion		S	S	S	S	S	-	S	S
Time to Level		-	-	-	-	-	-	-	-
Factor of Safety		-	-	-	-	-	-	-	-
Enviromental Resistance		+	+	+	+	+	+	+	+
Work		+	+	+	+	+	-	S	S
# of Pluses		5	5	5	5	5	4	4	4
# of Minuses		2	2	2	2	2	3	2	2

Table 7: Pugh Matrix 1

The above Pugh matrix is the first one that the team developed. When choosing the first datum to be used, the team had to decide between using the Apollo lander or an actual self-leveling system to compare to. The team selected an RV with an automatic self- leveling system as the datum because they felt it was a fairer assessment than the Apollo lander, which had no self-leveling capabilities. For the pluses, better angle resolution, quicker speeds for characteristics involving time, and better environmental resistance received a plus. The power requirements and work characteristics were given a positive for the concepts that required less of each.

From the initial Pugh matrix, the slider concept was chosen as the new datum to repeat the process as it received four pluses, but also the most minuses. The second Pugh matrix led to the elimination of the Telescopic Legs and Secondary Landing Gear concepts, and the Tripod as the datum for the third and final Pugh matrix. The final Pugh matrix resulted in the elimination of the Rack and Pinon concept, which left the team with the Bottle Jack, Spring System, and Gas Piston concepts as the ones to carry on further in the concept selection process. The results of the final Pugh matrix can be seen below.



Pugh Matrix					
Engineering Characteristics	Concepts				
		Actuating Rods	Spring System	Gas Piston	Rack and Pinion
Angle Resolution	Datum (Tripod)	S	S	S	S
Signal Processing		S	S	S	S
Power Requirements		+	+	+	S
Halt Mechanical Motion		+	+	-	-
Time to Level		+	+	+	S
Factor of Safety		+	+	-	S
Enviromental Resistance		+	+	+	-
Work		+	+	+	S
# of Pluses		6	6	4	0
# of Minuses		0	0	2	2

Table 8: Final Pugh Matrix

Analytical Hierarchy Process

Analytical Hierarchy Process								
Criteria Comparison Martrix								
	Angle Resolution	Signal Processing	Power Requirement	Halt Mechanical Motion	Time to Level	Factor of Safety	Enviromental Resistance	Work
Angle Resolution	1	3	5	3	3	3	5	7
Signal Processing	0.33	1	5	3	5	0.33	0.33	7
Power Requirement	0.20	0.20	1	0.20	3	0.20	0.33	3
Halt Mechanical Motion	0.33	0.33	5	1	0.33	0.33	0.33	5
Time to Level	0.33	0.20	0.33	3	1	0.33	0.33	5
Factor of Safety	0.33	3	5	3	3	1	3	5
Enviromental Resistance	0.20	3	3	3	3	0.33	1	7
Work	0.14	0.14	0.33	0.20	0.20	0.20	0.14	1
Sum	2.863	10.870	24.660	16.400	18.530	5.720	10.460	40.000

Table 9: Main Analytical Hierarchy Process

Consistency Check		
{Ws}=[C]{W} Weighted Sum Factor	{W} Criteria Weights	Cons={Ws}./{PI } Consistency Vector
2.894	0.294	9.852
1.391	0.141	9.865
0.532	0.056	9.583
0.743	0.080	9.270
0.676	0.075	9.040
1.988	0.191	10.427
1.469	0.143	10.302
0.190	0.021	8.850

Table 10: Consistency Check

λ	9.649
CI	0.210
CR	0.168

Table 11: Lambda, CI, and CR

The first step of the Analytical Hierarchy Process can be seen above. In this step, a pairwise comparison is done measuring the importance of each column to each row on a scale from 1-7 odd numbers. Once all the numbers were obtained, the columns were summed downwards to get the total sum of each column. To normalize the matrix, each element in a column was summed by its corresponding total sum to obtain numbers that when added together equal one. Once the matrix was normalized, the rows were then summed across to get criteria weight factors for each engineering characteristic. These criteria weight factors where then multiplied by the original AHP pairwise matrix to obtain weighted sum factors. The weighted sum factors where then divided by the criteria weights to get the consistency vector. Taking the average of the consistency vector and completing the above operations resulted in a CR value of 0.168, which means that the results of the Analytical Hierarchy Process for all engineering characteristics were slightly biased.

Final Rating Matrix

Following the above process, the AHP was then carried out for the three remaining concepts for each of the engineering characteristics. The average consistency checks for these matrices were approximately 0.12, which means there may have been some bias in calculating. For each engineering characteristic, a Pi column was obtained that was then put into the final rating matrix. The characteristics of angle resolution, signal processing, and halt mechanical motion all had a Pi column of ones because there was no distinguishable difference between the three concepts. The Final Rating Matrix and the criteria weights calculated from the first AHP step can be seen below. These matrices were multiplied together to get the alternative values for the final decision matrix, which can also be seen below.

Final Rating Matrix								
Selection Criteria	Angle Resolution	Signal Processing	Power Requirement	Halt Mechanical Motion	Time to Level	Factor of Safety	Enviromental Resistance	Work
Actuating Rods	1	1	0.575	1	0.575	0.575	0.286	0.575
Spring System	1	1	0.286	1	0.286	0.286	0.575	0.139
Gas Piston	1	1	0.139	1	0.139	0.139	0.139	0.286

Table 12: Final Rating Matrix

{W} Criteria Weights
0.294
0.141
0.056
0.080
0.075
0.191
0.143
0.021

Table 13: Criteria Weights from Main AHP

Concept	Alternative Value
Actuating Rods	0.753
Spring System	0.692
Gas Piston	0.586

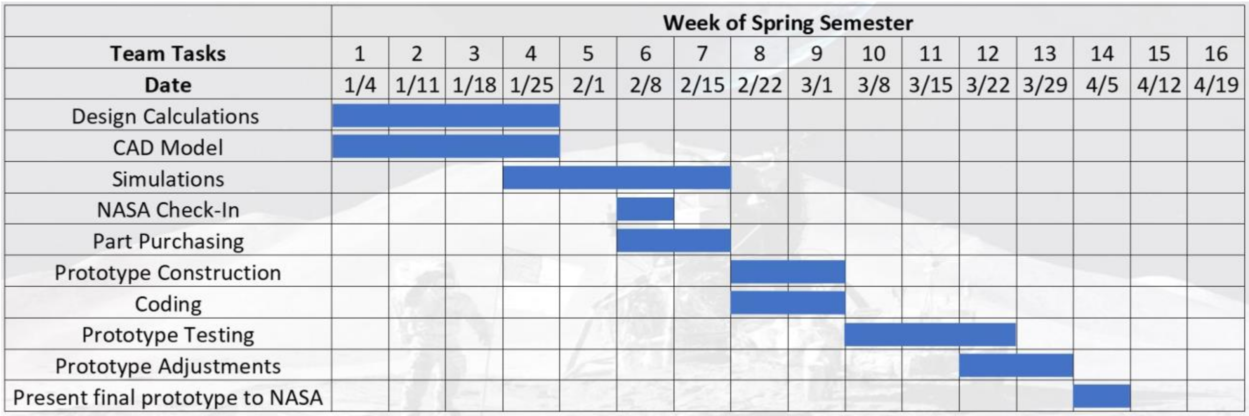
Table 14: Final Decision Table

Of the three concepts put through the Analytical Hierarchy Process, the winning concept was the Actuating rods system. This concept will use linear actuators placed between the lander base and legs, where they will be rigidly attached for support. These actuators will be fully retracted upon landing and will be extended to level the lander cabin. The drawing of this concept can be seen in Figure 2 above. This concept allows for the lander cabin to be raised and lowered, depending on the actuator positioning, to achieve a high tolerance of level.

Even though there was some slight bias potential throughout the AHP, proven by the consistency checks, the team feels that the final concept is ultimately the best option. One thing to note is the small difference in score between the actuating rods and spring system. This is because the two concepts are very similar and only differ in what is used to level. Both concepts would be in the same location and use the same process to level. The team feels the need to further explore both options and may determine that the springs could be a more viable option.

1.8 Spring Project Plan

Project Plan.



	Week of Spring Semester															
Team Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Date	1/4	1/11	1/18	1/25	2/1	2/8	2/15	2/22	3/1	3/8	3/15	3/22	3/29	4/5	4/12	4/19
Design Calculations	■	■	■	■												
CAD Model	■	■	■	■												
Simulations				■	■	■	■									
NASA Check-In						■										
Part Purchasing						■	■									
Prototype Construction								■	■							
Coding								■	■							
Prototype Testing										■	■	■				
Prototype Adjustments												■	■			
Present final prototype to NASA														■		

Table 15: Spring Project Plan

The above table shows the team's intended project plan for the spring semester. The team plans on finalizing the calculations and CAD model within the first four weeks of the semester. The calculations are important to prove the validity of the linear actuator concept as a leveling system. The finished CAD model will illustrate what the eventual prototype will look like and help to determine the number of parts and material needed to build the prototype. Growing from the CAD model, the idea is to conduct simulations to help better understand how the system is to work and how it will fit mission specifications. Once the concept is proven to be valid, the team intends to meet with NASA to discuss their findings before proceeding to the next steps of the project. Following this meeting, two weeks have been allocated for part purchasing in case there are delays in shipping. Even though construction and coding are to be worked on continuously until the end of the project, two weeks have been given to speed up these processes. Following these steps, testing and fine tuning of the project will bring the team to project completion and the end of the semester.

Build Plan.

The build plan for the project revolves around attempting to recreate the CAD model to have a physical prototype. The CAD model will be designed to the exact specifications mapped out by the team to ensure the proper size is achieved. For the steps for building the prototype, the intention is to first build the leveling component of the system, which is attaching the actuators to the two wooden platforms to begin preliminary testing. Once the actuators are in place, extensive wiring will take place to minimize clutter and enable the actuators to function properly and safely. The team plans on 3D printing electrical housing components for the upper platform of the prototype. These housing will be designed for functional and aesthetic purposes. After the main leveling component is built, the team will provide the machine shop with engineering drawings and material to develop the frame of the prototype. This frame will be combined with the leveling component to complete the prototype.

Chapter Two: EML 4552C

2.1 Restated Project Definition and Scope

Project Description

Last time NASA landed on the moon, the plan was for the Apollo mission to land on the lunar plains to provide the most stable environment for landing and takeoff. The next mission to the moon, anticipated to be in 2024, is projecting a lunar landing on the South Pole in search of water deposits. Due to the uneven terrain on this part of the moon’s surface, a self-leveling capability is needed for the lander to ensure a stable foundation for the next landing and takeoff, as well as a level working environment inside the lunar module’s cabin. The self-leveling system is to be designed to handle this uneven terrain, which is expected to have a slope, endure the effects of regolith, and encounter extreme temperatures.

Key Goals

The key goals for this project are to develop and prototype a system that allows the NASA lunar lander to land on uneven terrain. The system will account for basic environmental factors such as temperature, low-gravity, and the vacuum of space. Surface temperatures of the moon can vary between -170℃ and 120℃, rendering most electronics ineffective. The low gravity of the moon will require modifications of basic kinematic calculations.

The desired landing location of the moon is the southern hemisphere in search of water. Because of this, the system will need to account for the dusty, uneven conditions and the possibility of water. Additionally, the team will strive for a lightweight design that can operate with as little energy consumption as possible. The system must be able to level and stabilize in up to one hour. Reusability should be taken into account such that the system can be used for up to 10 missions or 10 years. The goal is to define a versatile system that meets the previous constraints.

Primary Markets

The Human Lander Program at NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) would be the primary market for the project. The team there is interested in a new self-leveling design for the Artemis missions to the lunar surface in 2024, as well as to Mars for future missions.

Another primary market could be for different commercial space exploration companies, such as SpaceX, Blue Origin, Virgin Galactic, and others. These companies work with NASA as partners on the Artemis missions to make the landers. They will be able to use the self-leveling system on their own projects in their missions to space as well.

Secondary Markets

The secondary markets for this system would include anything where self-leveling is a desired feature. This includes RV's, cruise ships, or construction machines, such as cranes. This system would apply to each of these markets because uneven terrain is a problem for each. If parked on a large slope or going over large waves, this technology could be repurposed to keep tables, beds, or appliances flat. This is also applicable to the construction industry where crews encounter environments with uneven terrain, making it difficult to see and operate large, heavy machinery.

Assumptions

Team 516 is only responsible for the design of a self-leveling system for a human lander; they are not responsible for the application of the system into various human landers. The team will test the prototype under Earth's conditions on a terrain similar to the lunar landing site. The team will then process the test results while considering the lunar impacts. The team will not be responsible for the mapping of the terrain prior to landing. The lander will contact the lunar surface and then adjust accordingly, operating within an acceptable range of slope, deemed ±12° from the local vertical. To account for the effects of space and the lunar atmosphere, specialized software will be used to design and simulate the lander in various situations. The team will aim to create an energy efficient design but will not be responsible for the energy production. The system will also assume that data for the landing environment will be available from the on board IMU. This sensor will be housed in a temperature-controlled climate and protected from the elements.

Stakeholders

The stakeholders for this project include the NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO), the companies NASA has enlisted in the Commercial Lunar Payload Services (CLPS), the FAMU-FSU College of Engineering, the senior design coordinator Dr. Shayne McConomy, and the team advisor Dr. Dorr Campbell. NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) is the main stakeholder in that it has provided the team with the task at hand and will provide the funding necessary for this project to be completed.

Other stakeholders for this project include the companies NASA enlisted in the Commercial Lunar Payload Services (CLPS). This project will have a direct impact for these companies in aiding them to develop future lunar technologies. The FAMU-FSU College of Engineering is a stakeholder as it is the main bridge between NASA and the engineering team working on the project. Dr. Shayne McConomy is a stakeholder because he oversees all the mechanical engineering senior design projects and must ensure the success of each, including this one. Lastly, our faculty advisor Dr. Dorr Campbell is a stakeholder due to the knowledge and support he provides to the team.

2.2 Results

Upon testing the physical prototype, the team was able to uncover some significant findings on the efficacy of the linear actuator design. The first part of testing the prototype was ensuring that the movement of the actuators did not add any additional movement to the rest of the lander. Since the design targeted the area between the ascent and descent stages of the lander, the team wanted to test to see if the initial landing position of the lander would be impacted from the leveling process. Testing proved that the starting position of the lander for each test was unphased by the leveling process.

The main tests for the prototype revolved around actual leveling abilities and how they met the project goals. The goals deemed most important for testing were the degree of angle, time to level, and reusability/calibration. For the degree of angle, the target number specified by NASA was a 12-degree slope. To test this, the team arranged and measured the prototype to a 12-degree slope in different orientations and used the actuators to level the upper platform. The distance the actuator needed to travel was determined using rotation matrices. The actuators move on what are called “counts” and it is possible to convert counts to inches. Once the rotation matrices were created for the distance traveled, the IMU fed the angle read into the rotation matrices and then the distance the actuator needed to travel was output in inches and then finally converted to counts to move the actuators to the proper position. The math for this can be seen in Appendix G: Calculations. The results of testing proved that the system was able to get consistently within five degrees of level and was able to achieve less than three degrees on nearly half of the tests performed. This was deemed a success for the ability of the system to properly level as needed. As the leveling tests took place, the team also timed how long it took for the system to start leveling until it reached its goal. The average time for testing was about 30 seconds, which was much faster than expected. Even though the system leveled quickly, there was no additional jerk or movement incurred on the rest of the lander. Rounding out the main testing was the ability for the system to return to its initial position for eventual take off. This was tested after each iteration in preparation for the next test. Having this ability proved the reusability of the system.

During testing, there was catastrophic failure to one of the actuators. As the team was testing more extreme angling cases, there proved to be too large of a load on the actuator and caused it to break at the connection between the actuator and encoder. The team had a goal of testing the system to failure to have test data and determine the limits of the system; there was approximately a 30-degree slope on the lander when the actuator broke. The reason for this failure was determined to be a horizontal creep force incurred on the actuators as they leveled. This means that the actuators were being forced towards each other by 0.3 inches towards the center; the overall setup restricted this movement. To lessen the moment felt by the baseplate, the team has determined rotating the actuator base ninety degrees would improve the longevity of the actuator and fully resolve the issue.

2.3 Discussion

At some points during this design process, the team had some doubts about the chosen design. On paper, the design seemed creative and effective for the given task. Clearly, it was a design that was more out of the box than anticipated, as NASA initially said their vision of the system was going to be something built into the legs of the lander. The team was satisfied with their ability to brainstorm and develop initial concepts that were more creative. The Local Vertical Leveling System (L.V.L.S) was chosen as an advanced concept to tackle the needs of NASA for future missions. The design can be optimized and there is a need for future work to be done.

One of the main concerns of this entire project was how the design would combat the harsh space environment. Included with the environment are the extreme temperature changes and the abrasive regolith on the moon. With the chosen actuator design, the idea was to shield the actuators, which are the main leveling component, as much as possible to avoid these conditions. Since the actuators are mainly housed in the lower stage, there is built in regolith protection and a small amount of thermal protection. The thermal protection is something that needs to be optimized moving forward to ensure the actuators do not have failure points due to the environment. Additional thermal shielding will be included in future work.

