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EML4551-2

Team 517: Stabilization of Payload for Legged Robots

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Acknowledgement

Thank you to our sponsor, Northrop Grumman, for their contributions to the project. We're grateful for their support of engineering pursuits at FAMU-FSU College of Engineering.

Thank you to our sponsor, Camilo Ordonez for assisting us through his expertise in robotics.

Table of Contents

Chapter One: EML 4551C

1.1 Project Scope

Project Description

This project will aim to stabilize the center of mass for legged, often bio-inspired, robots to improve sensor readings and camera video quality without compromising locomotion. The center of mass on these robots often has a high degree of oscillation and variance in pitch. The focus of this project will be on the stabilization aspect rather than the robot itself. A camera will serve as the payload and the goal will be to minimize the disruption caused to the camera as the robot moves in an unsteady fashion.

Key Goals

Our key goals are as follows:

- Accurately simulate the oscillatory motion of the Minitaur robot.
- Develop an active damping system to counteract unwanted motion.
- Utilize passive damping techniques to minimize vibration.
- Stabilize the center of mass for the robot to improve mounted camera usage.

Market

The market of this product would be any robot in need of a stabilization method especially for data collection. However, this stabilization system could be expanded passed the field of robotics to any stabilization application. This camera stabilization system would be suitable for mounting to larger systems such as bicycles or cars which would be of interest to law enforcement for dash cam video. In addition to dash cams, this could be applied to the body camera market as well. An additional market would be the military to stabilize weapons systems or drone footage.

Assumptions

Our team has assumed that the foundation for this project will be based on the Minitaur robot that Dr. Ordonez and David Balbuena work on in a lab at the AME building. We will also assume that the Minitaur is still approximately 4kg. We also assume that we are constrained within our $4500-$5000 budget.

Stakeholders

The primary stakeholder for this product is Northrop Grumman. Other stakeholders include Dr. Ordonez, the graduate student working on the Minitaur named David Balbuena, and other roboticists, such as Dr. Clark, at Florida State, other universities, and other research facilities. Dr. McConomy is also a stakeholder.

1.2 Customer Needs

The sponsor's main interest for this project is the stabilization. They want a stabilization system that will allow sensors and cameras to provide better return data. They want the team to utilize a pre-existing robot as a baseline for data and reduce the levels of oscillation in the feedback of a system that occur at the center of the robot's mass.

1.What final products are you looking for?

The sponsor said they are most concerned with the stabilization aspect. They want a final product that can be adapted to a variety of platforms to stabilize the payload. The robot itself was less of a concern.

1. What will qualify as "stabilized"?

   This was not a target that our sponsor specified. The sponsor wasn't sure what would be a reasonable improvement in stabilization so we will need to do some research to set our own targets. The decrease in angular oscillation is the focus of the stabilization effort.

2. How many legs?

   When speaking to our sponsor they were hopeful that there would be a robot in a lab here for us to work from. After later talking to Dr. Ordonez the robot we will be using is the Minitaur and that robot has four legs.

3. Generally, what do we have to work from? Do we have an existing robot or model to modify or are we starting from scratch?

   As stated in the answer to our third question, the robot will be provided by Dr. Ordonez and was not the primary concern of the sponsor.

4. What is our budget for this project?

   The sponsor told us our budget would be between $4500 and $5000. The team will receive closer to $2000.

5. What applications is this type of stabilized robot used for?

   Northrop doesn't actually fabricate or work on any legged robots. Therefore, the sponsor said their interest is in the stabilization and creating a system that would have many applications, rather than the robot.

6. What, if any, loads would the robot carry?

   The sponsor said the load will be a moderately sized camera centered on the robot.

7. What is your overall vision for this project?
   The sponsor described their vision as a targeting type system that was able to focus on a specific image or target and keep the camera's focus on that point.

8. When would be a good and consistent time for us to have a call?
   Our sponsor said that afternoons and evenings are best for us to call him.

9. How often would we like to have team calls with the sponsor?
   We discussed having more frequent calls, once every two weeks, at the beginning of the project and then communicating less frequently once our goals for the project were more clearly defined.

10. Best way to reach you outside of our regularly scheduled calls?
   The sponsor said email was hit or miss but that we could call his cell phone anytime we had a question. If it was a shorter question, a text message would also be appropriate.

1.3 Functional Decomposition

The primary function our system will need to satisfy is stabilizing the payload. In order to satisfy that function, the system will also need to be able to detect motion, counteract motion, operate in approved climate conditions, and ingrate with a larger system. To detect motion, it is important that the project can support sensors. Integration into a larger system is also important, and can be baseline with an ability to mount on the Minitaur. For mounting on the Mintaur to be successful, the system will need to take the impact of Minitaur movement and maintain the payload.

1.4 Target Summary

Our targets center around essential functions and objectives that our system will need to accomplish in order to stabilize the payload of a legged robot. Further, our targets also focus on the Minitaur as the robot we're using to assess our improvement. When speaking to our sponsor, their focus was on the stabilization on the payload, so our targets aim to streamline that objective by setting goals for the various components that will play a role in achieving that goal.

Our system will need to detect motion and support sensors which will be achieved through the use of gyroscopes and cameras. Reasonable detecting ranges and weight are the metrics assigned to each of those sensors. Our system will also counteract motion within a certain range. It will also need to operate in standard indoor climates, which were determined to be approximately room temperature. Lastly, the stabilization system will be required to integrate with larger systems, namely the Minitaur. To take the impact of the Minitaur and maintain a reasonable payload, metrics were assigned to the durability and weight of the system. A table of the critical targets is shown below in table 1 and a catalog of all targets and metrics can be found in Appendix C.

The most critical targets and metrics are the correction factor being 50% and keeping the weight of the system to 1.5kg or less. The main objective of this project is the stabilization aspect, so that target is the primary focus. Keeping the weight of the system down is also critical because the Minitaur is a small robot that can only sustain a small percent of mass increase.

