April 2017

CHAMP: Tree Climbing Robot

Devon Michael Bray
Worcester Polytechnic Institute

Mead Tucker Landis
Worcester Polytechnic Institute

Rachael May Putnam
Worcester Polytechnic Institute

Repository Citation
Bray, D. M., Landis, M. T., & Putnam, R. M. (2017). *CHAMP: Tree Climbing Robot*. Retrieved from https://digitalcommons.wpi.edu/mqp-all/1446

WORCESTER POLYTECHNIC INSTITUTE
MAJOR QUALIFYING PROJECT

CHAMP

COMPLIANT HOOK ARBOREAL MOBILITY PLATFORM

SUBMITTED BY:
Devon Bray, Electrical & Computer Engineering
Mead Landis, Robotics Engineering/Mechanical Engineering
Rachael Putnam, Robotics Engineering/Mechanical Engineering

ADVISED BY:
Michael Gennert, Robotics Engineering/Electrical & Computer Engineering
Bradley Miller, Robotics Engineering
Kenneth Stafford, Robotics Engineering/Mechanical Engineering

Abstract

Observing wildlife, monitoring forest health, conducting research, and detecting invasive species and infections are just a few of the crucial tasks that currently require humans to climb trees. Putting people into trees is an expensive, and potentially dangerous task. The CHAMP (Compliant Hook Arboreal Mobility Platform) is a tree climbing robot that carries and controls task-specific payloads to improve the safety and efficiency of these arboreal tasks. To traverse the tree, the CHAMP uses a three DOF (Degree of Freedom) continuum manipulator with rotating grippers at each end. Each gripper has an arrays of compliant acupuncture needles to attach to the tree without causing damage. The robot's systems enable easy support for a variety of custom payloads to be used for future expandability and development of arboreal mobility platforms.

Keywords: tree, climbing, robot, arboreal mobility

Acknowledgements

The CHAMP team would like to thank several individuals for making this project as successful as it was. Firstly, we would like to thank our project advisors Michael Gennert, Bradley Miller and Kenneth Stafford. Secondly, we would like to thank James Louiselle for his machining expertise, and Joeseph St. Germain for his various technical advice. We would like to thank a small group of our friends for their support and aid in assembling the robot; namely Logan Tutt, Avital Rabinovitch, Cecelia Cotter, Shahnaz Ghahremani, Jerish Brown, and Bernat Navarro Serer. We would finally like to thank our Maxon Motors contacts: Melissa Giramma and Eugene Sio.

Without the help of these individuals this roject would not have been possible. Your service is greatly appreciated.

Table of Contents

List of Figures

List of Tables

1 Introduction

As it stands, the state-of-the-art for interfacing with trees is lacking. Ecologists wanting to collect data about conditions of the upper canopy of a tree often construct large structures to move their sensors into trees. For scientists studying lichen, samples must be collected by humans who scale hundreds of feet at great personal risk. People also must scale and inspect trees for invasive species, such as the Emerald Ash Borer (EAB) or the Asian Longhorned Beetle (ALB). This manual tree-inspection process is slow, unnecessarily risky, and costly. It is particularly expensive for small municipalities which cannot afford full-time arborists. This presents an opportunity to improve these processes using robotics.

The CHAMP is a platform designed and implemented to be able to venture into trees and complete tree-based tasks by transporting custom payloads. This enables arborists to quickly and safely complete tree-based tasks. The AMP developed as a product of these efforts can complete a useful climb into the tree, navigate branches and limbs, and carry a mission-relevant payload. For the purpose of this project, an AMP is useful if it can carry a functional payload, climb up and down a tree, and navigate branches.

2 Background & Project Motivation

2.1 Applications of an Arboreal Mobility Platform

At a high level, research has identified three core groups of reasons as to why trees would need to be climbed. These break down as follows:

- Long Term Sensor Data Collection
- Animal Observation and Detection
- Tree Sample Collection

The following sections identify critical applications for this technology that fit into these three groups.

2.1.1 Observations in/from Trees

2.1.1.1 Long Term Data Collection With the advent of global climate change, more and more attention is being paid to the way trees are able to deal with changes in enviromental conditions. For many data-logging applications in trees, large and expensive structures like a 32-meter scaffolding [13], or 51-meter construction cranes [14] are used to gain access to the upper tree canopy for observation. These solutions are far from optimal as they are often expensive and disruptive to the local ecology of a section of forest. These structures could be replaced by an unmanned sensor package delivery robot to decrease the impact the research as on the forest, and make the process more cost-efficient. In tropical environments, tree climbing is often regarded as a particularly dangerous activity [15]. Tim Kovar, a professional tree climber for researchers states that “In the tropics, as much as 90 percent of animal life occurs in the canopy. Ants, scorpions, spiders and snakes live in the branches and use them as highways”. In summary, for researchers looking to use sensors to collect long- or short-term data about the upper canopy of a forest, it is often complex, expensive, or dangerous. An arboreal mobility robotics platform could easily mitigate these issues.