Through testing, the team was able to quantify the design and its abilities as a self-leveling system. The testing process was not as smooth as the team anticipated. The early stages of the code had trouble deciphering the initial orientation of the lander, leading to actuators moving in the opposite directions or not moving at all. In one of these cases, the system did not know its orientation which lead to an overcompensation of movement and broke an actuator. Following the critical failure of one of the actuators, an additional actuator was purchased to continue progress in developing the code and leveling system. From this continued testing, the rotation matrices were discovered as a useful tool for leveling and led the team to the realization of the internal creep force.

The contributions to engineering of this project are vast. Considering the current trajectory of space travel, it appears the frequency of missions will increase in the coming years. To minimize costs during these missions, elements of spacecraft are being reused for recurrent missions. The main struggle with reusing space equipment is the continued effects of the space environment and having materials and systems that can withstand this repeatedly. This project and design propose new ways to combat the environment.

In addition to facing the challenges of space, the leveling component of the system can have future applications. As more missions are on the horizon, there will be a need for a leveling component to counter potentially uneven or unstable landing conditions. Having a design with a minimal impact to the overall weight and design of the lander, yet still be able to effectively level, will be imperative. The coding of this project to continuously map out the lander position to level may prove beneficial for someone working in this space. The actuator system can be optimized in the future to not only provide leveling capabilities, but also add some structural integrity to the lander.

2.4 Conclusions

In conclusion, Team 516 was tasked with designing a reusable level system that could level a lander cabin up to a 12-degree slope within one hour. To do this, the team brainstormed 100 different concepts to come up with the best solution for the project. After taking several of the most promising concepts through an extensive concept selection process, the team deemed the linear actuator concept to be best overall. Deemed the Local Vertical Leveling System (L.V.L.S), the linear actuator concept uses four actuators placed between the legs and cabin of the lander to level the lander. The actuators are built into the lower stage to allow for thermal and environmental protection from the harsh space environment. After completing the CAD model for the system, a physical prototype was created to test the design and its functionality. Upon testing, the design met all the goals for the project and appears to have promising potential applications for the future.

2.5 Future Work

Team 516's future work is going to focus around three specific categories: failure prevention research, improvements of the control systems, and weight reduction. Failure prevention is something the team has considered greatly because the project will be implemented in space and failure is not an option. In the case something goes wrong with one of the actuators, the solution would be to create a control system that would enable the other three actuators to be able to level and support the cabin of the lunar lander. The main difference is that instead of doing calculations in rectilinear coordinates, you would convert to polar coordinates and create a dynamics control system based on these new constraints. Since failure prevention is so important to the NASA missions, Team 516 would like to include this topic in the future work. Even though failure was reached during testing and an actuator broke, failure can be taken further to ensure safety during the mission. One small part of this is exploring different techniques for lubricating all moving parts of our system. Currently, there is a lot of research being done on dry film lubricants and we believe this would be a good place to start in our own research.

The improvement of the control systems would greatly increase the speed of the time it takes to level. Currently, the design uses a two-axis system to level by taking two actuators on one axis and moving them in position and then moving the opposing two actuators on the other axis, which creates a plane. Team 516 hopes to do more improvements for the control systems to reduce the time it takes to level by going straight to the level point and moving more than two actuators at a time.

The final topic the team would like to research is weight reduction. Decreasing the number of actuators in the system will help reduce the weight, and as stated previously, only three points are needed to make a plane. With the number of actuators reduced it is possible to still achieve a level environment and reduce the weight of the system entirely. The next step would be looking into different materials to make the system lighter. Currently the team has specified using 2295 Aluminum Alloy and 301 stainless steel as the main materials used in the system. However, with increasing technologies there may be a better option on what to choose. These are the main concerns moving forward from the project and what we hope to see addressed in future work on this concept.

2.6 References

References

Kreslavsky, M. A., & Head, J. W. (2016). The steepest slopes on the Moon from Lunar Orbiter Laser Altimeter (LOLA) Data: Spatial Distribution and Correlation with Geologic Features. *Icarus*, *273*, 329–336. https://doi-org.proxy.lib.fsu.edu/10.1016/j.icarus.2016.02.036

Kreslavsky, M. A., & Head, J. W. (2016). The steepest slopes on the Moon from Lunar Orbiter Laser Altimeter (LOLA) Data: Spatial Distribution and Correlation with Geologic Features. *Icarus*, *273*, 329–336. https://doi-org.proxy.lib.fsu.edu/10.1016/j.icarus.2016.02.036Admin. (2017, July 27). A guide to aluminum use in the aerospace industry. Retrieved March 19, 2021, from https://continentalsteel.com/blog/aerospace-aluminum-guide/

Premium linear actuators. (n.d.). Retrieved February 13, 2021, from https://www.firgelliauto.com/products/premium-linear-actuators

Reichelt elektronik GmbH & Co. KG Internet Team (webmaster@reichelt.de). (n.d.). ARDUINO MEGA - Arduino Mega 2560, ATmega1280, USB. Retrieved January 11, 2021, from https://www.reichelt.com/de/en/arduino-mega-2560-atmega1280-usb-arduino-mega-p119696.html?GROUPID=6667&&r=1

S. (n.d.). *Landing Gear Concepts & Metrics Review*. NASA PowerPoint.

Fuchs, Y. (2007, June 28). Lunar Lander Landing System Dynamics Analysis, Testing, and Certification. NASA PowerPoint.

Project apollo diagrams. (n.d.). Retrieved February 13, 2021, from https://history.nasa.gov/diagrams/apollo.html

NASA’s Lunar Exploration Program Overview. (2020, September). Retrieved January 10, 2021, from https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

Appendices

Appendix A: Code of Conduct

Mission Statement

Team 516 strives to create a team-oriented environment in which all of its members feel confident in their ability to work, are open to new ideas, and are willing to voice their opinions. Through this, the team will be able to effectively synthesize innovative concept designs for the task at hand. Together, we are committed to achieving excellence through resilience and adaptive learning.

Team Roles

Jake Seaman- Project Manager and Systems Engineer

The project manager will act as the team leader and is responsible for keeping a schedule of project objectives and goals, delegating tasks to team members, finalizing documents, and the submission of all work. The project manager will keep the best interests of the project in mind, while maintaining an environment of open communication and teamwork amongst Team 516 and the project sponsor and advisor. The systems engineer will work alongside the controls engineer in helping to develop code for the dynamic system components of the project. This will include system integration and synergy between all components of the project design.

Parker Stensrud- Controls Engineer

The controls engineer is tasked with compiling the proper sensors and working with the design engineers and materials engineer to determine what method of controlling the system will work best and what hardware will interface with the software. The controls engineer is also responsible for writing and testing the code that will control the self-leveling system.

James Evans- Design/CAD Engineer

The design engineer will be responsible for the design of the system, working with the controls engineer on designing the dynamic system for the legs, and working with the materials/quality engineer for the testing of the legs. The design engineer will also be responsible for CAD models of these parts.

Dalton LeClair- Design/Test Engineer

The test engineer will be responsible for fully testing the system to determine if it fulfills the customer needs. They will measure the accuracy of system functionality and evaluate prototype satisfaction. The design engineer will also be responsible for modeling system components using holistic ideals and inputs from every team member.

Stephen Brown- Materials/Quality Engineer

The materials engineer will be responsible for carefully choosing the materials needed to best fit the project. This role includes, but is not limited to, calculating material strength as well as determining the weight of each component and how it will affect the project. The quality engineer will assist the test engineer in assuring the highest quality outcome and customer satisfaction.

All Team Members

All team members are responsible for the work that is assigned to them and their role for the project. For tasks that do not directly fall under one of the roles previously described, the team will work together to determine which member is most suited for the task. If help is needed, it is to be expressed to the group, but not taken advantage of. Team members will show support for each other and help in any ways that they can. They will always keep the project goal in mind and work together towards this goal. If there is an issue, the team will work to resolve it as a group in a constructive manner.

Communication

All group member meetings and official meetings with the team advisor and sponsor will be held via Zoom, dependent on the remote work situation. Formal communication concerning the project that does not require a meeting will be done through e-mail. All group members, the advisor, and the sponsor will be carbon copied on each email if they are not the direct recipient. The primary method of communication between group members will be done through phone call and text. All group members are to be active participants in communication, whether it be formal or informal. This involves being prepared to ask questions, provide ideas, and express their opinions on topics and issues in meeting and otherwise. All team members are expected to respond when necessary, within 24 hours.

Scheduling for meetings will be done between group members first, and then the group will reach out to the project sponsor or advisor once a time and date is agreed upon. The team will come up with at least two different meeting times to give everyone, including the sponsor and advisor, the ability to attend. Scheduling for work to be completed will be done based on when tasks are due. If there are time conflicts, the team will do its best to find a time suitable for everyone. If there is no way to find an agreed upon time for everyone, the time will be chosen where the most group members can attend.

Attendance Policy

Meetings will be held Tuesdays and Thursdays from 3:30-7:45pm, which is the allotted time scheduled for Senior Design class. Additional weekly meetings will be determined but the times may not be consistent. Attendance at these meetings is expected. Formal meetings are to be scheduled at least 48 hours prior to the meeting time. Anyone that cannot attend a formal meeting is to provide notice 24 hours in advance. Unless personal or urgent matters, attendance is mandatory. Attendance for all presentations is mandatory.

Attendance will be recorded when team members do not attend. There will be a three-strike policy for attendance before external support from Dr. McConomy will be included.

Time Management

All group members are responsible to effectively manage their time to complete their assigned tasks. This time management also includes completing non-Senior Design tasks to be able to attend meetings and complete work for Senior Design. The goal of this group is to have assignments completed 48 hours before the submission date.

Dress Code

Attire for formal and informal meetings, as well as presentations will be determined by the group on a case by case basis. This is expected to be suits for presentations and business casual for meetings with the project sponsor. For group meetings or meetings with the team advisor, informal attire is adequate. Dress code for any meeting not listed will be determined by the group.

Changes to Code of Conduct

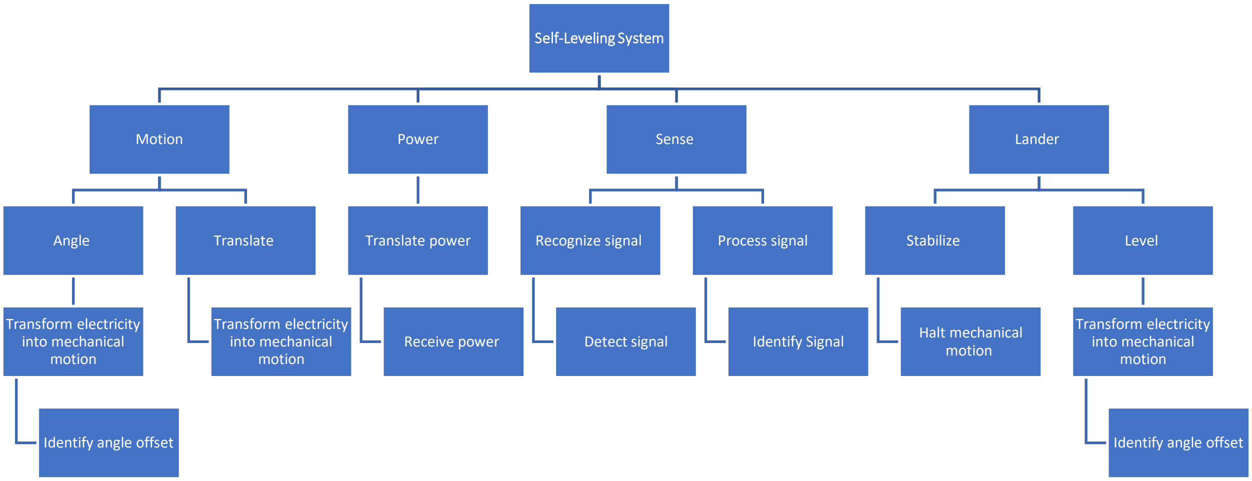
Any changes and or amendments to the Code of Conduct will be determined by the entire team. This will be done through a group meeting and will be changed in the document and uploaded to Basecamp.

Statement of Understanding

By signing this document, Team 516 and its members agree to the writing and guidelines set out by this Code of Conduct. Failing to abide by this document will result in the consequences outlined in this course.

J. T.	09/10/20
Team Member 1	Date
Parker	**09/10/2020**
Team Member 2	Date
	09/10/2020
Team Member 3	Date
	09/10/20
Team Member 4	Date
Stephen Brown	09/10/20
Team Member 5	Date

Appendix B: Functional Decomposition



Appendix C: Target Catalog

Attributes of Design	Target	Metric	Method of Validation
Identify Angle Offset	0° ± 15° Degrees	Angle	Inertial Measurement Unit (IMU), used to measure physical orientation attributes
Transform Electricity into Mechanical Motion	142.7 kW into 470.88 kNm (Earth) 23.6 kW to 77.76 kNm (Moon)	Power	Observe if the motors run when voltage is sent through the system.
Receive Power	142.7 kW (Earth) 23.6 kW (Moon)	Power	Wattmeter connected to the input/output of the locations for power input/output
Translate Power	142.7 kW (Earth) 23.6 kW (Moon)	Power	Wattmeter connected to the input/output of the locations for power input/output
Recognize Signal	1 ms	Time	Oscilloscope, used to plot the signals over time, clock rate measured in clock cycles per second
Detect Signal	1 ms	Time	Oscilloscope, used to plot the signals over time, clock rate measured in clock cycles per second
Process Signal	1 ms	Time	Oscilloscope, used to plot the signals over time, clock rate measured in clock cycles per second
Identify Signal	1 ms	Time	Oscilloscope, used to plot the signals over time, clock rate measured in clock cycles per second
Halt Mechanical Motion	5 minutes	Time	Inertial Measurement Unit (IMU), used to measure physical orientation attributes
Time to level	55 minutes	Time	Inertial Measurement Unit (IMU), used to measure physical orientation attributes

Leveling angle	0° ± 5°	Angle	Inertial Measurement Unit (IMU), used to measure physical orientation attributes
Factor of Safety	1.4	Stress ratio	Dividing the maximum stress by the working stress
Work Required for Motion	470.88 kNm (Earth) 77.76 kNm (Moon)	Work	Measure the distance that the Lander travels from start of level to end of level and calculate the work done.

Appendix D: Operation Manual

Project Overview

Team 516 was tasked with creating a self-leveling system for the NASA lunar landers for the Artemis missions scheduled in 2024. During these missions, NASA will be landing on the South Pole of the moon in search of water deposits. In this area, the lunar terrain is expected to be uneven which is anticipated to cause stability issues for the astronauts inside the lunar capsule. Because of this, the self-leveling system is intended to provide a level environment inside the capsule for the astronauts to work effectively.

In addition to leveling the capsule, other key goals for this project are for the system to be lightweight, reusable, and level the capsule within one hour of landing. Since weight is one of the most important characteristics of any NASA design, it was very important for the system to have as minimal impact to overall weight as possible. When considering future missions, NASA place an importance on a system that can be reusable for approximately 10 missions or 10 years. The issues with having a reusable design are the harsh conditions that exist on the moon and the need for easy calibration of the system after each mission. Finally, when considering the con-ops of the astronauts, a leveling time of less than one hour is important so it will not take up time from the rest of the mission.

To assist with simplifying the design, some important assumptions were made. These were that the self-leveling system would have available power to draw from the lander and that the system would be able to use the on-board IMU and measuring equipment to help with knowing position and level.

Design/Prototype Breakdown

From the project objective, goals, and assumptions, as well as extensive concept selection analysis, Team 516 decided on a linear actuator system implemented between the leg base and the lunar capsule. The team wanted a design that was not only efficient in meeting NASA's needs, but also one that involved creative thinking. Linear actuators, placed within the leg base, enable the design to be very reusable. The actuators are kept out of the lunar environment to avoid damage from regolith, as well as allow for some temperature regulation. Four actuators were chosen to aid with leveling accuracy and to prevent malfunction. There was an overall weight addition from the actuators of roughly nine pounds to the prototype. The image below illustrates the prototype design for better understanding.

Figure 1: Full Design CAD

Other components of the prototype include the lander base and the electronics platform. The lander base was modeled as a wire frame design to display the actuators and their function. Also, the base is inspired by the design for the Apollo mission lander due to NASA not disclosing which lander will participate in the Artemis mission. The electronics platform models the lander cabin, where most of the lander's electronics are held. All three of these prototype components and their specifications are described in further detail below.

Prototype Breakdown

The prototype base is made up of two main components: the tube chassis housing for actuators and the legs to hold up the housing. The tube chassis housing is made up of four different types of cut rod that are all made from12-inch aluminum 6061 and are welded to form a hexagonal cage. The rods that are used for the two hexagonal shapes on the top and bottom of the chassis are comprised of 12 rods with cuts on either ends of the rods at 120-degree angles allowing them to be welded together in the desired shape. The next tube is a 9.75-inch flat cut tube that connects the hexagonal pieces together vertically. These tubes are welded together at the nodes of the top and bottom hexagonal pieces. The last two pieces of tube are support for the bottom platform to sit on top of. One of the tubes for the support has a cut on a single end that is a circle in the diameter of the 0.5-inch rod. The other tube for the support has two cuts on either end of the rod that are circles with the diameter of the 0.5-inch rod. There will be two of each type of support rod in order to span the distance of the platform. The single cut support rod will be welded to the flat section of the hexagonal tube chassis and the two-cut support will be welded on at the nodes of the hexagonal pieces.