Table 1. Critical targets and metrics

Target	**Value**
Minimum Correction Factor	50%
Maximum Weight of System	1.5kg

1.5 Concept Generation

Concepts were generated to solve all aspects of stabilization project, primarily considering the logic system, active stabilization, and passive stabilization. The top three concepts are discussed under concept 1, concept 2, and concept 3. Secondary concepts are discussed in concepts 5-8. Many of these ideas will be used in combination with each other for the overall system. These concepts will be evaluated during the concept selection phase, considering weight and stabilization as the most important criteria. A full list of ideas can be found in Appendix D.

Concept 1

A second idea for a microcontroller would be using an Arduino. Arduinos have lots of open source code and use C as the programming language. Like Raspberry Pi, they come in different bit sizes and prices. They also have models within our specified power ranges. Arduinos are also known to be very simple to work with.

Concept 2

A way to implement passive stabilization is to add dynamics vibration absorbers (DVA) on the linkages. A DVA would be a mass-spring-damper addition to each linkage which would absorb a degree of the vibration when the system is excited. Adding a system like this would be more complicated than just adding a rubber layer but may also be more effective because of the addition spring component compensating for vibration.

Concept 3

To control the motion, one concept is to use servo motors. Servo motors have quick reactions and would control the motion as fast as we would need. They will add weight to the system so we will need to actively try to reduce weight in other areas.

Concept 4

A concept for powering the system would be to use standard batteries. Lithium ion batteries are rechargeable and would provide the amount of power to the system that we would need. They're not too expensive and are a moderate weight so they won't add critical mass to the system.

Concept 5

One option for the control system of our project would be to use a Raspberry Pi. Raspberry Pi uses Python as the programming language. These devices also come in different bit sizes and price ranges. Volt ranges on different models also allow us to meet our constraints. Raspberry Pi may be more complicated than other controllers to use but also will run faster.

Concept 6

One way to add damping would be with a layer of rubber shock absorbing pads under the base connection of the system. The rubber shock absorption pad would help to remove a degree of the systems vibration and would be relatively easy to implement. Rubber is a good dampening material and can also be found for a good price.

Concept 7

An option for attaching the system is with screws. Machine screws are inexpensive and adding screw holes to whatever linkages we have would be easy. Screws will also strongly secure the system, are long lasting, and would not add significant weight to the system. They are also inexpensive and would be easy to use.

Concept 8

An alternative idea for controlling motion would be to use linear actuators. Linear actuators are slower than servo motors but can also control the direction or orientation of our system. They have also been known to be more complicated and more difficult to work with.

1.6 Concept Selection

The concept selection process included using a house of quality and an analytical hierarchy process to determine the best concept from the overall list of concepts generated. This process allowed the team to identify the most important engineering characteristics and then evaluate their weight. It also helped to clarify how each of the concepts ranked according to the engineering characteristic, which ultimately led to the selection of a final concept.

Requirements for the project were gathered from the customer requirements which were identified a number of weeks ago. The engineering characters were evaluated from the targets and metrics set for the project. The weight factors of the customer requirements were created from a pairwise comparison which can be found in the appendix. These components were then put in a house of quality.

Our first concept is to use four servo motors connected by brackets and link arms in order to counteract motion on x, y, and z axis. Three of the motors would focus solely on counteracting the movements in the specified axis, while the fourth motor controls the angle at which the payload deviates from the target.

A second concept would be a telescoping linkage with each end having a 3 degree of freedom joint. The telescoping linkage would expand and contract vertically, removing the bounce of the robots walk.

The third concept was to use 2 linear actuators to control the each the x and y axes. One linear actuator corrects one degree of motion on a hinge and the other corrects the other degree of motion on a hinge. The entire system can have a flat platform about both hinges for the camera to be attached to.

House of Quality

Table 2. House of Quality

		Characteristics											
Units		%	meters/seconds(squared)	grams	mm	Celsius	runs x feet	runs x feet	runs x feet	kg	Volts	%	seconds/degrees
Requirements	**Weight Factor**	Correction Factor	Motion Detection	System Payload Weight	Motion Counteraction Range	Operating Temperature Range	Larger System Integration	Stay on Minitaur	Take Minitaur Impact	System Weight	Power Requirement	Feedback Loop	Correction Speed
1. Small	2	1		9	1		3	1		9	9		3
2. Lightweight	4			9			3	1	1	9	3		3
3. Improves Stabilization	6	9	9		3						3	3	3
4. Simple	3			3			1		1	3	3		1
5. Cost Effective	5	3	3	3	1	1			1	3	3		3
6. Durable	1			3		9		1	9	3	3		3
7. Operating Efficiency	1	1	1	3	3					1	9	1	3
Raw Score (560)		72	70	82	28	14	21	7	21	82	84	19	60
Relative Weight		0.129	0.125	0.146	0.05	0.025	0.038	0.013	0.038	0.146	0.15	0.034	0.107
Rank Order		4	5	2	7	11	8	12	8	2	1	10	6

The house of quality done for concept selection can be seen in table 1. For the house of quality, customer requirements were selected based off customer needs previously identified. Those requirements can be seen on the left side of the table. The weight factor next to the customer requirements was determined using a pairwise comparison. The pairwise comparison can be found in the appendix. Next, the engineering characteristics were determined from the targets and metrics previously set for this project. Those are listed across the top of the table, including units for clarity. The customer requirements were then evaluated as to whether or not they had a correlation with the engineering characteristics and how significant that correlation is. A 1 indicates a low correlation, a 3 indicates a moderate correlation, and a 9 indicates a high correlation. Once all the customer requirements had been connected to their corresponding engineering requirements, a raw score of each engineering characteristic was determined by summing the multiplication of the weight factor by the correlation factor for each correlation. A relative weight was found by taking each raw score and dividing it by the total of all the raw scores. The top four engineering characteristics were then selected by those that had the highest weights.

Pugh Matrix

For concept selection, our team had 3 primary concepts for the active stabilization of our project that could be evaluated with the tools described here. For this reason, a Pugh matrix was not a necessary step.

Analytical Hierarchy Process

Table 3. AHP Final Rating Matrix

Final Rating Matrix			
	Concept 1	**Concept 2**	**Concept 3**
Power Requirement	0.6	0.2	0.2
System Weight	0.43	0.43	0.14
System Payload Weight	0.303	0.156	0.577
Correction Factor	0.575	0.139	0.286

Table 4. Alternative Values for Final Selection

FINAL SELECTION			
	Concept 1	**Concept 2**	**Concept 3**
AV	0.5216	0.2085	0.2728

For the final selection of a concept, an analytical hierarchy process was used. This began with a critical comparison matrix of the engineering characteristics, which was then normalized and used to determine their weighting and rank. It was found that the correction factor was the primary criteria, followed by system weight, system payload weight, and power requirement, in that order. Both the critical comparison matrix and the normalized critical comparison matrix can be found in the appendix. The next step was to create a pairwise comparison of all three concepts for each of the selection criteria, and then normalize the results. The tables of all pairwise comparisons and their normalized values are found in the appendix. The average of the normalized values is also listed in those tables and are the values found in the table 3, the final rating matrix. The transverse of that matrix was then multiplied by the engineering characteristic weighs found from the normalized criteria comparison matrix to determine the concept ranks. From table 4 it can be seen that concept 1 is the mostly highly ranked and is chosen for our concept selection.

In conclusion, our team used house of quality, multiple pairwise comparisons, and analytical hierarchy process to select a final concept for our project. Concept 1 was found to have the highest rating and will therefore be pursued as the solution to our project.

1.8 Spring Project Plan

The team's Spring Project Plan is laid out in the Gannt chart which can be found in Appendix F. This chart shows that once classes being, detail design will occur and materials will be ordered. Once parts arrive, 3D printing will begin followed by assembly of the testing rig and stabilization system. Testing should happen at the end of February and into the very beginning of March. Based on the data of the initial tests, a redesign will take place and build adjustments will be made by the team. The project will then be retested, finalized, and documentation will be done by mid-April, leaving a few weeks lead time before the semesters end and graduation. The Gannt chart also shows which team members are specifically responsible for certain tasks.

Major Milestones

Detail Design Review

Once the final CAD files are complete, the team will be able to confirm the assembly of the system and STL files can be made for 3D printing.

Parts Arrive

When the parts arrive, then assembly of the stabilization of the system can take place and formalized prototyping will begin.

Build Test Rig and Build Stabilization System Prototype

The complete of these two milestones are related because they must work in testing together. This step will allow for system verification and redesign.

Rebuild

Based on the data collected from initial testing, a redesign will take place to improve the system and a rebuild will occur to correct system errors. Once the rebuild is complete, further testing can take place.

Project Finalization

The series of testing will lead to a finalized product meant to improve the payload stabilization of legged robots. This will be presented at Engineering Design Day.

Engineering Design Day

The culmination of all the teams work will occur on Engineering Design Day when a summary of our yearlong project is presented and the system will be final.

Finals

In order to graduate, team members will need to take and pass the final exams of their other classes.

Graduation

Graduation will mark the completion of the academic year and the undergraduate degree for all team members. Engineering degrees will be awarded on this day.

Appendices

Appendix A: Code of Conduct

Mission Statement

The Northrop Grumman Stabilization of Payload for Legged Robots team will strive to create an ethical and professional environment aimed at overcoming the natural oscillation of legged robots. The team members will provide fair contributions and work together to utilize everyone's experience, talents, and engineering knowledge to produce the best solution possible to this issue. Our team will work with our client to deliver the most effective and efficient solution.

Team Member Roles

Team Lead – Ariel Mathias

The team lead will be the main point of contact for our team and will be responsible for corresponding with the advisor and sponsor. It will fall on the team lead to ensure that all team members feel their contributions are valued and feel comfortable participating in team discussions. The team lead will also be responsible for making sure that all team members are contributing fairly and that tasks are distributed equally. The leader will make sure that all deadlines are met and assignments thoroughly completed on time. Should any conflicts arise within the team, the team lead will facilitate the efforts to resolve that issue.

Mathematician – Junyi Wang

The calculator will primarily be responsible for designing the structure of the machine and calculating the size which is appropriate for the system. They will do the majority of the necessary background calculations, supported by the rest of the team. Additionally, they may serve to assist in computer programming.

Programmer – John Bryant

The programmer will be responsible for the electrical and software components of the system. The roles will consist of but not limited to editing previous code if needed, wiring and programing sensors to help improve stability, and coding the system that will control the payload stabilization.

CAD Specialist – Tristan Kirby

The CAD specialist will be responsible for all computer models of potential solutions. This includes but is not limited to; creating mock ups of preliminary designs, running simulations to compare and improve possible solutions, and drafting detailed drawings to be used for prototyping. It also falls to the CAD specialist to ensure that any design considered for prototyping is feasible to manufacture.

Systems Specialist – Anthony Wyrick

The financial advisor is responsible for handling the funds of the team. This will include but not be limited to, creating a budget and spreadsheets to show where and what the money is spent on**.** The financial advisor will also be responsible for ordering the required parts and materials needed to complete the project.

Duties not specifically outlined in these job descriptions will be evenly distributed among team members according to everyone's skills, talents, and availability. It is the team leaders responsibility to keep track that all assignments are distributed.