There are four legs that are also made from the same aluminum 6061 tubing and will be welded to the chassis at the flat points of the hexagonal pieces. These four legs are created from four tubes, two of the 12-inch tubes and two three-foot tubes that would be cut down to 17.5 inches and 18.16 inches. The 17.5-inch and the 18.16-inch rods will be oriented so that they can come together at one point in order for the feet of the base to be connected with a foot. The figure below shows the base fully assembled with the wooden platform in please for reference.

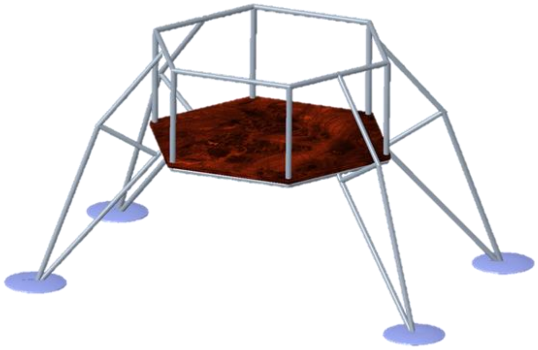


Figure 2: Prototype Base

Linear Actuators

The main leveling component of this design is comprised of four optical feedback linear actuators supplied by Firgelli automations. The linear actuators chosen for this application can produce a two-hundred-pound dynamic force, five-hundred-pound static force, and reach a maximum stroke length of six inches. This is output is driven by a worm gear system which is powered by a built-in motor. Each actuator has a total of five wires, three of which run directly to an Arduino mega 2560 while the remaining two run to the motor driver that is responsible for powering the actuators. Each actuator has been converted to a column style lift actuator by making use of the base mounting bracket also supplied by Firgelli automations; this allows the actuators to apply a linear force normal to the platform base, ultimately leveling the platform. No maintenance is required for the actuators to perform as intended; however, occasional examination of the actuators and wire connection is advised. The actuators have a IP66 rating which means that they are both dust proof and water resistance. This rating allows the prototype to be tested in many situations and environments while still performing as intended. Paired with a CE and RoHS certification, these actuators will remain safe and functional through many tests. Finally, and internal limit switch is built in to add another safety measure; once the actuator reaches its desired position, it will shut off. Below is a visual reference of the linear actuator in its original configuration; if any actuator does not match this image or appears to be damaged in any way, do not proceed with operation of the prototype.

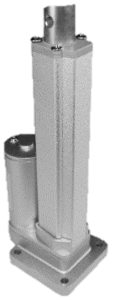


Figure 3: Linear Actuators

Joint Connection

In order reduce the number of possible failure points, each actuator is fitted with a joint between the actuator tip and the cabin floor. Without this extra insurance there is the possibility of unwelcomed stresses acting on the actuator that could ultimately lead to design failure. The joint chosen is a sailboat block base sourced through West Marine and repurposed for our needs. The joint consists of two intertwined u-shaped metal connectors which are held stiffly in place by a spring that encases the joint. The diamond base has four mounting holes which ensures a secure connecting to the cabin floor. On the opposing end, a sleeve is used to connect the end of the actuator rod into the slot of the joint and is secured using a provided pin. Due to this configuration, the joint is very versatile and can be easily manipulated for desired outcomes; the spring can also be changed for a desired and optimal stiffness depending on the weight it must support. In the current configuration of the joint, it has a safe working load of four-hundred and forty pounds which is more than enough for our intended use. No maintenance is required to operate the joint in the system. It is advised to examine each joint for debris or any possible failure point prior to each test for guaranteed results; occasional lubrication will increase performance and longevity but is not required to be functional. Below is a visual reference of the joint in its original configuration; if any actuator does not match this image or appears to be fractured or damaged in any way, do not proceed with operation of the prototype.

Figure 4: Actuator Joint Connection

Electronics

Our system will be powered using a 12V 37.5A power supply. This specific power supply was chosen because its physical dimensions were small enough to fit on our prototype platform while simultaneously supplying enough amperage for each motor driver. This power supply also allows us to plug directly into a wall outlet simulating a deployed solar array which would be available to the lander on the moon. Our prototype uses a GY-521 IMU which gives us the x and y data of our platform. This represents the on-board lunar module IMU and will determine when our system has reached an acceptable state of level. Our system logic is being housed in an Arduino Mega 2560. The Mega allows enough ports to connect our motor drivers and different sensors to paired with ample processing power. To move our prototype platform team 516 decided to use linear actuators with optical encoders. The choice to use linear actuators derives from our environmental constraints. Pistons were the original design choice but due to problems with a working fluid i.e., pneumatic/hydraulic a worm gear design was chosen Pistons were the original design choice but due to problems with a working fluid i.e., pneumatic/hydraulic a worm gear design was chosen to be best suited to our needs. These actuators are coupled with optical encoders meaning each actuator will have a running sense of how far they have moved and will in turn be very precise. This lets our final state be much more precise than if we used a hydraulic or pneumatic jack. Each actuator will be connected to an IBT-2 43A Motor Driver which will be used to ensure the power and information from the Arduino gets distributed to each actuator. Below is a wiring diagram for a single actuator as reference, however in our assembled system there will be 4 times as many motor drivers and actuators as shown.

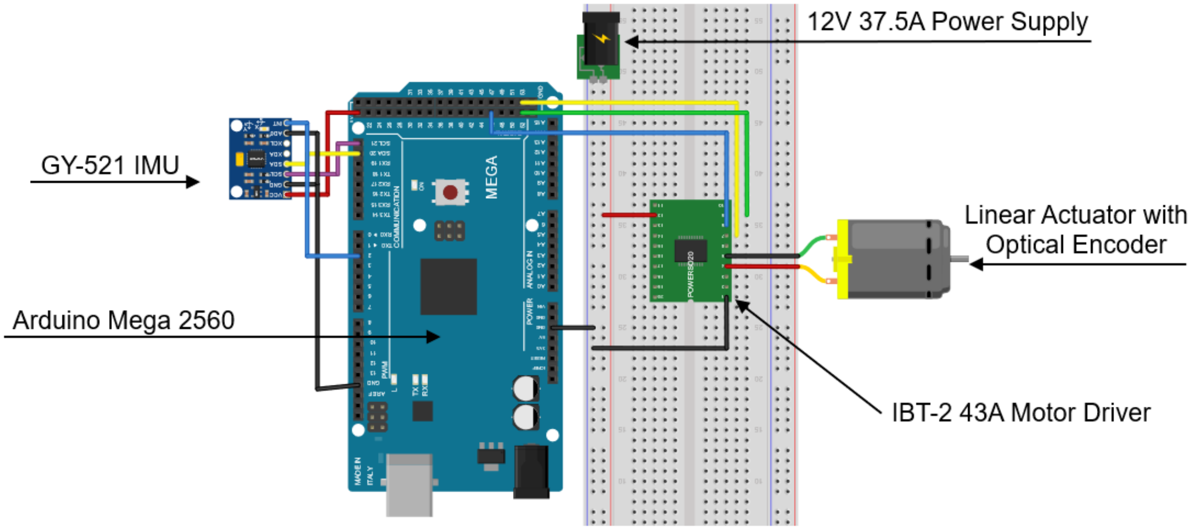


Figure 4: Wiring Diagram for a Single Actuator

System Logic and Coding

The system operates on code written in C for the Arduino Mega 2560. The code regulates where it is during the operation by using a switch statement with different cases for different operations. This allows for the system to check if one process is complete and depending on the result, send it to different locations within the code. The system communicates with the IMU via I2C. The code for the encoders is currently being developed and fine-tined.

Operation

To operate the system, the user must first plug the power cord into a standard US wall outlet. Upon startup, the LCD will prompt the user to press either the green START button or red STOP button. If the green button is pressed the actuators will rise to half of their maximum height and the IMU will collect the current orientation data. The system will begin to level one axis at a time based off of the data collected from the IMU. Once first axis is level the system will read in current orientation data from the IMU and begin to level the second axis. Upon completion, the LCD will display to the user the initial orientation and its final orientation. If during the operation the user needs to stop the system, the red button can be pressed at any time to stop the movement. In this stopped state the user can press the green button to begin operation from where it was stopped or press the red button to have the actuators fully retract to the starting position.

Trouble Shooting

The project requires different systems to be able to run and those systems may need trouble shooting in order to get the project working to its full potential. The main part of the project that needs to be able to work is if the inertial measurement unit (IMU) is calibrated properly. Without this, the device will not be able to level accurately. The inertial measurement unit comes with a calibration file, which uses a PI controller to calculate the zero offset of the IMU at a level position. The program will output offset values that can be entered into programs where the IMU is used to offset the data to the correct reading. The next trouble shooting part would be to make sure the device is on a stable surface when the process of leveling is complete. If the device moves the program for leveling may need to run again as it will now be offset from the original level process. If the system does not turn on when plugged in and powered make sure the fuse is not blown, if it is not blown make sure the power distribution block connector is connected to the power supply. If an actuator is not moving, ensure the red and black cables are properly secured into its respective motor driver. If the entire system does not turn on make sure the green light on the power supply is turned on, if not, ensure the connection from the power supply to the wall outlet is secure and the wall outlet is producing the correct voltage output.