Communication Procedure

Team members will communicate in person at weekly meetings held on Tuesdays at 4pm and/or Wednesdays at 5pm as appropriate. Electronic communication between the team will be done using iMessage. All electronic materials will be accessible to team members via a Google Drive. Communication with our advisor and sponsor will be done through email, in person meetings, and conference calls. All team members are expected to be active participants in group conversations regardless of the mean of communication. Responses should be thoughtful, timely, and within 24 hours of the initial messaging.

Ethics

Team 517 will adhere to the FAMU-FSU College of Engineering Student Handbook policies as well as the Northrop Grumman Code of Conduct. Our team is expected to conduct themselves in an ethical and professional manner.

Dress Code

During team meetings, casual attire may be appropriate. For sponsor and advisor meetings business casual is expected. When giving presentations the team will dress business professional. For other types of events or meetings, attire will be discussed and decided upon at the team's discretion. All team members will be notified prior to any meetings requiring non-casual dress with at least 24 hours notice.

Attendance Policy

Team members are expected to be present at all sponsor and advisor meetings, as well as group presentation. For prescheduled full team meetings, all members should be in attendance. If a member cannot attend a meeting for a valid reason, they will be expected to provide reasonable notice to the other team members. If schedules are in conflict, the team will try to accommodate the majority of the members. Should a member miss a meeting, it is their responsibility to discuss what they missed and what tasks they may be responsible for with their other teammates. Weekly team meetings will take place on Tuesday at 4pm and, if necessary, Wednesdays at 5pm.

Conflict Resolution

All conflicts should aim to be resolved between the relevant team members first. A team member having an issue with another teammate should bring the situation to the project manager. If the individuals cannot resolve the issue amongst themselves than the entire team will strive to come to a resolution, lead by the project manager's discretion. Should the issue persist past a possible team solution, the issue will be brought to the ME advisor.

Amendment Process

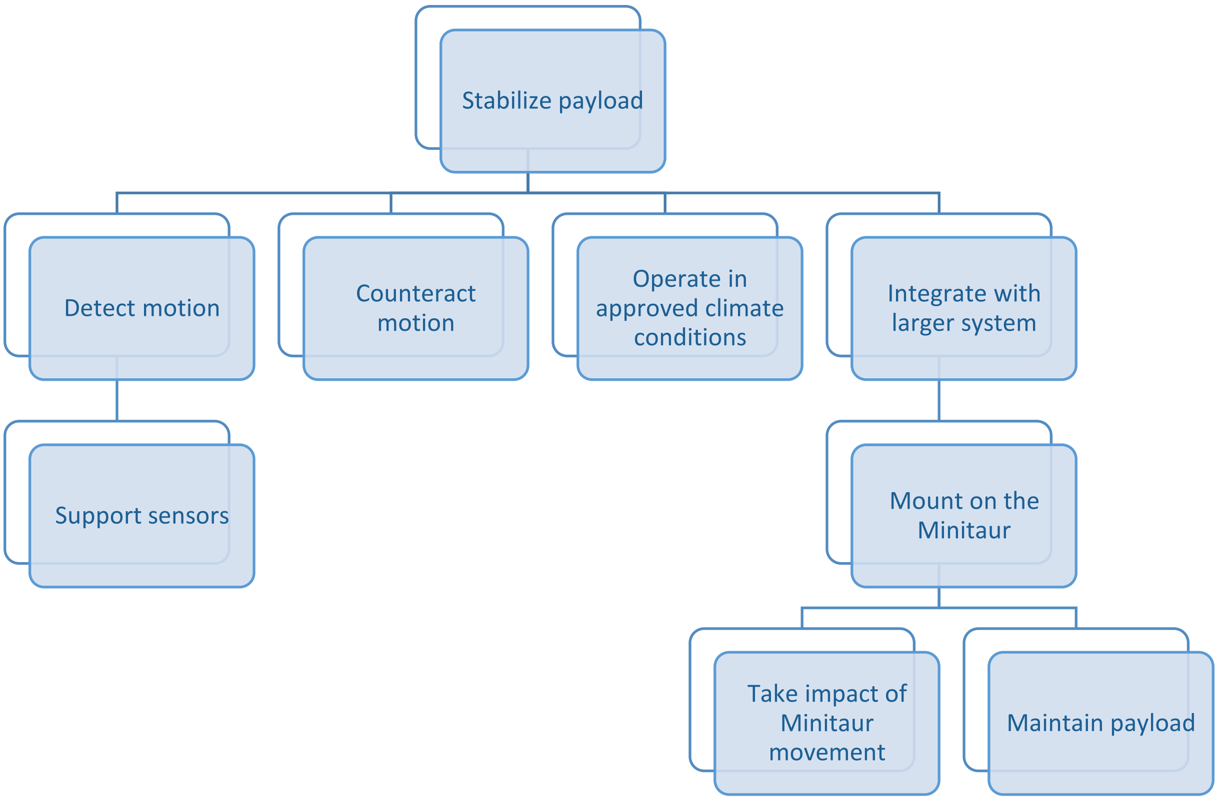
If the Code of Conduct needs to be amended, a team meeting to discuss changes will take place and if the majority of the group approves the edits than the charter will be amended.

Statement of Understanding

By signing this document, all team members of Team 517 agree to the above code of conduct.

Name	*Signature*	*Date*
Ariel Mathias	[illegible]	9-12-18
Tristan Kirby	[illegible]	9-12-18
Junyi Wang	Junyi Wang	9-12-18
Anthony Wyrick	Anthony Wyrick	9-12-18
John Bryant	John Bryant	9-12-18

Appendix B: Functional Decomposition



Appendix C: Target Catalog

Stabilize Payload

- The target correction factor will be a percentage of at least 50%.
- Stabilizing the payload will be measured by the correction factor, calculated as the difference from the pre-system results and the post-system results. The Minitaur will be outfitted with a laser to measure the deviation from the desired target.
- This value was derived because 50% improvement is provement of repeatable improvement, confirming that our system actively corrected stabilization rather than improving the system as a fluke.