Appendix E: Code

```
#include <BasicLinearAlgebra.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 20, 4); // set the LCD address to 0x27 for a 16 chars and 2 line
display
#include<Wire.h>
#include <PID_v1.h>
#include <elapsedMillis.h>
elapsedMillis timeElapsed;

using namespace BLA;

//------------WIRING------------
// port B / port L is used for direction control of the motor drivers
// pin 53 -> actuator0 R_EN (green)
// pin 52 -> actuator0 L_EN (white)
// pin 51 -> actuator1 R_EN (green)
// pin 50 -> actuator1 L_EN (white)
// pin 49 -> actuator2 R_EN (green)
// pin 48 -> actuator2 L_EN (white)
// pin 47 -> actuator3 R_EN (green)
// pin 46 -> actuator3 L_EN (white)

// PWM
// pin 13 -> actuator0 R_PWM (blue)
// pin 12 -> actuator0 L_PWM (yellow)
// pin 11 -> actuator1 R_PWM (blue)
// pin 10 -> actuator1 L_PWM (yellow)
// pin 9 -> actuator2 R_PWM (blue)
// pin 8 -> actuator2 L_PWM (yellow)
// pin 7 -> actuator3 R_PWM (blue)
// pin 6 -> actuator3 L_PWM (yellow)


//ENCODER
// pin 2 -> actuator0 encoder (red)
// pin 3 -> actuator1 encoder (red)
// pin 19 -> actuator2 encoder (red)
// pin 18 -> actuator3 encoder (red)


//------------PID SETUP------------
```

```
double Setpoint0, Input0;
double Setpoint1, Input1;
double Setpoint2, Input2;
double Setpoint3, Input3;

double Output[4]  = {0, 0, 0, 0};

double Kp0 = 45, Ki0 = 0.1, Kd0 = 5;
double Kp1 = 45, Ki1 = 0.1, Kd1 = 5;
double Kp2 = 45, Ki2 = 0.1, Kd2 = 5;
double Kp3 = 45, Ki3 = 0.1, Kd3 = 5;

double minimum = -200, maximum = 200;

PID myPID0(&Input0, &Output[0], &Setpoint0, Kp0, Ki0, Kd0, DIRECT);
PID myPID1(&Input1, &Output[1], &Setpoint1, Kp1, Ki1, Kd1, DIRECT);
PID myPID2(&Input2, &Output[2], &Setpoint2, Kp2, Ki2, Kd2, DIRECT);
PID myPID3(&Input3, &Output[3], &Setpoint3, Kp3, Ki3, Kd3, DIRECT);

//------------IMU SETUP------------
const int MPU_addr = 0x68;
int16_t AcX, AcY, AcZ, Tmp, GyX, GyY, GyZ;

double angle_rad_X = 0;
double angle_rad_Y = 0;
long distance_X = 0;
long distance_Y = 0;
long desired_count0 = 0;
long desired_count1 = 0;
long desired_count2 = 0;
long desired_count3 = 0;

int minVal = 265;
int maxVal = 402;
double x_sum = 0;
double x_avg = 0;
double y_sum = 0;
double y_avg = 0;
double z_sum = 0;
double z_avg = 0;
double x;
double y;
```

```
double z;


//------------ENCODER SETUP------------
#define numberOfActuators 4
#define falsepulseDelay 30 //noise pulse time, if too high, ISR will miss pulses.
volatile int counter[numberOfActuators] = {0, 0, 0, 0};
volatile int prevCounter[numberOfActuators] = {0, 0, 0, 0};
volatile long act_position[numberOfActuators] = {0, 0, 0, 0};
int RPWM[numberOfActuators] = {13, 11, 9, 7};
int LPWM[numberOfActuators] = {12, 10, 8, 6};
int opticalPins[numberOfActuators] = {2, 3, 19, 18};
int Direction[numberOfActuators] = { -1, -1, -1, -1};
volatile long lastDebounceTime_0 = 0; //timer for when interrupt was triggered
volatile long lastDebounceTime_1 = 0;
volatile long lastDebounceTime_2 = 0; //timer for when interrupt was triggered
volatile long lastDebounceTime_3 = 0;


//-1 = retracting
// 0 = stopped
// 1 = extending

int extensionCount[numberOfActuators] = {0, 0, 0, 0};
int retractionCount[numberOfActuators] = {0, 0, 0, 0};
int pulseTotal[numberOfActuators] = {0, 0, 0, 0}; //stores number of pulses in one full
extension/actuation


//------------BUTTON SETUP------------
int switchValue;
int switchOldValue;
int dt = 20; //debounce time in ms


//------------GENERAL SETUP------------
int state = 0;



void setup() {
  // put your setup code here, to run once:
```

```
// IMU
Wire.begin();
Wire.beginTransmission(MPU_addr);
Wire.write(0x6B);
Wire.write(0);
Wire.endTransmission(true);
Serial.begin(9600);

// MOTOR DRIVER STUFF
DDRB = 0xFF;
PORTB = 0b11111111;
DDRL = 0xFF; // 4-7 are inputs 0-3 outputs for direction
PORTL = 0b11111111; // 4-7 pull up resistors 0-3 tied high for R_EN & L_EN

// BUTTON STUFF
DDRA = 0x00; // inputs for push buttons
PORTA = 0xFF; //pull up resistors for button
switchOldValue = (PINA & 0b00000001); // 1 if not pressed, 0 if pressed

// ENCODER

for (int i = 0; i < numberOfActuators; i++) {
  pinMode(RPWM[i], OUTPUT);
  pinMode(LPWM[i], OUTPUT);
  pinMode(opticalPins[i], INPUT_PULLUP);
  analogWrite(RPWM[i] , 0);
  analogWrite(LPWM[i] , 0);
  counter[i] = 0; //initialize variables as array of zeros
  prevCounter[i] = 0;
  extensionCount[i] = 0;
  retractionCount[i] = 0;
  pulseTotal[i] = 0;
}

attachInterrupt(digitalPinToInterrupt(opticalPins[0]), count_0, RISING);
attachInterrupt(digitalPinToInterrupt(opticalPins[1]), count_1, RISING);
attachInterrupt(digitalPinToInterrupt(opticalPins[2]), count_2, RISING);
attachInterrupt(digitalPinToInterrupt(opticalPins[3]), count_3, RISING);

moveTillLimit(Direction[0], 200);
for (int i = 0; i < numberOfActuators; i++) {
```

```
  counter[i] = 0;
  Direction[i] = 1;
}

// PID
myPID0.SetOutputLimits(minimum, maximum);
myPID0.SetControllerDirection(DIRECT);
myPID1.SetOutputLimits(minimum, maximum);
myPID1.SetControllerDirection(DIRECT);
myPID2.SetOutputLimits(minimum, maximum);
myPID2.SetControllerDirection(DIRECT);
myPID3.SetOutputLimits(minimum, maximum);
myPID3.SetControllerDirection(DIRECT);

myPID0.SetMode(AUTOMATIC);
myPID1.SetMode(AUTOMATIC);
myPID2.SetMode(AUTOMATIC);
myPID3.SetMode(AUTOMATIC);

Input0 = counter[0];
Input1 = counter[1];
Input2 = counter[2];
Input3 = counter[3];

Setpoint0 = 298;
Setpoint1 = 298;
Setpoint2 = 298;
Setpoint3 = 298;

int sampleTime = 5;
myPID0.SetSampleTime(sampleTime);
myPID1.SetSampleTime(sampleTime);
myPID2.SetSampleTime(sampleTime);
myPID3.SetSampleTime(sampleTime);


//LCD STARTUP MENU
lcd.init();  //initialize the lcd
lcd.backlight();  //open the backlight


lcd.setCursor ( 0, 0 );           // go to the top left corner
```

```
  lcd.print("      L.V.L.S       "); // write this string on the top row
  lcd.setCursor ( 0, 1 );           // go to the 2nd row
  lcd.print("                    "); // pad string with spaces for centering
  lcd.setCursor ( 0, 2 );           // go to the third row
  lcd.print("Press Start to Level"); // pad with spaces for centering
  lcd.setCursor ( 0, 3 );           // go to the fourth row
  lcd.print(" Power Off to Stop  ");

}

void loop() {
  // put your main code here, to run repeatedly:
  switch (state) {
    case 0: {

        switchValue = (PINA & 0b00000001); // bitmasking to read the negative increment button
        if ( (switchOldValue == 1 ) && (switchValue == 0) ) // detect falling edge
        {
          state = 1;
          Setpoint0 = 298;
          Setpoint1 = 298;
          Setpoint2 = 298;
          Setpoint3 = 298;
          delay(dt); // it'll wait 20ms to ensure the bouncing isn't recorded
        }
        if ( (switchOldValue == 0) && (switchValue == 1)) // the button was just released
        {
          delay(dt);
        }
        switchOldValue = switchValue;
        break;
      }

    case 1: {

        lcd.setCursor(0, 0);
        lcd.print("                    ");
        lcd.setCursor(0, 1);
        lcd.print(" Rising to Midpoint ");
        lcd.setCursor(0, 2);
        lcd.print("                    ");
        lcd.setCursor(0, 3);
```

```
lcd.print("                ");

for (int i = 0; i < 3000; i++) { // run the PID for 3000 loops; get to midpoint
  Input0 = counter[0];
  Input1 = counter[1];
  Input2 = counter[2];
  Input3 = counter[3];
  myPID0.Compute();
  myPID1.Compute();
  myPID2.Compute();
  myPID3.Compute();
  my_motor0(Output[0]);
  my_motor1(Output[1]);
  my_motor2(Output[2]);
  my_motor3(Output[3]);
  Serial.println(i);
}

my_motor0(0); //stop the motors
my_motor1(0);
my_motor2(0);
my_motor3(0);

x_sum = 0;
x_avg = 0;
y_sum = 0;
y_avg = 0;
for (int i = 0; i <= 20; i++) { // average of the imu reading
  Wire.beginTransmission(MPU_addr);
  Wire.write(0x3B);
  Wire.endTransmission(false);
  Wire.requestFrom(MPU_addr, 14, true);
  AcX = Wire.read() << 8 | Wire.read();
  AcY = Wire.read() << 8 | Wire.read();
  AcZ = Wire.read() << 8 | Wire.read();
  int xAng = map(AcX, minVal, maxVal, -90, 90);
  int yAng = map(AcY, minVal, maxVal, -90, 90);
  int zAng = map(AcZ, minVal, maxVal, -90, 90);

  x = RAD_TO_DEG * (atan2(-yAng, -zAng) + PI);
  y = RAD_TO_DEG * (atan2(-xAng, -zAng) + PI);
  z = RAD_TO_DEG * (atan2(-yAng, -xAng) + PI);
```

```
  x_sum = x_sum + x;
  y_sum = y_sum + y;
}

x_avg = x_sum / 21;
y_avg = y_sum / 21;

//      Serial.print("X-Avg: ");
//      Serial.println(x_avg);
//      Serial.print("Y-Avg: ");
//      Serial.println(y_avg);

angle_rad_X = (PI / 180) * x_avg;
angle_rad_Y = (PI / 180) * y_avg;


BLA::Matrix<3, 3> R_x = {1, 0, 0, // Rotation matrix about X
                        0, cos(angle_rad_X) , sin(angle_rad_X),
                        0, -sin(angle_rad_X), cos(angle_rad_X)
                       };

BLA::Matrix<3, 3> R_y = { cos(angle_rad_Y), 0, sin(angle_rad_Y), // Rotation matrix about Y
                         0, 1, 0,
                         -sin(angle_rad_Y), 0, cos(angle_rad_Y)
                       };

BLA::Matrix<3, 1> R_0 = { -6.75, // Position vector of actuator 0
                         0,
                         0
                       };
BLA::Matrix<3, 1> R_1 = { 6.75, // Position vector of actuator 1
                         0,
                         0
                       };
BLA::Matrix<3, 1> R_2 = { 0, // Position vector of actuator 2
                         -6.75,
                         0
                       };
BLA::Matrix<3, 1> R_3 = { 0, // Position vector of actuator 3
                         6.75,
                         0
                       };
```

```
    BLA::Matrix<3, 1> R_0_rot = R_y * R_0; // find the position in reference to another orientation
    BLA::Matrix<3, 1> R_1_rot = R_y * R_1;
    BLA::Matrix<3, 1> R_2_rot = R_x * R_2;
    BLA::Matrix<3, 1> R_3_rot = R_x * R_3;

    desired_count0 = R_0_rot(2) / 0.010084; // convert distance to encoder counts
    desired_count1 = R_1_rot(2) / 0.010084;
    desired_count2 = R_2_rot(2) / 0.010084;
    desired_count3 = R_3_rot(2) / 0.010084;

    Setpoint0 = 298 + desired_count0;
    Setpoint1 = 298 + desired_count1;
    Setpoint2 = 298 + desired_count2;
    Setpoint3 = 298 + desired_count3;
    state = 2;
    break;
   }

  case 2: {

    clearLCD(); // LCD prompt
    lcd.setCursor(0, 0);
    lcd.print("                    ");
    lcd.setCursor(0, 1);
    lcd.print("    Leveling...     ");
    lcd.setCursor(0, 2);
    lcd.print("                    ");
    lcd.setCursor(0, 3);
    lcd.print("                    ");

    for (int i = 0; i < 2000; i++) { // run the PID; leveling
      Input0 = counter[0];
      Input1 = counter[1];
      Input2 = counter[2];
      Input3 = counter[3];
      myPID0.Compute();
      myPID1.Compute();
      myPID2.Compute();
      myPID3.Compute();
      my_motor0(Output[0]);
```

```
        my_motor1(Output[1]);
        my_motor2(Output[2]);
        my_motor3(Output[3]);
        Serial.println(i);
      }
      state = 3;
      break;
    }
  case 3: {
      my_motor0(0);
      my_motor1(0);
      my_motor2(0);
      my_motor3(0);
      lcd.setCursor ( 0, 0 );          // go to the top left corner
      lcd.print("     L.V.L.S      "); // write this string on the top row
      lcd.setCursor ( 0, 1 );          // go to the 2nd row
      lcd.print("                  "); // pad string with spaces for centering
      lcd.setCursor ( 0, 2 );          // go to the third row
      lcd.print("Press Start to Level"); // pad with spaces for centering
      lcd.setCursor ( 0, 3 );          // go to the fourth row
      lcd.print(" Power Off to Stop  ");
      state = 0;
      break;
    }
  }
}


void clearLCD() {
  lcd.setCursor(0, 0);
  lcd.print("                  ");
  lcd.setCursor(0, 1);
  lcd.print("                  ");
  lcd.setCursor(0, 2);
  lcd.print("                  ");
  lcd.setCursor(0, 3);
  lcd.print("                  ");
}

void displayMenu() {
  lcd.setCursor ( 0, 0 );          // go to the top left corner
  lcd.print("     L.V.L.S      "); // write this string on the top row
```

```
  lcd.setCursor ( 0, 1 );           // go to the 2nd row
  lcd.print("                    "); // pad string with spaces for centering
  lcd.setCursor ( 0, 2 );           // go to the third row
  lcd.print("Press Start to Level"); // pad with spaces for centering
  lcd.setCursor ( 0, 3 );           // go to the fourth row
  lcd.print(" Power Off to Stop  ");
}


void my_motor0(int duty) { // positive duty will raise -x
  if (duty >= 0) {
    Direction[0] = 1;
    set_pwm0(Direction[0], duty);
  } else if (duty < 0) {
    Direction[0] = -1;
    duty = duty * -1;
    set_pwm0(Direction[0], duty);
  }
}

void my_motor1(int duty) { // positive duty will raise -x
  if (duty >= 0) {
    Direction[1] = 1;
    set_pwm1(Direction[1], duty);
  } else if (duty < 0) {
    Direction[1] = -1;
    duty = duty * -1;
    set_pwm1(Direction[1], duty);
  }
}

void my_motor2(int duty) { // positive duty will raise -x
  if (duty >= 0) {
    Direction[2] = 1;
    set_pwm2(Direction[2], duty);
  } else if (duty < 0) {
    Direction[2] = -1;
    duty = duty * -1;
    set_pwm2(Direction[2], duty);
  }
}
```

```
void my_motor3(int duty) { // positive duty will raise -x
  if (duty >= 0) {
    Direction[3] = 1;
    set_pwm3(Direction[3], duty);
  } else if (duty < 0) {
    Direction[3] = -1;
    duty = duty * -1;
    set_pwm3(Direction[3], duty);
  }
}

void set_pwm0(int Direction, int duty) {
  switch (Direction) {
    case 1: //extension
      analogWrite(RPWM[0], duty);
      analogWrite(LPWM[0], 0);
      break;

    case 0: //stopping
      analogWrite(RPWM[0], 0);
      analogWrite(LPWM[0], 0);
      break;

    case -1: //retraction
      analogWrite(RPWM[0], 0);
      analogWrite(LPWM[0], duty);
      break;
  }
}
void set_pwm1(int Direction, int duty) {
  switch (Direction) {
    case 1: //extension
      analogWrite(RPWM[1], duty);
      analogWrite(LPWM[1], 0);
      break;

    case 0: //stopping
      analogWrite(RPWM[1], 0);
      analogWrite(LPWM[1], 0);
      break;

    case -1: //retraction
```

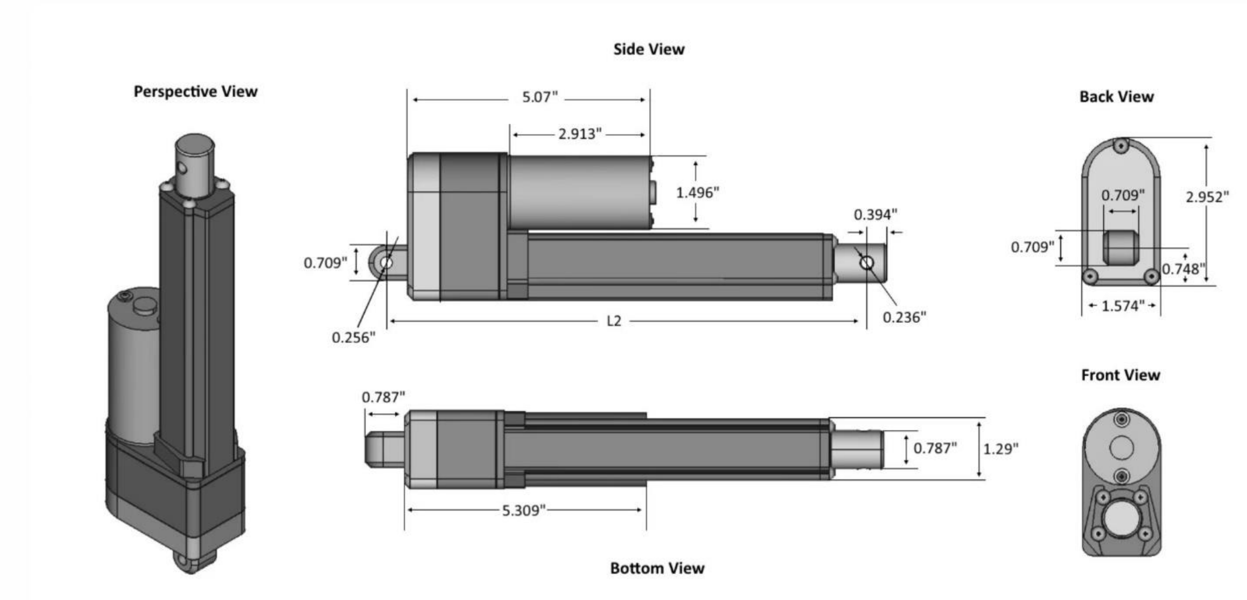
```
      analogWrite(RPWM[1], 0);
      analogWrite(LPWM[1], duty);
      break;
  }
}
void set_pwm2(int Direction, int duty) {
  switch (Direction) {
    case 1: //extension
      analogWrite(RPWM[2], duty);
      analogWrite(LPWM[2], 0);
      break;

    case 0: //stopping
      analogWrite(RPWM[2], 0);
      analogWrite(LPWM[2], 0);
      break;

    case -1: //retraction
      analogWrite(RPWM[2], 0);
      analogWrite(LPWM[2], duty);
      break;
  }
}
void set_pwm3(int Direction, int duty) {
  switch (Direction) {
    case 1: //extension
      analogWrite(RPWM[3], duty);
      analogWrite(LPWM[3], 0);
      break;

    case 0: //stopping
      analogWrite(RPWM[3], 0);
      analogWrite(LPWM[3], 0);
      break;

    case -1: //retraction
      analogWrite(RPWM[3], 0);
      analogWrite(LPWM[3], duty);
      break;
  }
}
```

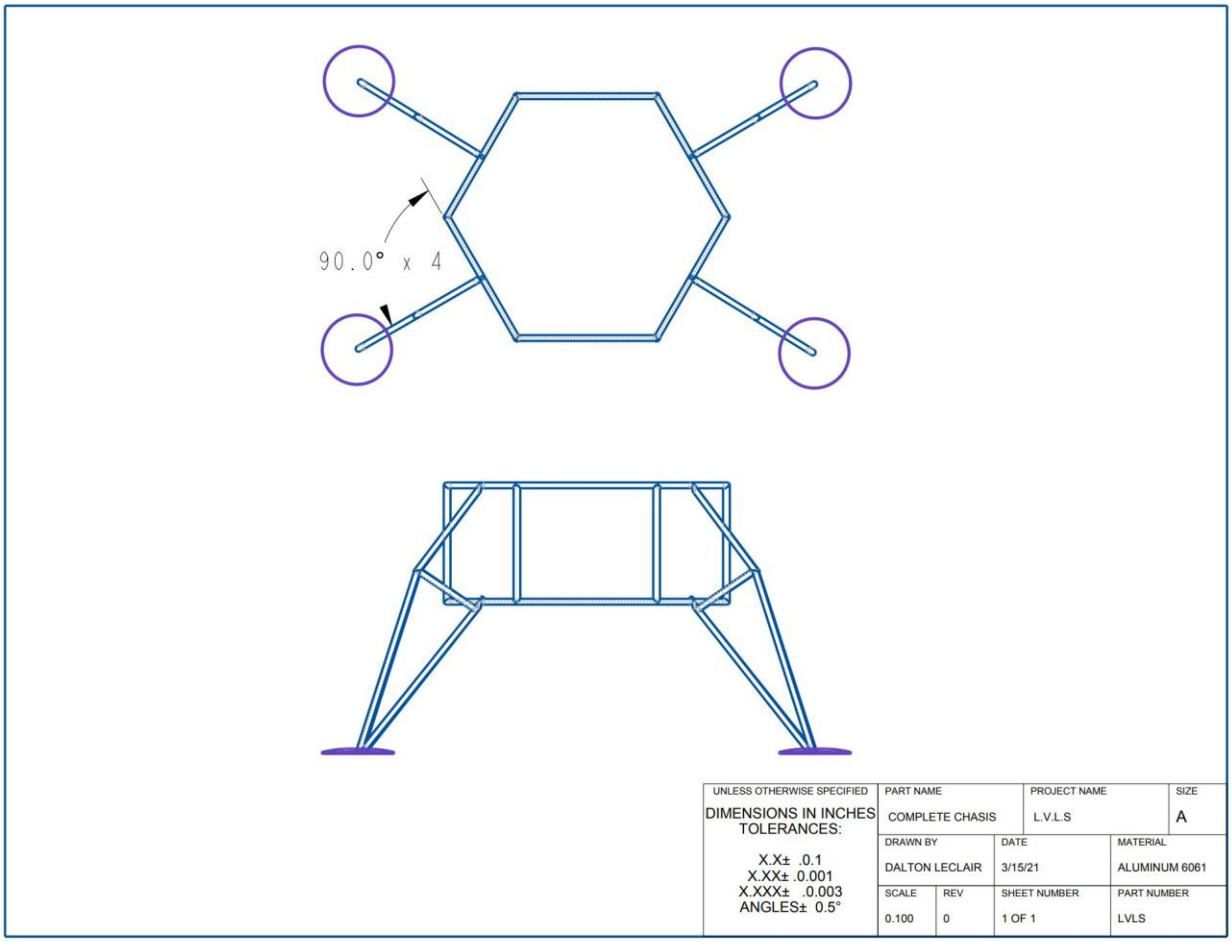
```
void moveTillLimit(int Direction, int Speed) {
  //this function moves the actuator to one of its limits
  for (int i = 0; i < numberOfActuators; i++) {
    counter[i] = 0; //reset counter variables
    prevCounter[i] = 0;
  }
  do {
    for (int i = 0; i < numberOfActuators; i++) {
      prevCounter[i] = counter[i];
    }
    timeElapsed = 0;
    while (timeElapsed < 200) { //keep moving until counter remains the same for a short
duration of time
      for (int i = 0; i < numberOfActuators; i++) {
        driveActuator(i, Direction, Speed);
      }
    }
  } while (compareCounter(prevCounter, counter)); //loop until all counts remain the same
}

bool compareCounter(volatile int prevCounter[], volatile int counter[]) {
  //compares two arrays and returns false when every element of one array is the same as its
corresponding indexed element in the other array
  bool areUnequal = true;
  for (int i = 0; i < numberOfActuators; i++) {
    if (prevCounter[i] == counter[i]) {
      areUnequal = false;
    }
    else { //if even one pair of elements are unequal the entire function returns true
      areUnequal = true;
      break;
    }
  }
  return areUnequal;
}

void driveActuator(int Actuator, int Direction, int Speed) {
  int rightPWM = RPWM[Actuator];
  int leftPWM = LPWM[Actuator];

  switch (Direction) {
    case 1: //extension
```

```
      analogWrite(rightPWM, Speed);
      analogWrite(leftPWM, 0);
      break;

    case 0: //stopping
      analogWrite(rightPWM, 0);
      analogWrite(leftPWM, 0);
      break;

    case -1: //retraction
      analogWrite(rightPWM, 0);
      analogWrite(leftPWM, Speed);
      break;
  }
}
void count_0() {
  //This interrupt function increments a counter corresponding to changes in the optical pin
status
  if ((millis() - lastDebounceTime_0) > falsepulseDelay) { //reduce noise by debouncing IR signal
    lastDebounceTime_0 = millis();
    if (Direction[0] == 1) {
      counter[0]++;
    }
    if (Direction[0] == -1) {
      counter[0]--;
    }
  }
}

void count_1() {
  if ((millis() - lastDebounceTime_1) > falsepulseDelay) {
    lastDebounceTime_1 = millis();
    if (Direction[1] == 1) {
      counter[1]++;
    }
    if (Direction[1] == -1) {
      counter[1]--;
    }
  }
}

void count_2() {
```

```
  if ((millis() - lastDebounceTime_2) > falsepulseDelay) {
    lastDebounceTime_2 = millis();
    if (Direction[2] == 1) {
      counter[2]++;
    }
    if (Direction[2] == -1) {
      counter[2]--;
    }
  }
}

void count_3() {
  if ((millis() - lastDebounceTime_3) > falsepulseDelay) {
    lastDebounceTime_3 = millis();
    if (Direction[3] == 1) {
      counter[3]++;
    }
    if (Direction[3] == -1) {
      counter[3]--;
    }
  }
}
```