Detect Motion

- The gyroscope will detect motion at a minimum of 1 g (g=9.81 m/s).
- If when the robot runs with an acceleration of at least 1 g, we receive data from the gyroscope than this target is validated. We will use the gyroscope output to validate that.
- This value was derived by evaluating the minimum speed of the Minitaur based on the video we have of its motion. That value was compared with detection values of gyroscope spec sheets to choose a reasonable detection rate.

Support Sensors

- The system will hold a sensor payload of under 150 grams.
- We will validate this based off the runs on the Minitaur. If the system runs 3 times for 10 feet without a camera of 150 grams detaching, then it will be successful. This will be validated with test runs.

- This value was derived based off the approximate weight of cameras that may be used as the payload for this system. It is also based off the weight that most types of motors applicable for this project can support.

Counteract Motion

- Our system will counteract linear motion between the range of 5mm < x < 150mm that occurs at at least 1g.
- We will validate this with our test runs. As long as the system responds within these conditions this is validated.
- This metric was derived from the data sheets that state the sensitivity of our sensors and a reasonable correction range.

Operate in Approved Climates

- The system will properly operate between 60-80 degrees Fahrenheit.
- We will validate this target with a temperature sensor within the confines of our system to confirm it is within the set temperature ranges.
- Standard room temperature is approximately 70 degrees Fahrenheit, our target aims to satisfy this temperature as well as a moderate variation.

Integrate with Larger System

- The system satisfies the mount on Minitaur targets.
- We will validate this the same way we validate the mounting on the Minitaur value. It will need to sustain 3 runs on a 10-foot path on the Mintaur.

- We derived this target because the Minitaur is the robot provided at us to use for this project.

Mount on Minitaur

- The system will stay on the Minitaur for 3 trials of 10 feet without detaching from the robot.
- We will validate this with test runs where the Minitaur runs a 10-foot path 3 times without having the system fall off or be adjusted between trials.
- We chose this metric based off the video we have the Minitaur running. We evaluated the motion of the robot and how many steps it takes per foot to reach a set distance and cycle value.

Take Impact of Minitaur Movement

- The system must withstand 3 trials of 10 feet without failing or deforming.
- We will validate this with test runs where the Minitaur runs a 10-foot path 3 times without having the system fall off or be adjusted between trials.
- We chose this metric based off the video we have the Minitaur running. We evaluated the motion of the robot and how many steps it takes per foot to reach a set distance and cycle value.

Maintain Payload

- The system will not increase the payload of the Minitaur by more than 1.5 kg.

- We will validate this measure with a scale to determine the weight of the camera on the Minitaur.
- This value was derived based on the need to keep weight of the Minitaur down but the necessity to add weight for the system to work. This value was suggested as a reasonable load for this robot by Dr. Ordonez.

Power

- The system will run on 5 Volts.
- We will measure this with the battery pack we use. Validation of this will be based on if the system completely runs off no more than 5 Volts.
- We derived this by evaluating what we perceive our power needs to be at this point in exploring project ideas. 5 volts is also a standard voltage value for most mechatronic systems.

Feedback Loop

- The movement detected at the sensor must be less than 50% of the movement at the mount to insure that any active correction is working as intended.
- This will be verified by comparing the gyroscope data collected at the sensor to the gyroscope data collected from the robot
- This value was derived because 50% improvement is provement of repeatable improvement, confirming that our system actively corrected stabilization rather than improving the system as a fluke.

Correction Speed

- Our system will have a correction speed of 0.25 seconds per 60 degrees.
- We will measure this through test runs where we evaluate if the system is responding at this rate. A timer and an angular measurement device will be needed to accurately measure this.
- We derived this value based off a standard servo motor spec sheet. The spec sheet gave a rate of 0.18 seconds per 60 degrees as its operating speed without payload. With the addition of a payload and considering the operating speed of the microcontroller and the gyroscope, the overall system should be able to run at this speed.

Table 1
Critical Targets and Values

Target	**Value**
Minimum Correction Factor	50%
Maximum Weight of System	1.5kg

Table 2
Required Targets and Values

Target	**Value**
Minimum Correction Factor	50%
Minimum Motion Detection	1 g
Maximum System Payload Weight	150 grams

Motion Counteraction Range	5mm<x<150mm at at least 1g
Operating Temperature Range	60-80 degrees Celsius
Integrate with Larger System	3 runs of 10 feet on Minitaur
Stay on Minitaur	3 runs of 10 feet
Take Minitaur Impact without Damage	3 runs of 10 feet
Maximum Weight of System	1.5kg
Power Requirement	5V
Feedback Loop	50% decrease
Correction Speed	0.25 seconds per 60 degrees

Appendix D: Concept Generation List

1. Chicken head stability - system of cables attached to actuators simulate a chicken keeping its head balanced
2. Cheetahs keep their head stable as they walk - can study their neck movement, muscles, nerves, structure, etc.
3. Human eyes that adjust - can look into cameras that auto adjust and autofocus for movement
4. Dog tails for stabilization - can use a counterweight to help with balance
5. Attach to other systems by Velcro
6. **Attach to other systems with screws**
7. Super glue it to the robot
8. Tape it the robot
9. Nail it to the robot
10. Weld it to the robot
11. Snap on to robot
12. Button the system in
13. Ratchet strap stabilization system to robot
14. Drones at high accelerations and extreme temperatures - need to use sensors and materials that would withstand that
15. Withstand high impact - springs to relieve vibration and impact
16. **Withstand high impact - rubber mats to dampen the system**
17. Withstand high impact - foam mats to dampen the system
18. Amphibious - corrosion resistant materials
19. Amphibious - O rings to seal the system
20. Amphibious - Rubber gaskets to seal the system
21. Amphibious - Flexible sealed outer shell
22. Amphibious - cover the entire system in silicon
23. Durable - use fan to blow away dust and dirt
24. Durable - use a vacuum to suck in dust and dirt to a controlled zone
25. Durable - hard protective outer shell