Appendix F: Engineering Drawings



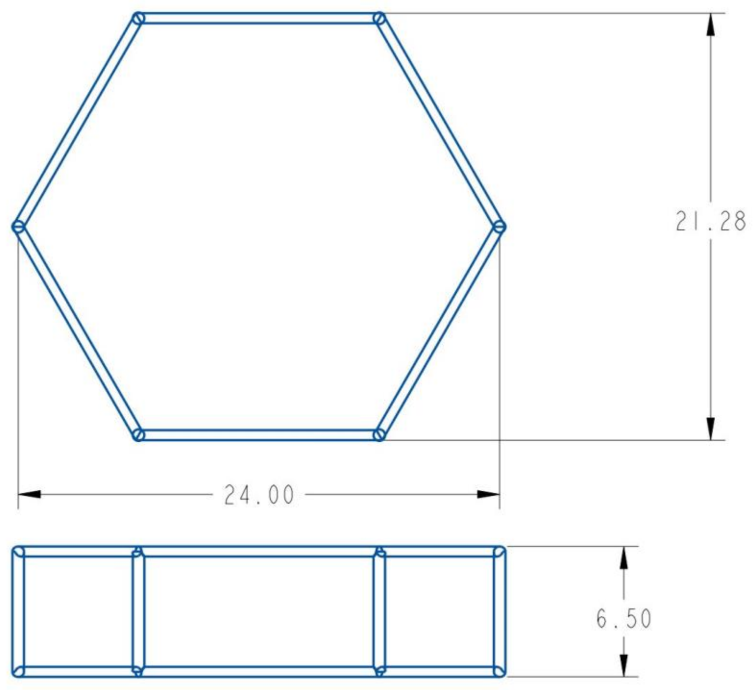


UNLESS OTHERWISE SPECIFIED

DIMENSIONS IN INCHES
TOLERANCES:

X.X± .0.1
X.XX± .0.001
X.XXX± .0.003
ANGLES± 0.5°

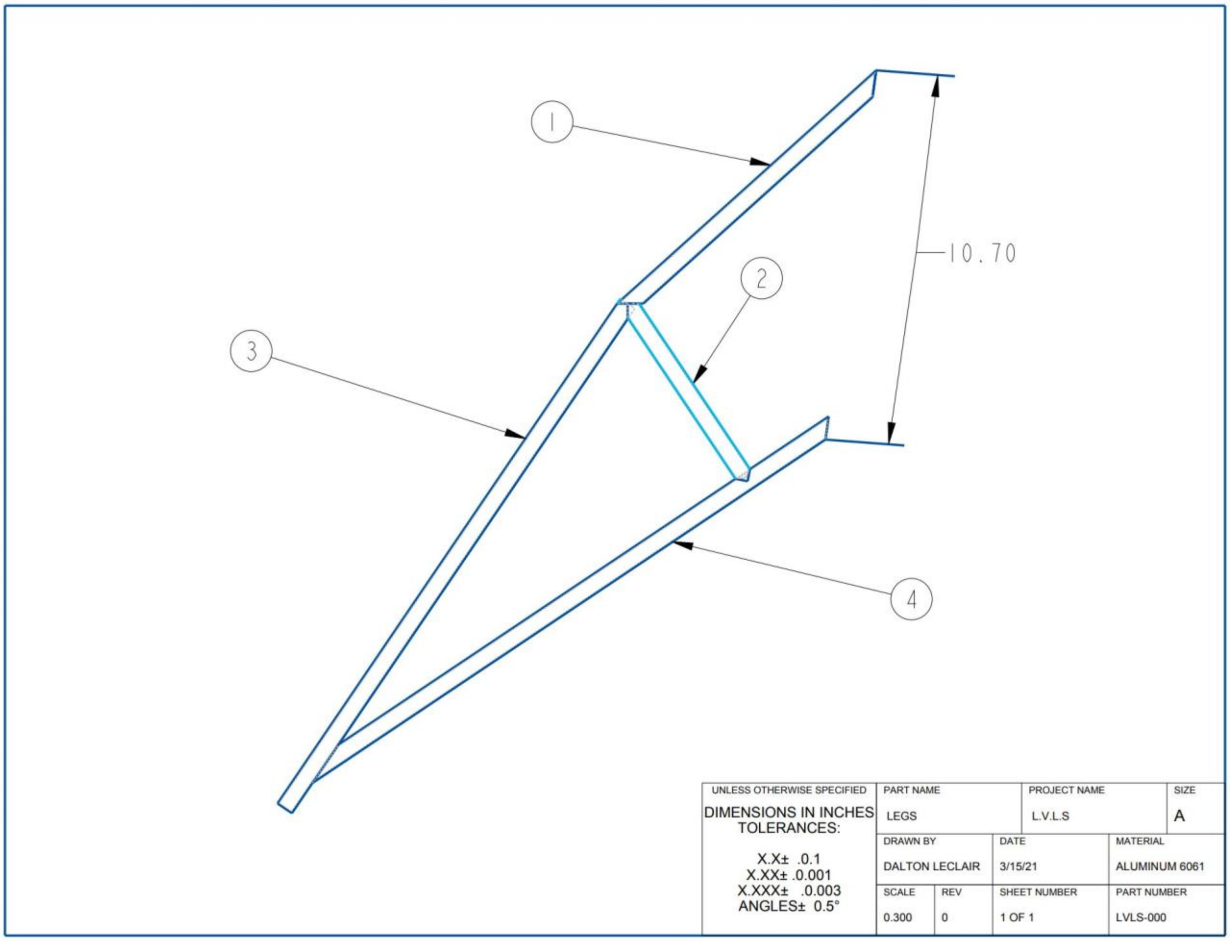
PART NAME	COMPLETE CHASIS	PROJECT NAME	L.V.L.S
SIZE	A	DRAWN BY	DALTON LECLAIR
DATE	3/15/21	MATERIAL	ALUMINUM 6061
SCALE	0.100	REV	0
SHEET NUMBER	1 OF 1	PART NUMBER	LVLS



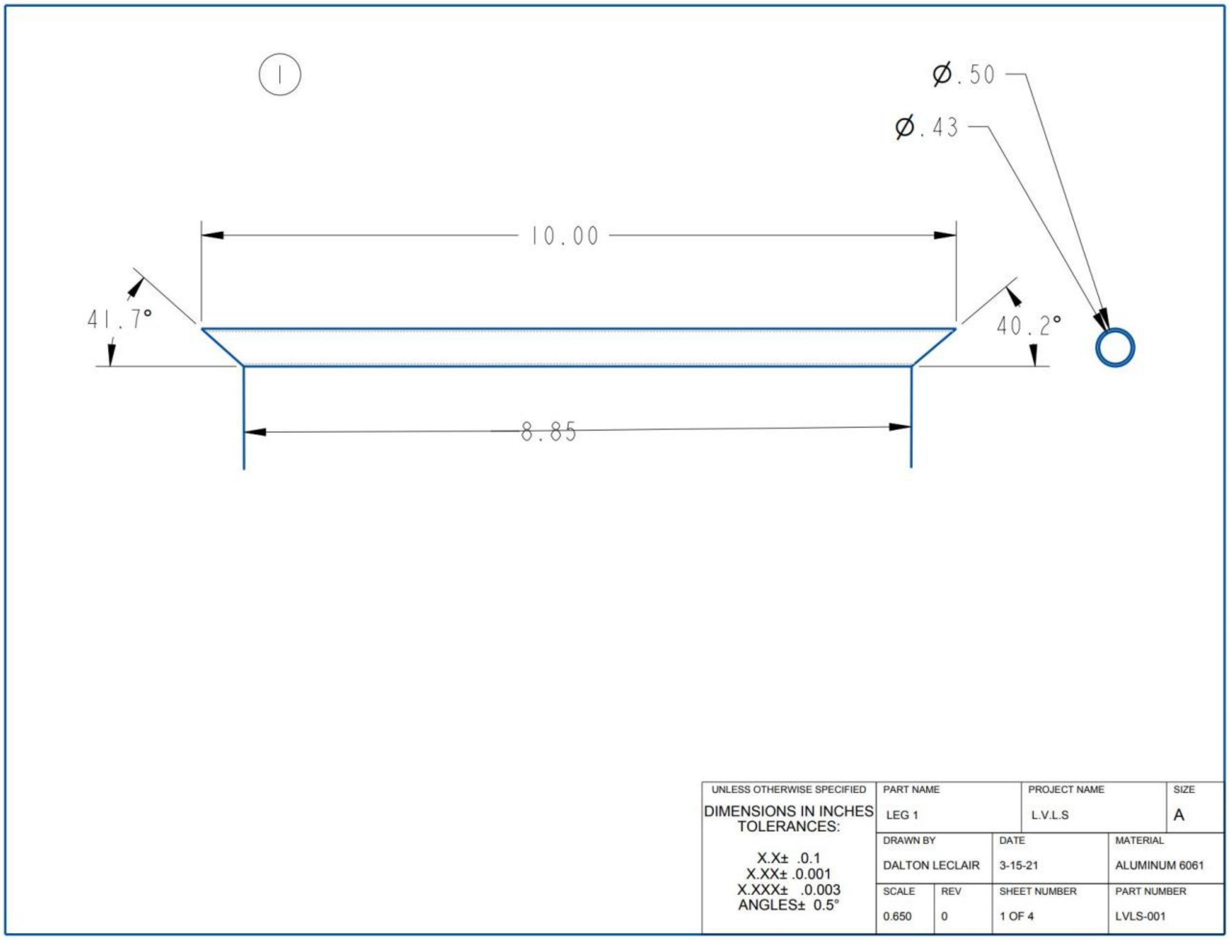
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:

X.X± .0.1
X.XX± .0.001
X.XXX± .0.003
ANGLES± 0.5°

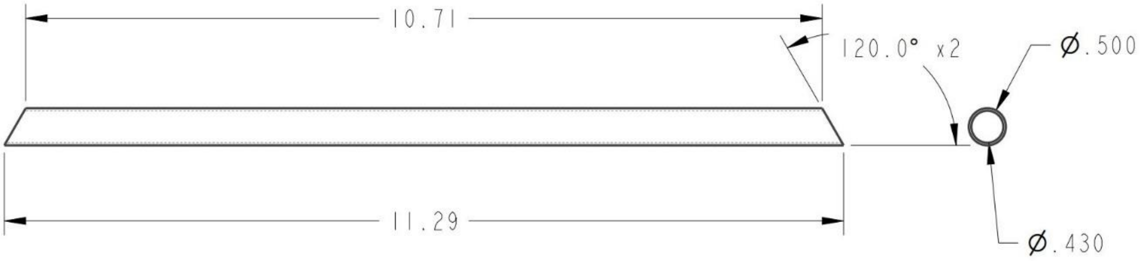
PART NAME		PROJECT NAME	SIZE
Chasis		Lunar Lander Prototype	A
DRAWN BY	DATE	MATERIAL	
DALTON LECLAIR	3/15/21	Auminum 6061	
SCALE	REV	SHEET NUMBER	PART NUMBER
1.000	0	1 OF 1	NES-JE-001



UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X± .0.1 X.XX± .0.001 X.XXX± .0.003 ANGLES± 0.5°	PART NAME LEGS		PROJECT NAME L.V.L.S	SIZE A
	DRAWN BY DALTON LECLAIR		DATE 3/15/21	MATERIAL ALUMINUM 6061
	SCALE 0.300	REV 0	SHEET NUMBER 1 OF 1	PART NUMBER LVLS-000

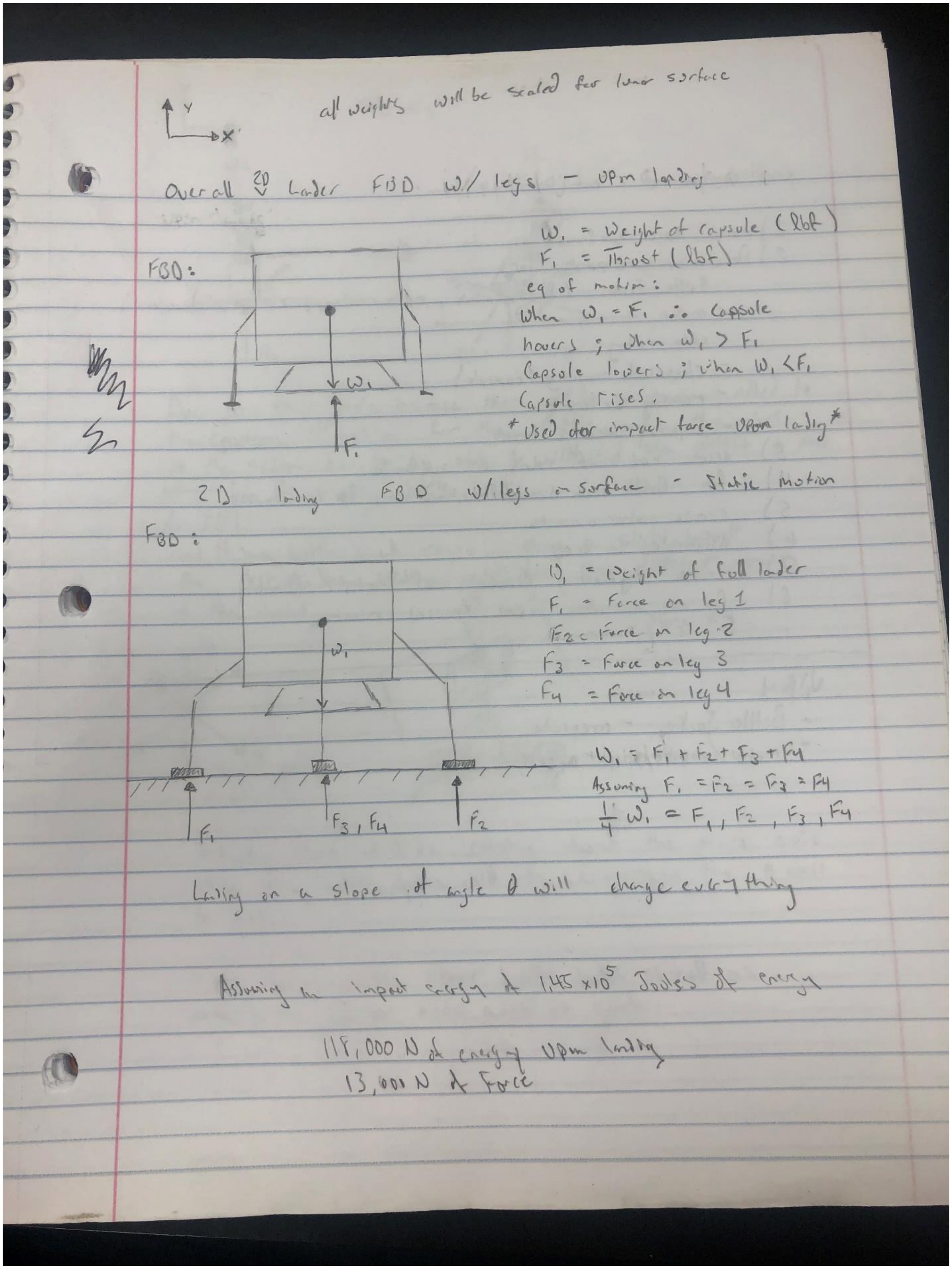


UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X± .0.1 X.XX± .0.001 X.XXX± .0.003 ANGLES± 0.5°	PART NAME LEG 1		PROJECT NAME L.V.L.S	SIZE A
	DRAWN BY DALTON LECLAIR		DATE 3-15-21	MATERIAL ALUMINUM 6061
	SCALE 0.650	REV 0	SHEET NUMBER 1 OF 4	PART NUMBER LVLS-001



UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X± .0.1 X.XX± .0.001 X.XXX± .0.003 ANGLES± 0.5°	PART NAME HEXAGONAL TUBE		PROJECT NAME L.V.LS	SIZE
	DRAWN BY JAMES EVANS		DATE 2/22/2021	MATERIAL AL - 6061 - T6
	SCALE 0.65	REV A	SHEET NUMBER 1 OF 1	PART NUMBER

Appendix G: Calculations



all weights will be scaled for lunar surface

Overall 2D Lander FBD w/ legs – upon landing

FBD:

W_1 = Weight of capsule (lbf)
F_1 = Thrust (lbf)
eq of motion:
When $W_1 = F_1$ ∴ Capsule hovers ; when $W_1 > F_1$ Capsule lowers ; when $W_1 < F_1$ Capsule rises.
* Used for impact force upon lading *

2D landing FBD w/ legs on surface – Static motion

FBD:

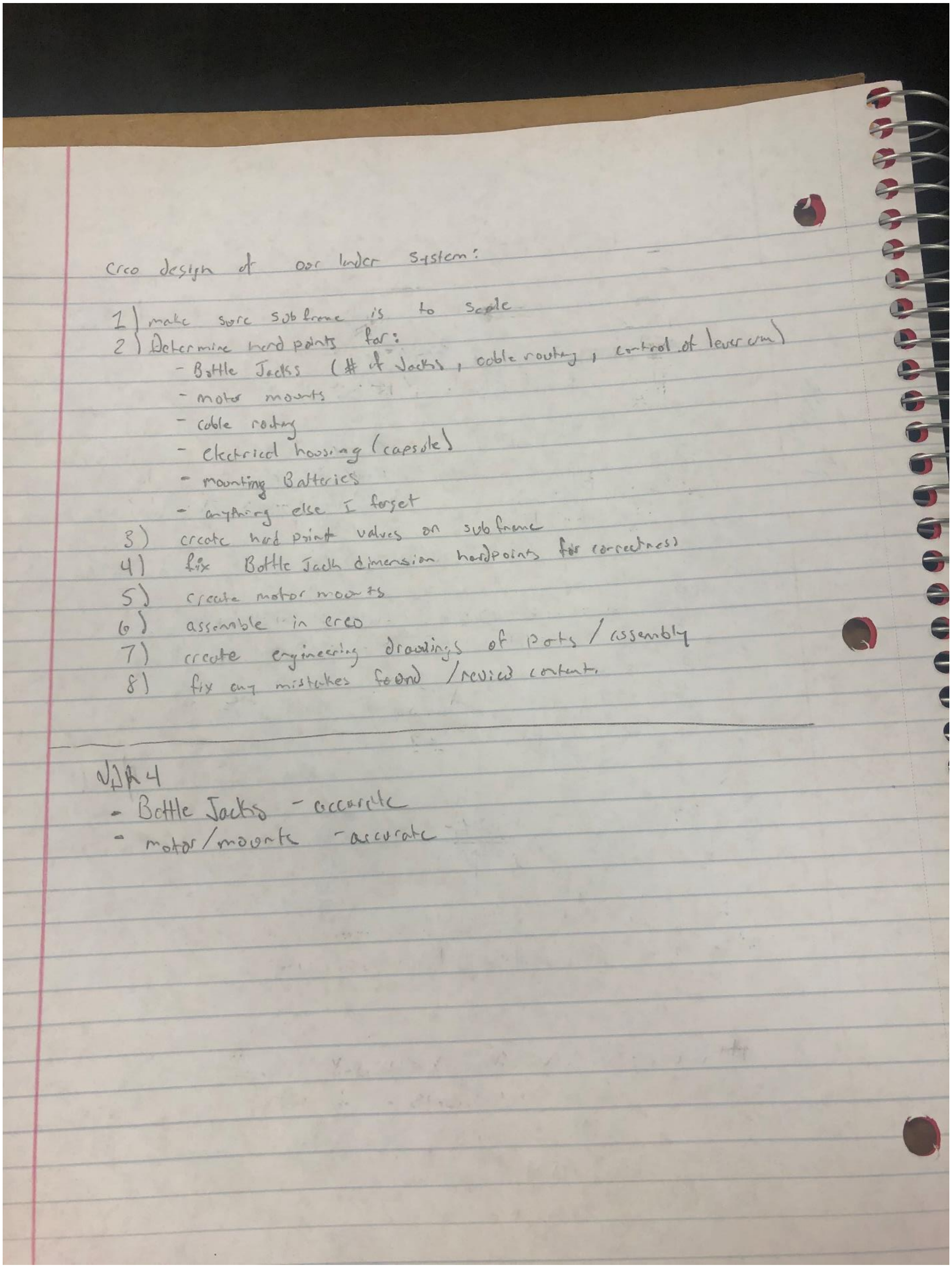
W_1 = Weight of full lander
F_1 = Force on leg 1
F_2 = Force on leg 2
F_3 = Force on leg 3
F_4 = Force on leg 4

$W_1 = F_1 + F_2 + F_3 + F_4$
Assuming $F_1 = F_2 = F_3 = F_4$
$\frac{1}{4} W_1 = F_1, F_2, F_3, F_4$

Landing on a slope of angle θ will change everything

Assuming an impact energy of 1.45×10^5 Joules of energy

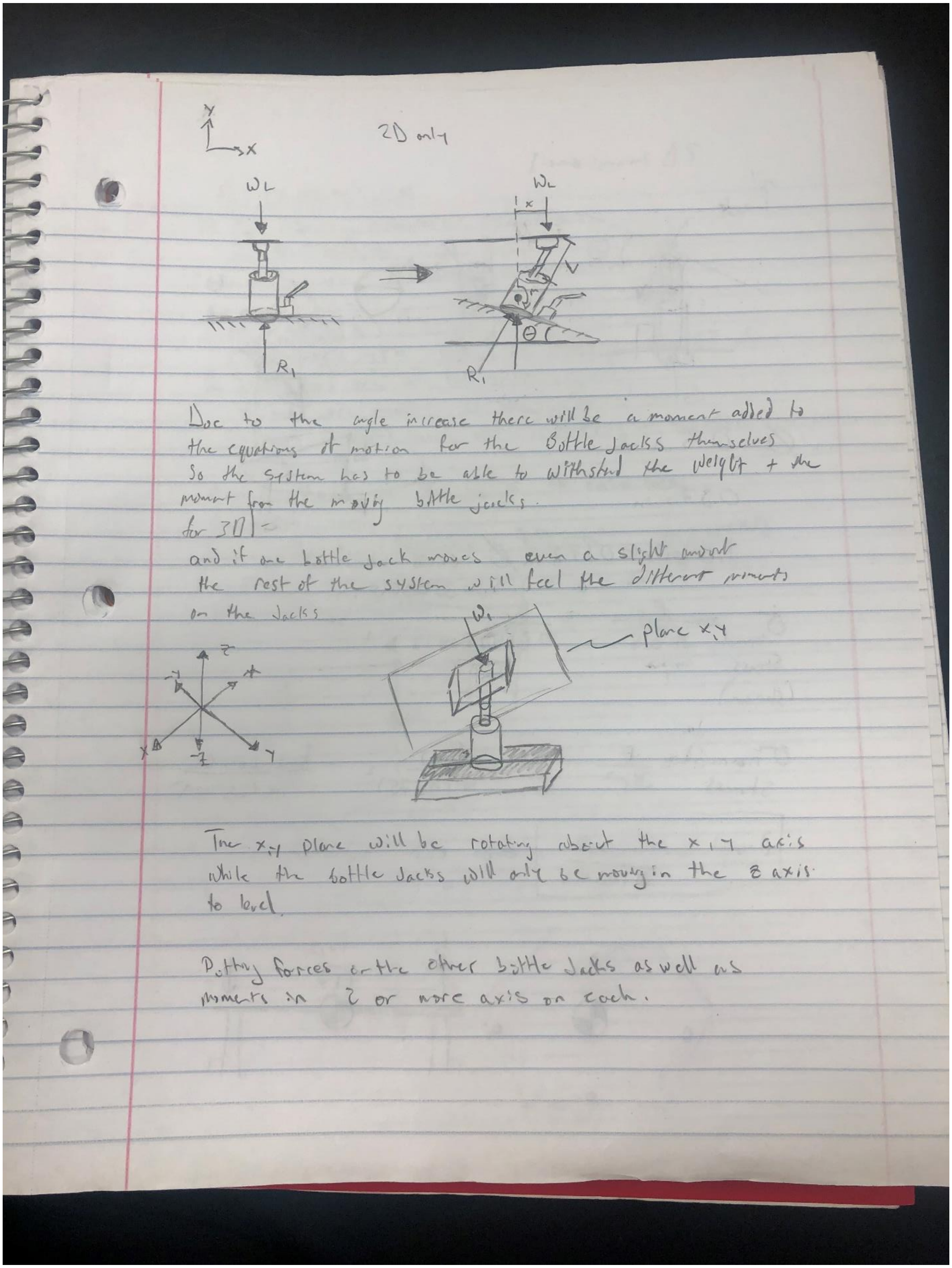
118,000 N of energy upon landing
13,000 N of Force



creo design of our lander system:

1) make sure sub frame is to scale
2) Determine hard points for:
   - Bottle Jacks (# of Jacks, cable routing, control of lever arm)
   - motor mounts
   - cable routing
   - electrical housing (capsule)
   - mounting Batteries
   - anything else I forget
3) create hard point values on sub frame
4) fix Bottle Jack dimension hardpoints for correctness)
5) create motor mounts
6) assemble in creo
7) create engineering drawings of parts / assembly
8) fix any mistakes found / review content.

VDR 4
- Bottle Jacks - accurate
- motor/mounts - accurate



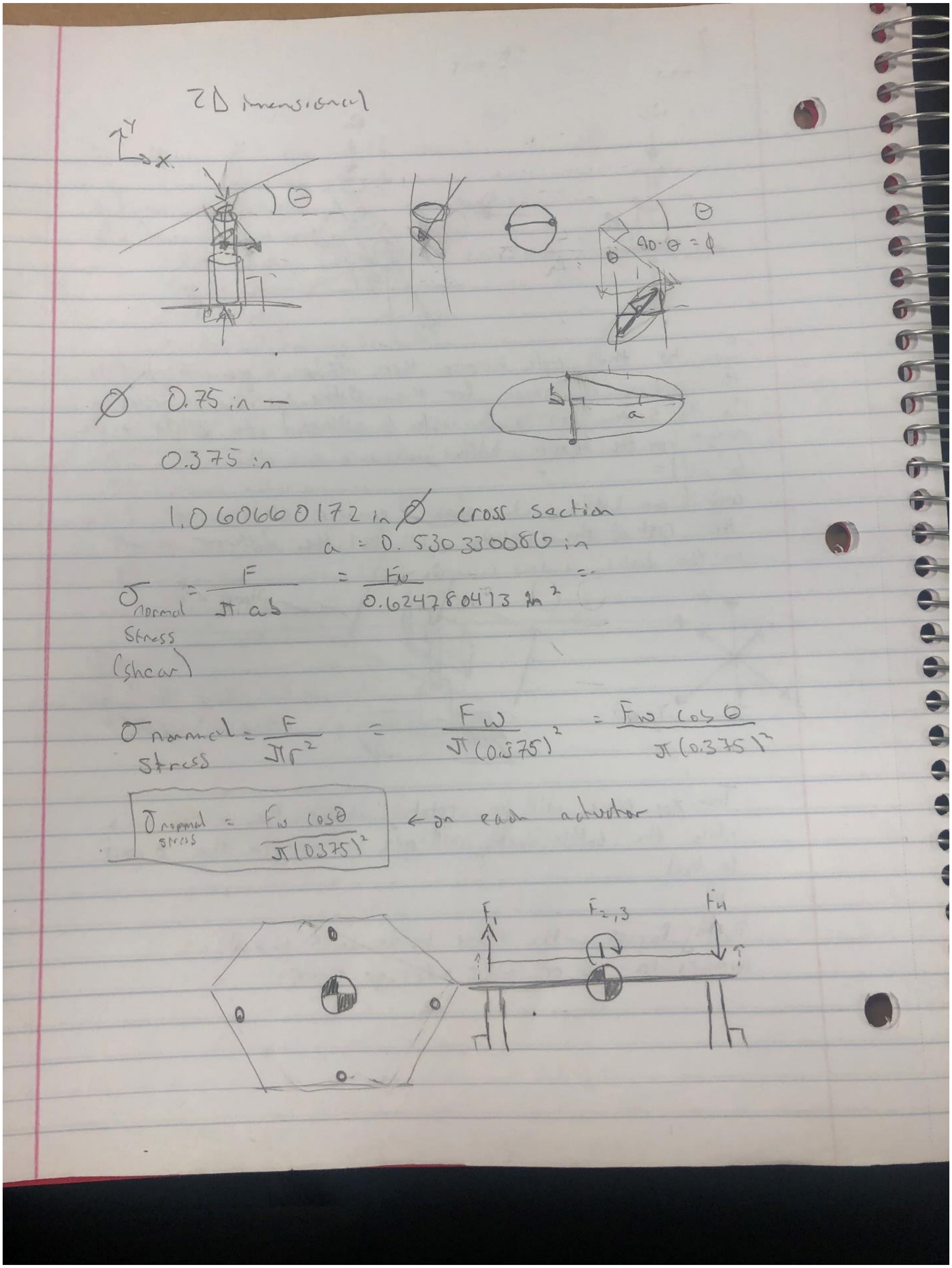
Due to the angle increase there will be a moment added to the equations of motion for the Bottle Jacks themselves So the system has to be able to withstand the weight + the moment from the moving bottle jacks.

for 3D -

and if one bottle Jack moves even a slight amount the rest of the system will feel the different moments on the Jacks

The x,y plane will be rotating about the x, y axis while the bottle Jacks will only be moving in the z axis. to level.

Putting forces on the other bottle Jacks as well as moments in 2 or more axis on each.



2D imensional

90 - θ = ϕ

⌀ 0.75 in —

0.375 in

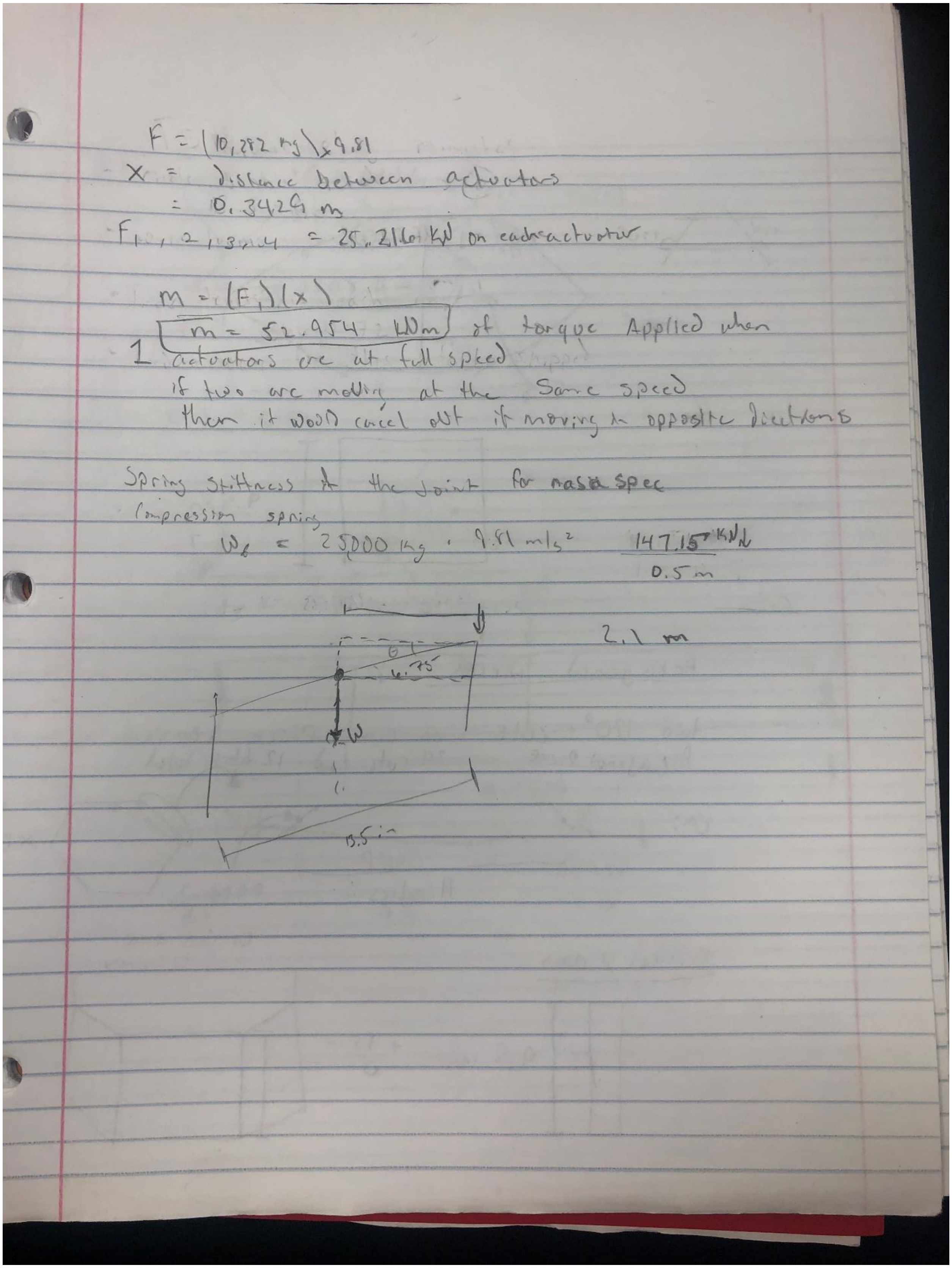
1.060660172 in ⌀ cross section

a = 0.530330086 in

$\sigma_{\text{normal stress (shear)}} = \dfrac{F}{\pi a b} = \dfrac{F_w}{0.624780413\ \text{in}^2} =$