26. Durable - use high strength and high fatigue limit materials
27. Long lasting power source - could just interchange rechargeable batteries
28. Long lasting power source - normal batteries
29. Long lasting power source - solar powered
30. Long lasting power source - gasoline powered
31. Long lasting power source - wind powered
32. Long lasting power source - motion charged, can use the motion of the robot to create power
33. Long last power source - nuclear powered
34. Temperature constraints - use a flame retardant material
35. Temperature constraints - use a fan to cool the system down
36. Temperature constraints - gel cooled
37. Temperature constraints - liquid cooled
38. Temperature constraints - add a gas heater
39. Temperature constraints - put a heat sink in the system
40. Temperature constraints - add a chemical heater
41. Temperature constraints - put a sunshade on the top of the system
42. Control Logic - arduino
43. Control Logic - raspberry pi
44. Control Logic - teensy
45. Robust - add rubber bumpers
46. Robust - add air bumpers
47. Robust - use overmolded rubber around linkages
48. Robust - use a tough printing material
49. Price Reduction - 3D print it
50. Price Reduction - forge it
51. Price Reduction - cast it
52. Price Reduction - mold (injection)
53. Price Reduction - extrusion
54. Use a dynamic vibration absorber to stabilize the system and take out some damping

55. Use air jet buffers
56. Use electro-magnetic levitation
57. Use pneumatic pistons for motion
58. Use linear actuators for motion
59. Use DC motors
60. Use stepper motors
61. **Use servo motors**
62. Connect wires with breadboards
63. Connect wires with prototyping board
64. Connect wires with printed circuit board
65. Connect a telescopic lens to the camera to improve range
66. Connect linkages with hinges
67. Connect linkages by welding
68. Connect linkages by screws
69. Connect linkages with hot glue
70. Use optical image stabilization
71. Add a laser to track path
72. Use a camera video footage to track path
73. Use a flashlight to track path
74. Add gyroscope to the robot
75. Add gyroscope to the sensor (camera)
76. Use piezoelectric actuators to control motion

Appendix E: Concept Selection

Table 1A. Critical Comparison Matrix

Customer Requirements	1	2	3	4	5	6	7	Total
1. Small	~	0	0	0	0	1	1	2
2. Lightweight	1	~	0	1	0	1	1	4
3. Improves Stabilization	1	1	~	1	1	1	1	6
4. Simple	1	0	0	~	0	1	0	3
5. Cost Effective	1	1	0	1	~	1	1	5
6. Durable	0	0	0	0	0	~	1	1
7. Operating Efficiency	0	0	0	1	0	0	~	1
Total	4	2	0	3	1	5	5	6

Table 2A. Pairwise Comparison of Customer Requirements

Criteria Comparison Matrix					
Selection Criteria	Power Requirement	System Weight	System Payload Weight	Correction Factor	W
Power Requirement	1	0.143	0.333	0.111	1.587
System Weight	7	1	5	0.143	13.143
System Payload Weight	3	0.2	1	0.111	4.311
Correction Factor	9	7	9	1	26
Sum	20	8.343	15.333	1.365	45.041

Table 3A. Normalized Pairwise Comparison of Customer Requirements

Normalized Criteria Comparison Matrix					
Selection Criteria	Power Requirement	System Weight	System Payload Weight	Correction Factor	W
Power Requirement	0.05	0.017	0.022	0.081	0.043
System Weight	0.35	0.13	0.326	0.105	0.228
System Payload Weight	0.15	0.024	0.065	0.081	0.08
Correction Factor	0.45	0.839	0.587	0.733	0.652
Sum	1	1.01	1	1	1.003

Table 4A. Pairwise of Concepts for Correction Factors

Correction Factors			
	Concept 1	**Concept 2**	**Concept 3**
Concept 1	1	3	3
Concept 2	0.33	1	0.33
Concept 3	0.33	3	1
Sum	1.66	7	4.33

Table 5A. Pairwise of Concepts for System Payload Weight

System Payload Weight			
	Concept 1	**Concept 2**	**Concept 3**
Concept 1	1	3	0.33
Concept 2	0.33	1	0.33
Concept 3	3	3	1
Sum	4.33	7	1.66

Table 6A. Pairwise of Concepts for System Weight

System Weight			
	Concept 1	**Concept 2**	**Concept 3**
Concept 1	1	1	3
Concept 2	1	1	3
Concept 3	0.33	0.33	1
Sum	2.33	2.33	7

Table 7A. Pairwise of Concepts for Power Requirement

Power Requirement			
	Concept 1	**Concept 2**	**Concept 3**
Concept 1	1	3	3
Concept 2	0.33	1	1
Concept 3	0.33	1	1
Sum	1.66	5	5

Table 8A. Normalized Pairwise of Concepts for Correction Factors

Normalized Correction Factor				
	Concept 1	**Concept 2**	**Concept 3**	**Pi**
Concept 1	0.602	0.429	0.693	0.575
Concept 2	0.199	0.143	0.076	0.139
Concept 3	0.199	0.429	0.231	0.286
Sum	1	1.001	1	

Table 9A. Normalized Pairwise of Concepts for System Payload Weight

Normalized System Payload Weight				
	Concept 1	**Concept 2**	**Concept 3**	**Pi**
Concept 1	0.23	0.43	0.248	0.303
Concept 2	0.08	0.14	0.248	0.156
Concept 3	0.7	0.43	0.602	0.577
Sum	1.01	1	1.098	

Table 10A. Normalized Pairwise of Concepts for System Weight

Normalized System Weight				
	Concept 1	**Concept 2**	**Concept 3**	**Pi**
Concept 1	0.43	0.43	0.43	0.43
Concept 2	0.43	0.43	0.43	0.43
Concept 3	0.14	0.14	0.14	0.14
Sum	1	1	1	

Table 11A. Normalized Pairwise of Concepts for Power Requirement

Normalized Power Requirement				
	Concept 1	**Concept 2**	**Concept 3**	Pi
Concept 1	0.6	0.6	0.6	0.6
Concept 2	0.2	0.2	0.2	0.2
Concept 3	0.2	0.2	0.2	0.2
Sum	1	1	1	

Appendix F: Gannt Chart

Task Name	Start Date	End Date	Duration	Predecessors	% Complete	Status	Assigned To
Classes Begin	01/07/19	01/07/19	1d		0%	Not Started	
Detail Design (CAD)	01/07/19	01/11/19	5d		10%	In Progress	T Tristan
Design Review	01/14/19	01/15/19	2d	2	0%	Not Started	Team
Order Materials	01/16/19	01/16/19	1d	3	0%	Not Started	A Anthony
Parts Arrive	01/17/19	01/25/19	7d	4	0%	Not Started	A Anthony
3D Print Parts	01/29/19	01/30/19	2d	5FS +1d	0%	Not Started	Z John
Build Testing Rig	02/04/19	02/15/19	10d	6FS +2d	0%	Not Started	A Anthony
Build Stabilization System Prototype	02/04/19	02/15/19	10d	6FS +2d, 7FF	0%	Not Started	J Junyi
Testing	02/19/19	03/04/19	10d	7FS +1d, 8FS +1d	0%	Not Started	Team
Redesign	03/05/19	03/06/19	2d	9	0%	Not Started	Team
Rebuild	03/07/19	03/13/19	5d	10	0%	Not Started	Z John
Retest	03/14/19	03/15/19	2d	11	0%	Not Started	Team
Spring Break	03/18/19	03/22/19	5d	12	0%	Not Started	Team
Retest	03/25/19	03/29/19	5d	13	0%	Not Started	T Tristan
Project Finalization	04/01/19	04/09/19	7d	14	0%	Not Started	Team
Documentation	04/10/19	04/17/19	6d	15	0%	Not Started	A Ariel Mathi
Engineering Design Day	04/18/19	04/18/19	1d	16	0%	Not Started	Team
Finals	04/29/19	05/03/19	5d		0%	Not Started	Team
Graduation	05/04/19	05/04/19	1d		0%	Not Started	Team

Figure 1F. Gannt chart task view.

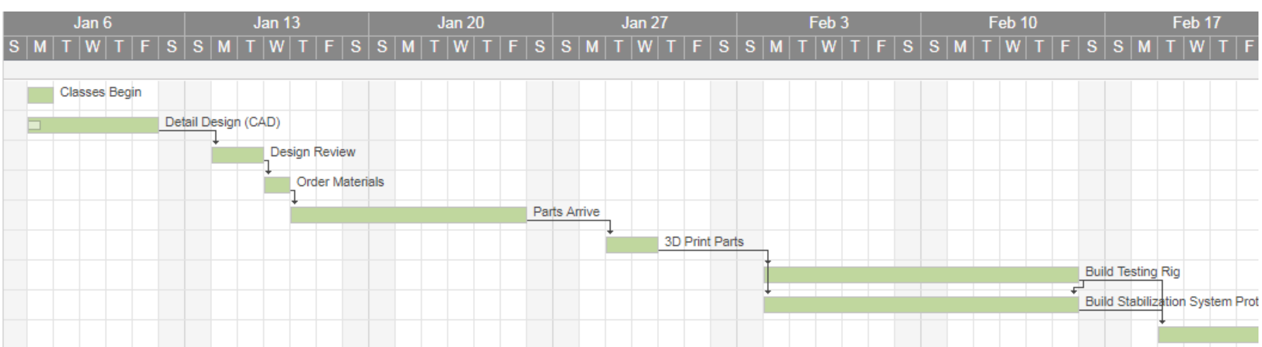


Figure 2F. Gannt chart part 1.

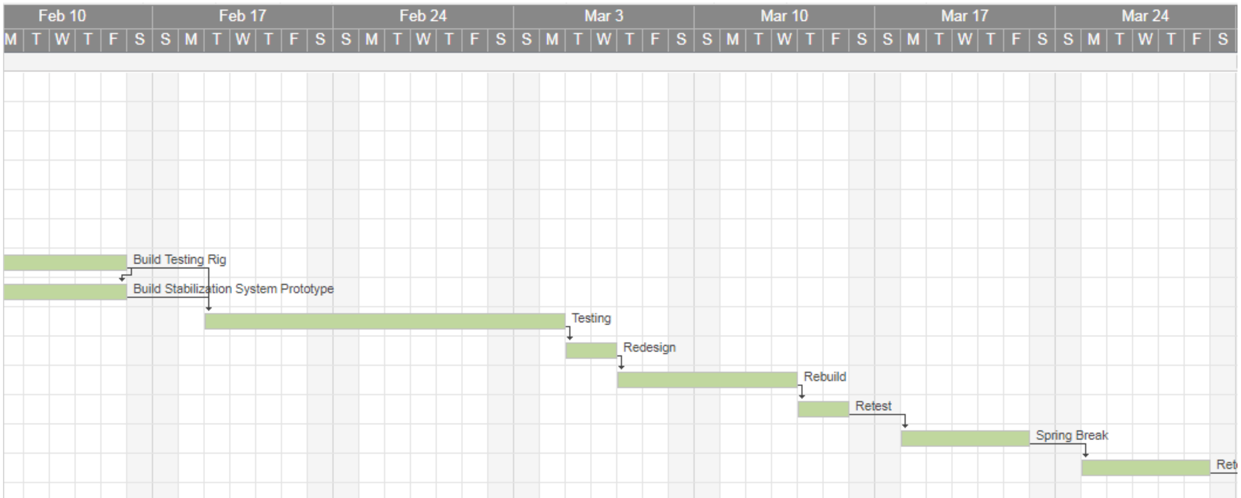


Figure 3F. Gannt chart part 2.