$\sigma_{\text{normal stress}} = \dfrac{F}{\pi r^2} = \dfrac{F_w}{\pi (0.375)^2} = \dfrac{F_w \cos\theta}{\pi (0.375)^2}$

$\boxed{\sigma_{\text{normal stress}} = \dfrac{F_w \cos\theta}{\pi (0.375)^2}}$ ← on each actuator



$F = (10{,}282\ kg) \times 9.81$

x = distance between actuators

= 0.3429 m

$F_{1,2,3,4}$ = 25.216 kN on each actuator

$m = (F_1)(x)$

1 $\boxed{m = 52.954\ kNm}$ of torque Applied when actuators are at full speed

if two are moving at the Same speed

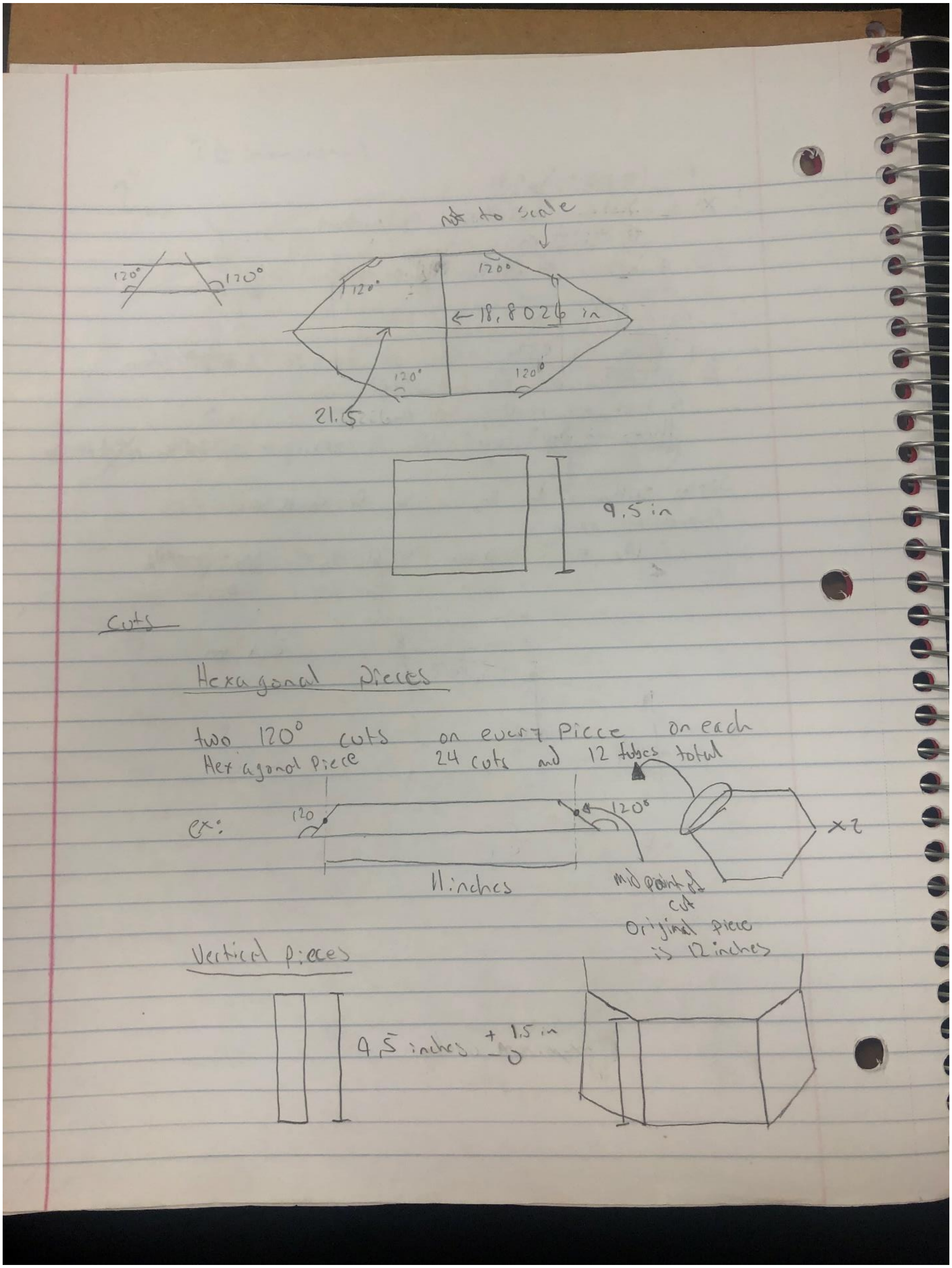
then it would cancel out if moving in opposite directions

Spring stiffness at the joint for nasa spec

Compression spring

$W_b = 25{,}000\ kg \cdot 9.81\ m/s^2$ $\quad \frac{147.15\ kN}{0.5\ m}$

2.1 m



Cuts

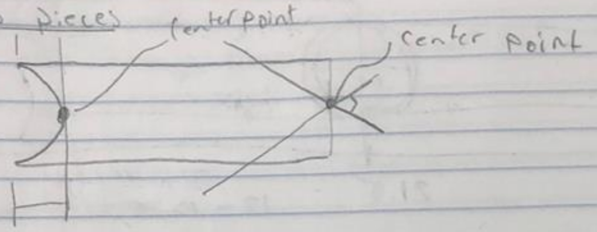
Hexagonal Pieces

two 120° cuts on every Piece on each Hexagonal Piece 24 cuts and 12 tubes total

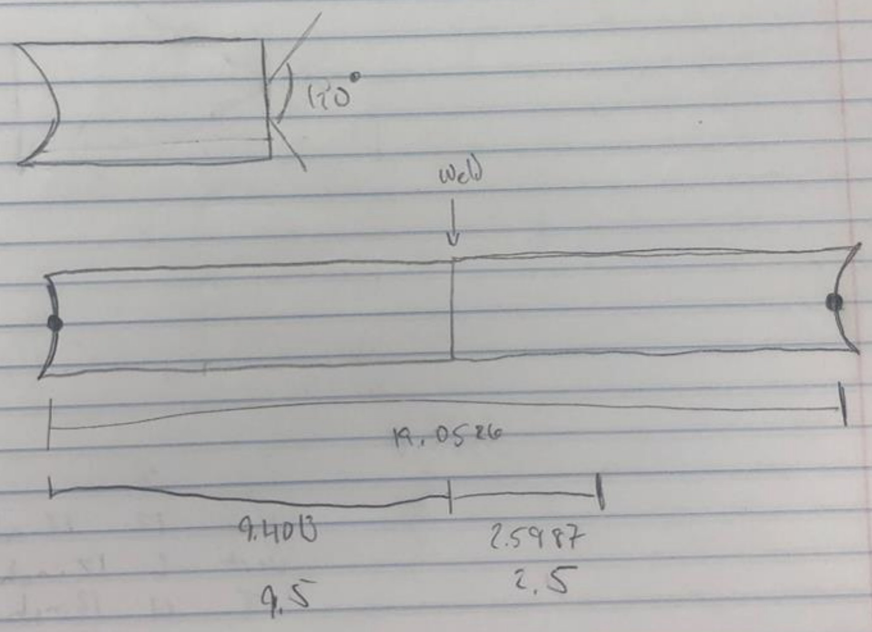
Original piece is 12 inches

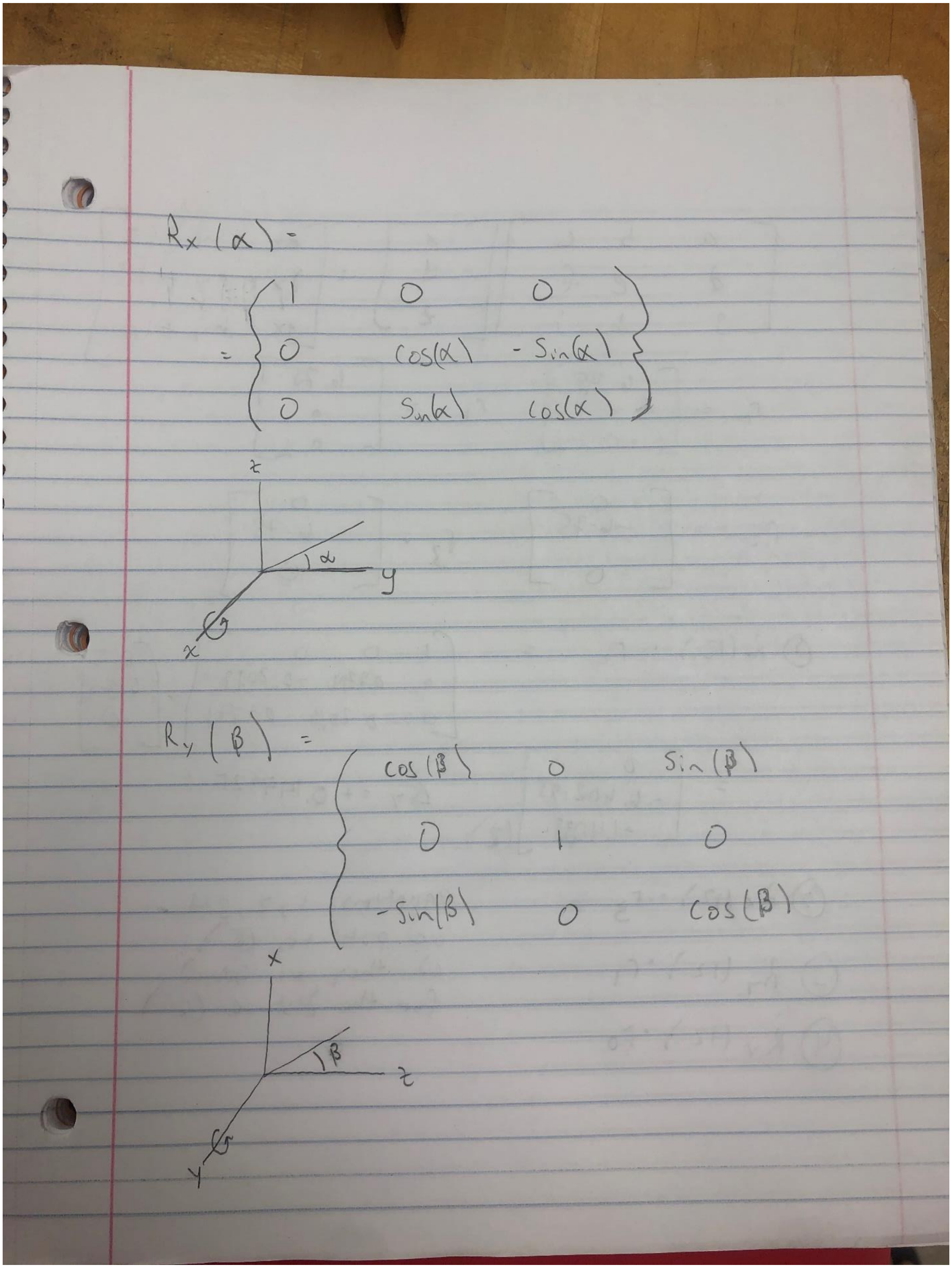
Vertical pieces

2 cross pieces



2 verteces pieces

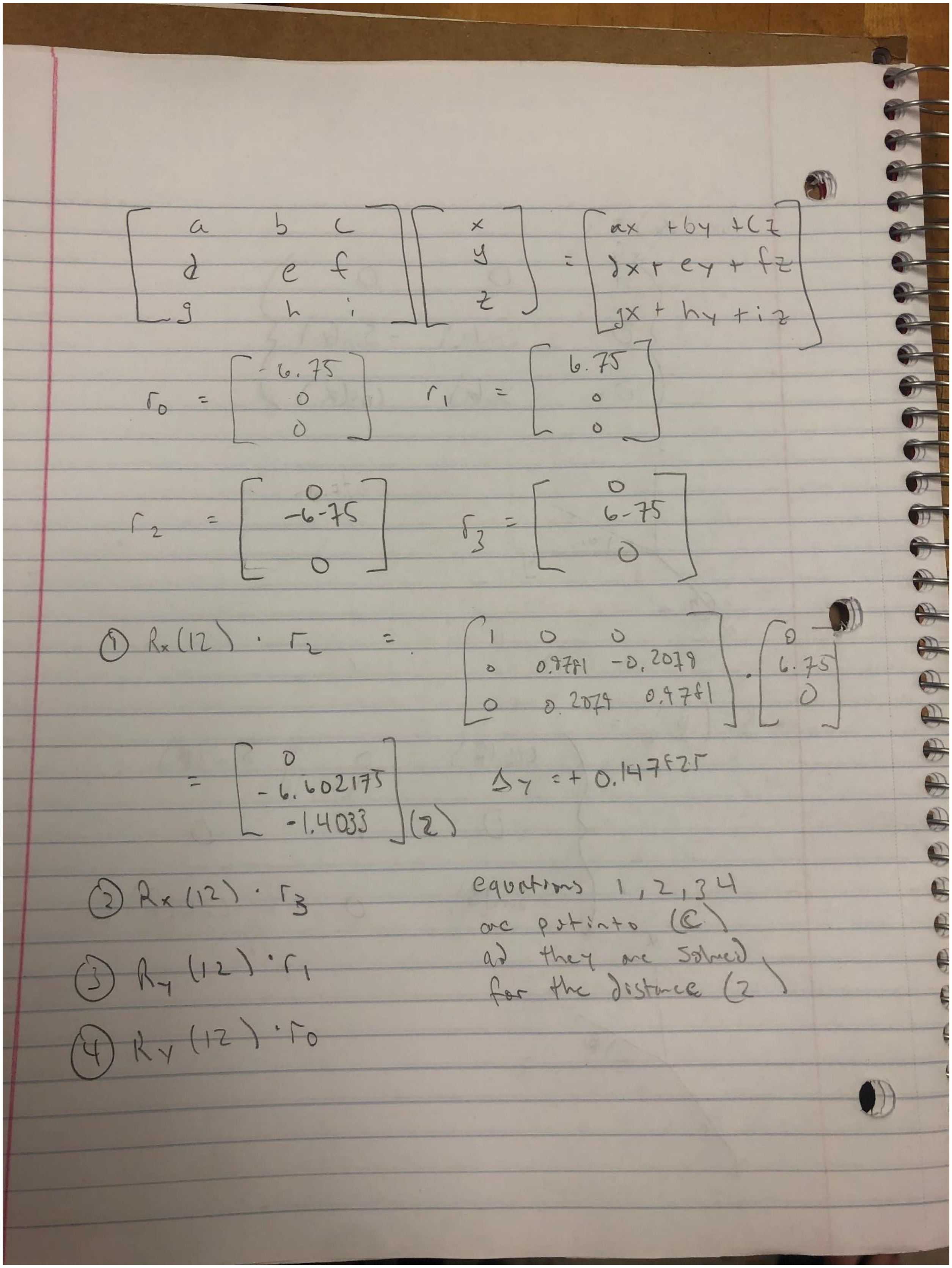




$R_x(\alpha) =$

$$= \begin{Bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{Bmatrix}$$

$$R_y(\beta) = \begin{Bmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{Bmatrix}$$



$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} ax + by + cz \\ dx + ey + fz \\ gx + hy + iz \end{bmatrix}$$

$$r_0 = \begin{bmatrix} -6.75 \\ 0 \\ 0 \end{bmatrix} \qquad r_1 = \begin{bmatrix} 6.75 \\ 0 \\ 0 \end{bmatrix}$$

$$r_2 = \begin{bmatrix} 0 \\ -6.75 \\ 0 \end{bmatrix} \qquad r_3 = \begin{bmatrix} 0 \\ 6.75 \\ 0 \end{bmatrix}$$

① $R_x(12) \cdot r_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.9781 & -0.2079 \\ 0 & 0.2079 & 0.9781 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 6.75 \\ 0 \end{bmatrix}$

$= \begin{bmatrix} 0 \\ -6.602175 \\ -1.4033 \end{bmatrix} (2)$ $\qquad \Delta y = +0.147825$

② $R_x(12) \cdot r_3$

③ $R_y(12) \cdot r_1$

④ $R_y(12) \cdot r_0$

equations 1, 2, 3 4
are put into (C)
and they are solved
for the distance (z)

Appendix H: Risk Assessment

Project Hazard Control- For Projects with Medium and Higher Risks

Name of Project: NASA Self-Leveling System		**Date of submission: 12/04/2020**
Team member	**Phone number**	**e-mail**
James Evans	561-714-6144	jte18@my.fsu.edu
Jake Seaman	954-621-7573	jts16d@my.fsu.edu
Dalton LeClair	941-894-9093	ddl16@my.fsu.edu
Parker Stensrud	407-749-4444	pls17@my.fsu.edu
Stephen Brown	850-865-3639	sjb18g@my.fsu.edu
Faculty mentor	**Phone number**	**e-mail**
Dr. Shayne McConomy	850-410-6624	smcconomy@eng.famu.fsu.edu

Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

Our subframe assembly will require the use of a pipe cutter/saw and welding. The possible consequences that could occur during these processes are loss of a body part/appendage, burns, and visual impairment. The safety measures put in place to prevent these accidents are always mandatory PPE, consisting of but not limited to protective eyewear, weld mask, gloves, long pants, and close toed shoes as well as the use of a weld and assembly fixture to assist in the construction of our frame. The assembly of our mechanism will require the use of a drill press, soldering iron, and the handling of live electrical components. The risks associated with these steps include appendage puncture and burns (mechanical and electrical). To prevent these accidents, we will use the drill press with extreme caution, use PPE, and ensure correct electrical grounding**.** The next step is the mounting of our mechanism which again requires the use of a drill press. We will reduce these safety hazards by having multiple students actively watching during drill press operation and wearing PPE. Our electrical system assembly has the potential for electrocution and soldering iron burns. To prevent these hazards, we will ensure proper grounding while handling these components and the PPE as previously described with the addition of a ventilation mask during soldering. Our final step is the testing of our full assembly. Possible risks include a total system failure in which our frame would collapse or fall over. Another possible risk is exposure to electricity if any alterations are made to the electronic components during testing. To prevent this, a "test radius" will be implemented during active testing to prevent any bodily harm in case of system collapse. Proper grounding will also be ensured prior to any alterations being made to the electronic components of the design.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

In the event of an emergency, the faculty mentor will be the first person notified of the situation. It will be at the discretion of the advisor to determine the severity of the situation and the level of medical attention necessary. A team member's emergency contact will be notified in the case of a severe emergency. As per OSHA guidelines to handle workplace injuries, "29 CFR 1910.151 Medical services and first aid",

The team is to ensure that medical assistance will be notified and needed in the case of an emergency. Trained personnel and adequate first aid supplies are to be provided to render first aid when a medical facility is not in near proximity to the lab/workplace. In severe cases, the need for emergency care of a hospital visit will be taken.

List emergency response contact information:

- Call 911 for injuries, fires or other emergency situations
- Call your department representative to report a facility concern

Name	Phone number	Faculty or other COE emergency contact	Phone number
Rochelle Seaman (Jake Seaman)	954-803-8121	Dr. Shayne McConomy	850-410-6624
Tiffney Evans (James Evans)	561-307-9224	Dr. Dorr Campbell	850-410-6610
Lisa Parker (Parker Stensrud)	407-529-5744		
Kimberly LeClair (Dalton LeClair)	941-232-9040		
Vicki Brown (Stephen Brown)	850-642-2080		

Safety review signatures

Team member	Date	Faculty mentor	Date
	12/04/2020		
	12/04/2020		
Parker Stensrud	12/04/2020		
Stephen Brown	12/04/2020		
	12/04/2020		

Report all accidents and near misses to the faculty mentor.

FAMU-FSU College of Engineering
Project Hazard Assessment Policy and Procedures

INTRODUCTION

University laboratories are not without safety hazards. Those circumstances or conditions that might go wrong must be predicted and reasonable control methods must be determined to prevent incident and injury. The FAMU-FSU College of Engineering is committed to achieving and maintaining safety in all levels of work activities.

PROJECT HAZARD ASSESSMENT POLICY

Principal investigator (PI)/instructor are responsible and accountable for safety in the research and teaching laboratory. Prior to starting an experiment, laboratory workers must conduct a project hazard assessment (PHA) to identify health, environmental and property hazards and the proper control methods to eliminate, reduce or control those hazards. PI/instructor must review, approve, and sign the written PHA and provide the identified hazard control measures. PI/instructor continually monitor projects to ensure proper controls and safety measures are available, implemented, and followed. PI/instructor are required to reevaluate a project anytime there is a change in scope or scale of a project and at least annually after the initial review.

PROJECT HAZARD ASSESSMENT PROCEDURES

It is FAMU-FSU College of Engineering policy to implement followings:

1. Laboratory workers (i.e. graduate students, undergraduate students, postdoctoral, volunteers, etc.) performing a research in FAMU-FSU College of Engineering are required to conduct PHA prior to commencement of an experiment or any project change in order to identify existing or potential hazards and to determine proper measures to control those hazards.
2. PI/instructor must review, approve, and sign the written PHA.
3. PI/instructor must ensure all the control methods identified in PHA are available and implemented in the laboratory.
4. In the event laboratory personnel are not following the safety precautions, PI/instructor must take firm actions (e.g. stop the work, set a meeting to discuss potential hazards and consequences, ask personnel to review the safety rules, etc.) to clarify the safety expectations.
5. PI/instructor must document all the incidents/accidents happened in the laboratory along with the PHA document to ensure that PHA is reviewed/modified to prevent reoccurrence. In the event of PHA modification a revision number should be given to the PHA, so project members know the latest PHA revision they should follow.
6. PI/instructor must ensure that those findings in PHA are communicated with other students working in the same laboratory (affected users).
7. PI/instructor must ensure that approved methods and precautions are being followed by:
   a. Performing periodic laboratory visits to prevent the development of unsafe practice.
   b. Quick reviewing of the safety rules and precautions in the laboratory members meetings.
   c. Assigning a safety representative to assist in implementing the expectations.
   d. Etc.
8. A copy of this PHA must be kept in a binder inside the laboratory or PI/instructor’s office (if experiment steps are confidential).

Project Hazard Assessment Worksheet				
PI/instructor: Dr. Shayne McConomy	Phone #: (850) 410-6624	Dept.: ME	Start Date: 09/03/2020	Revision number: 1
Project: NASA Self-Leveling System			Location(s): FAMU-FSU College of Engineering, 2525 Pottsdamer St, Tallahassee, FL 32310 Sliger Building, 2035 E Paul Dirac Dr, Tallahassee, FL 32310 Marshall Space Flight Center, Martin Rd SW, Huntsville, AL 35808	
Team member(s): James Evans, Jake Seaman, Parker Stensrud, Dalton LeClair, Stephen Brown			Phone #: 561-714-6144 954-621-7573 407-749-4444 941-894-9093 850-865-3639	Email: jte18@my.fsu.edu jts16d@my.fsu.edu pls17@my.fsu.edu ddl16@my.fsu.edu sjb18g@my.fsu.edu

Experiment Steps	Location	Person assigned	Identify hazards or potential failure points	Control method	PPE	List proper method of hazardous waste disposal, if any.	Residual Risk	Specific rules based on the residual risk

Subframe Assembly	FAMU-FSU College of Engineering/ Machine shop	Stephen Brown	Pipe cutter/saw (loss of body part/ appendage), Welding (Burns, visual impairment).	Weld Fixture and Assembly Fixture	Protective Eyewear, Weld Mask, Gloves, Long Pants, Closed toed shoes	N/A	HAZARD: 2 CONSEQ: Severe Residual: Medium	Always wear the correct PPE while operating machinery. Do not operate any machinery without supervision of others. Always remain aware of surroundings and appendages. If the above rules are not followed and an accident occurs, either 911 or the faculty contact will be notified immediately.
Mechanism Assembly	FAMU-FSU College of Engineering/ Sliger Building Garage	James Evans	Drill Press Accident (Drill bit into hand or clothing), Soldering Iron (Burns), Electrical shock from	Electrical grounding, PPE, extreme care when necessary.	Eyewear (safety glasses), gloves, ventilation mask.	N/A	HAZARD: 2 CONSEQ: Moderate Residual: Low Med	Always wear proper PPE and ensure electric tools are grounded. Additional team member present always. If the above rules are not followed and an accident occurs, either 911

			power source.					or the faculty contact will be notified immediately.
Mounting of Mechanism	FAMU-FSU College of Engineering/ Sliger Building Garage	Jake Seaman	Drill Press Accident (Drill bit into hand or clothing).	Careful use of drill will be enforced. No loose clothing is to be worn when operating drill or other mounting machine. At least one other team member to be present when mounting takes place.	Eyewear (safety glasses), long pants, closed toed shoes, and no loose clothing.	N/A	HAZARD: 2 CONSEQ: Moderate Residual: Low Med	Always wear proper PPE and ensure electric tools are grounded. Additional team member present always. If the above rules are not followed and an accident occurs, either 911 or the faculty contact will be notified immediately.
Electrical System Assembly	FAMU-FSU College of Engineering/ Sliger Building Garage	Parker Stensrud	Electrocution from power source, Soldering Iron (Burns), Heat Gun (Burns).	Proper grounding while assembling. Caution while using heating elements.	Mask / Ventilation while soldering. Long pants and closed toe shoes.	N/A	HAZARD: 2 CONSEQ: Significant Residual: Medium	Always be grounded while working with electronics and be aware of what you are touching. Use proper PPE while soldering and operating heat gun.

								Additional team member present. If the above rules are not followed and an accident occurs, either 911 or the faculty contact will be notified immediately.
Full Assembly and Test	FAMU-FSU College of Engineering/ Sliger Building Garage	Dalton LeClair	Collapse of system (blunt trauma), electrical shock from power source.	A "testing radius" will be implemented during active testing. Proper grounding during system alterations.	Protective eyewear, long pants, close toed shoes, no loose clothing.	N/A	HAZARD: 2 CONSEQ: Moderate Residual: Low Med	Safety controls are planned by both the worker and supervisor. A second team member must be present always Proceed with supervisor authorization. If the above rules are not followed and an accident occurs, either 911 or the faculty contact will be notified immediately.
Final Assembly Transport	FAMU-FSU College of Engineering/ Sliger	Parker Stensrud	Collapse of system or falling onto a person.	The entire team will be present for the	Close toed shoes (tied	N/A	HAZARD: 2 CONSEQ: Moderate	Before moving the final assembly, the team will have a

	Building Garage to an unspecified location			transportation of the final assembly. The team will act slowly and carefully to avoid damage to assembly or harm to anyone.	shoelaces), no loose clothing,		Residual: Low	plan for how the assembly will be moved. This will include the path taken, where/how the assembly will be lifted, and each team members role in moving. If the above rules are not followed and an accident occurs, either 911 or the faculty contact will be notified immediately.

Principal investigator(s)/ instructor PHA: I have reviewed and approved the PHA worksheet.

Name	**Signature**	**Date**	**Name**	**Signature**	**Date**
Dr. Shayne McConomy					

Team members: I certify that I have reviewed the PHA worksheet, am aware of the hazards, and will ensure the control measures are followed.

Name	**Signature**	**Date**	**Name**	**Signature**	**Date**
Jake Seaman		12/03/2020	Parker Stensrud	Parker Stensrud	12/03/2020
James Evans		12/03/2020	Stephen Brown	Stephen Brown	12/03/2020
Dalton LeClair		12/03/2020			

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DEFINITIONS:

Hazard: Any situation, object, or behavior that exists, or that can potentially cause ill health, injury, loss or property damage e.g. electricity, chemicals, biohazard materials, sharp objects, noise, wet floor, etc. OSHA defines hazards as "*any source of potential damage, harm or adverse health effects on something or someone".* A list of hazard types and examples are provided in appendix A.

Hazard control: Hazard control refers to workplace measures to eliminate/minimize adverse health effects, injury, loss, and property damage. Hazard control practices are often categorized into following three groups (priority as listed):

1. **Engineering control:** physical modifications to a process, equipment, or installation of a barrier into a system to minimize worker exposure to a hazard. Examples are ventilation (fume hood, biological safety cabinet), containment (glove box, sealed containers, barriers), substitution/elimination (consider less hazardous alternative materials), process controls (safety valves, gauges, temperature sensor, regulators, alarms, monitors, electrical grounding and bonding), etc.
2. **Administrative control:** changes in work procedures to reduce exposure and mitigate hazards. Examples are reducing scale of process (micro-scale experiments), reducing time of personal exposure to process, providing training on proper techniques, writing safety policies, supervision, requesting experts to perform the task, etc.
3. **Personal protective equipment (PPE):** equipment worn to minimize exposure to hazards. Examples are gloves, safety glasses, goggles, steel toe shoes, earplugs or muffs, hard hats, respirators, vests, full body suits, laboratory coats, etc.

Team member(s): Everyone who works on the project (i.e. grads, undergrads, postdocs, etc.). The primary contact must be listed first and provide phone number and email for contact.

Safety representative: Each laboratory is encouraged to have a safety representative, preferably a graduate student, in order to facilitate the implementation of the safety expectations in the laboratory. Duties include (but are not limited to):

- Act as a point of contact between the laboratory members and the college safety committee members.
- Ensure laboratory members are following the safety rules.
- Conduct periodic safety inspection of the laboratory.
- Schedule laboratory clean up dates with the laboratory members.
- Request for hazardous waste pick up.

Residual risk: Residual Risk Assessment Matrix are used to determine project's risk level. The hazard assessment matrix (table 1) and the residual risk assessment matrix (table2) are used to identify the residual risk category.

The instructions to use hazard assessment matrix (table 1) are listed below:

1. Define the workers familiarity level to perform the task and the complexity of the task.
2. Find the value associated with familiarity/complexity (1 – 5) and enter value next to: HAZARD on the PHA worksheet.

Table 1. Hazard assessment matrix.

	Complexity

		Simple	Moderate	Difficult
Familiarity Level	Very Familiar	1	2	3
	Somewhat Familiar	2	3	4
	Unfamiliar	3	4	5

The instructions to use residual risk assessment matrix (table 2) are listed below:

1. Identify the row associated with the familiarity/complexity value (1 – 5).
2. Identify the consequences and enter value next to: CONSEQ on the PHA worksheet. Consequences are determined by defining what would happen in a worst case scenario if controls fail.
    a. Negligible: minor injury resulting in basic first aid treatment that can be provided on site.
    b. Minor: minor injury resulting in advanced first aid treatment administered by a physician.
    c. Moderate: injuries that require treatment above first aid but do not require hospitalization.
    d. Significant: severe injuries requiring hospitalization.
    e. Severe: death or permanent disability.
3. Find the residual risk value associated with assessed hazard/consequences: Low –Low Med – Med– Med High – High.
4. Enter value next to: RESIDUAL on the PHA worksheet.

Table 2. Residual risk assessment matrix.

Assessed Hazard Level	**Consequences**				
	Negligible	Minor	Moderate	Significant	Severe
5	Low Med	Medium	Med High	High	High
4	Low	Low Med	Medium	Med High	High
3	Low	Low Med	Medium	Med High	Med High
2	Low	Low Med	Low Med	Medium	Medium
1	Low	Low	Low Med	Low Med	Medium

Specific rules for each category of the residual risk:

Low:

- Safety controls are planned by both the worker and supervisor.
- Proceed with supervisor authorization.

Low Med:

- Safety controls are planned by both the worker and supervisor.
- A second worker must be in place before work can proceed (buddy system).

- Proceed with supervisor authorization.

Med:

- After approval by the PI, a copy must be sent to the Safety Committee.
- A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the Safety Committee.
- A second worker must be in place before work can proceed (buddy system).
- Limit the number of authorized workers in the hazard area.

Med High:

- After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
- A written Project Hazard Control is required and must be approved by the PI and the Safety Committee before proceeding.
- Two qualified workers must be in place before work can proceed.
- Limit the number of authorized workers in the hazard area.

High:

- The activity will not be performed. The activity must be redesigned to fall in a lower hazard category.

Appendix A: Hazard types and examples

Types of Hazard	**Example**
Physical hazards	Wet floors, loose electrical cables objects protruding in walkways or doorways
Ergonomic hazards	Lifting heavy objects Stretching the body Twisting the body Poor desk seating
Psychological hazards	Heights, loud sounds, tunnels, bright lights
Environmental hazards	Room temperature, ventilation contaminated air, photocopiers, some office plants acids
Hazardous substances	Alkalis solvents
Biological hazards	Hepatitis B, new strain influenza
Radiation hazards	Electric welding flashes Sunburn
Chemical hazards	Effects on central nervous system, lungs, digestive system, circulatory system, skin, reproductive system. Short term (acute) effects such as burns, rashes, irritation, feeling unwell, coma and death.

	Long term (chronic) effects such as mutagenic (affects cell structure), carcinogenic (cancer), teratogenic (reproductive effect), dermatitis of the skin, and occupational asthma and lung damage.
Noise	High levels of industrial noise will cause irritation in the short term, and industrial deafness in the long term.
Temperature	Personal comfort is best between temperatures of 16°C and 30°C, better between 21°C and 26°C. Working outside these temperature ranges: may lead to becoming chilled, even hypothermia (deep body cooling) in the colder temperatures, and may lead to dehydration, cramps, heat exhaustion, and hyperthermia (heat stroke) in the warmer temperatures.
Being struck by	This hazard could be a projectile, moving object or material. The health effect could be lacerations, bruising, breaks, eye injuries, and possibly death.
Crushed by	A typical example of this hazard is tractor rollover. Death is usually the result
Entangled by	Becoming entangled in machinery. Effects could be crushing, lacerations, bruising, breaks amputation and death.
High energy sources	Explosions, high pressure gases, liquids and dusts, fires, electricity and sources such as lasers can all have serious effects on the body, even death.
Vibration	Vibration can affect the human body in the hand arm with `white-finger' or Raynaud's Syndrome, and the whole body with motion sickness, giddiness, damage to bones and audits, blood pressure and nervous system problems.
Slips, trips and falls	A very common workplace hazard from tripping on floors, falling off structures or down stairs, and slipping on spills.
Radiation	Radiation can have serious health effects. Skin cancer, other cancers, sterility, birth deformities, blood changes, skin burns and eye damage are examples.
Physical	Excessive effort, poor posture and repetition can all lead to muscular pain, tendon damage and deterioration to bones and related structures
Psychological	Stress, anxiety, tiredness, poor concentration, headaches, back pain and heart disease can be the health effects
Biological	More common in the health, food and agricultural industries. Effects such as infectious disease, rashes and allergic response.