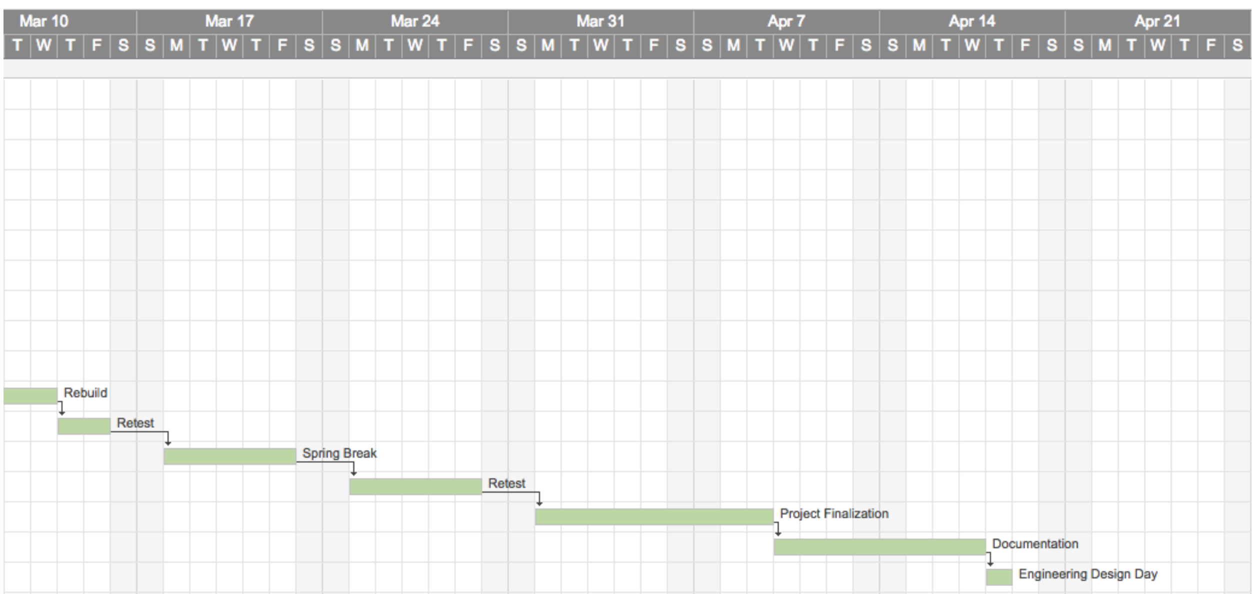


Figure 4F. Gannt chart part 3.

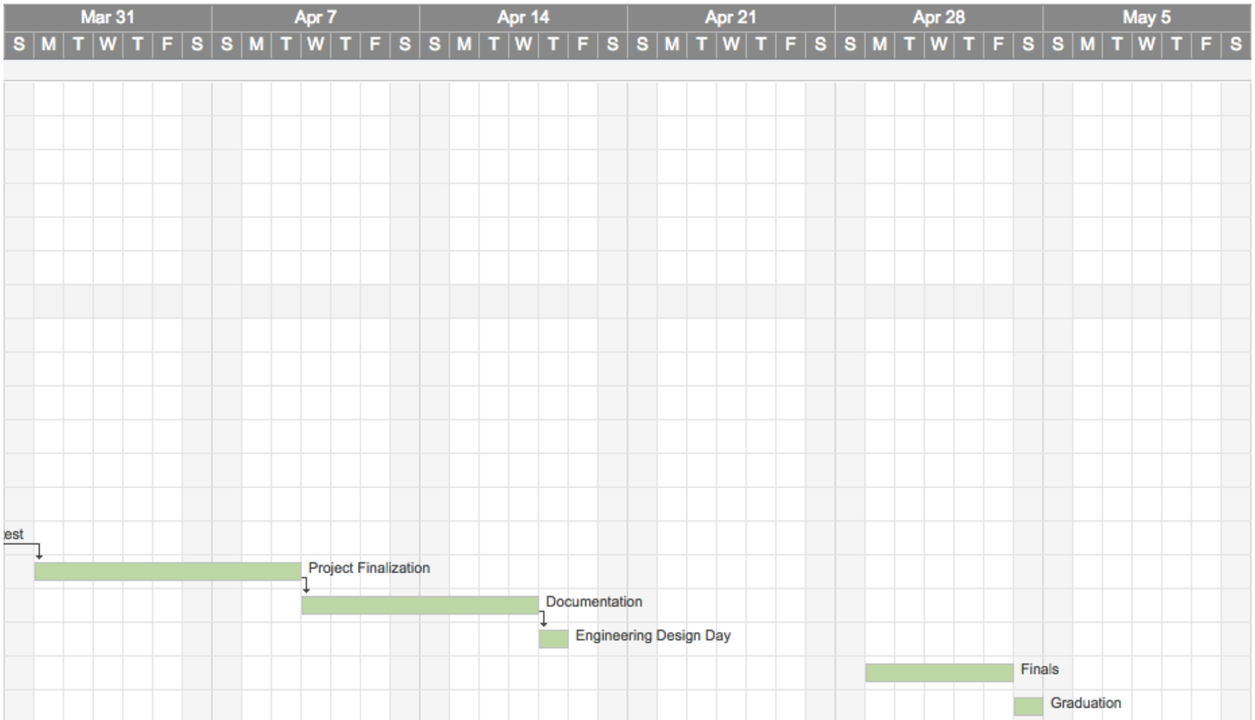


Figure 4F. Gannt chart part 4.

References

There are no sources in the current document.