2.1.1.2 Animal Detection and Observation

The original goal of the of WPI's past Arboreal Mobility Projects was to be able to detect Asian Longhorned Beetle (ALB) infestation. Since these projects were completed, the threat posed by the beetle has only increased, and is still a critical application of this technology. The ALB is native to China, the Koreas, and Japan, but is an invasive species that has spread to North America within the last 20 years due to global trade [16]. The beetle has successfully become established in five U.S. states, Canada, and at least 11 countries in Europe.

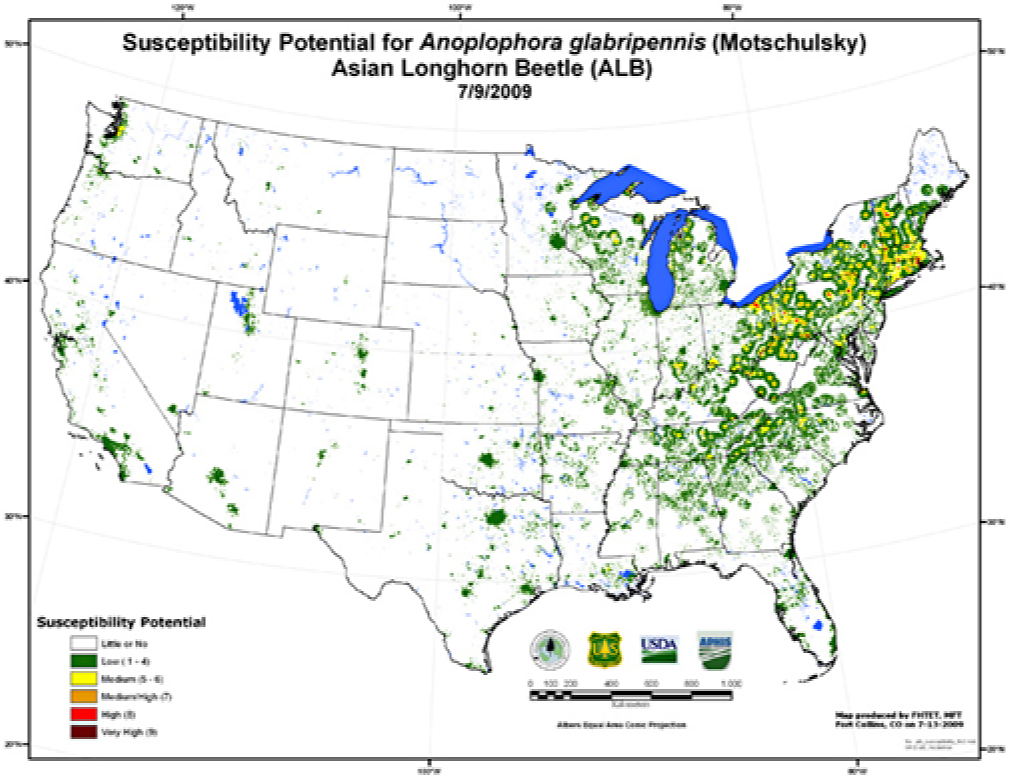


Figure 1: Susceptibility Potential for ALB in the US [1]

To quantify the impact that this beetle could have on the U.S, it is estimated that ALB is capable of destroying 30.3% of the urban trees in the United States at an economic loss of $669 billion [17]. The adult female beetle bores its way into the bark of the host tree, creating an oviposition pit in the summer or early fall. The real damage is done to the tree after the egg hatches into a larvae. The larvae can tunnel into the heartwood of the tree, causing irreversible damage [17]. The best method for eradicating this pest is to destroy the tree entirely. Doing this prevents the beetles from spreading to nearby trees. There are two methods that surveyors generally use to investigate trees for ALB infection, but neither is completely effective. Researchers score how effective a method is by recording the percentage of the time a method can successfully identify an ALB infestation. The first method is ground inspection with binoculars and is approximately 30% effective. The alternative is the use of a tree climber, which is shown to be 60-75% effective [1]. Tree climbing is significantly more effective, but is also more expensive, time consuming, and dangerous.

There is also the Emerald Ash Borer (EAB), another highly destructive invasive species. This insect is originally native to Eastern Asia, and out of its native range is very destructive to ash trees in North America and Europe. As it stands, the impact of this tree killer is immense. It has killed tens of millions of trees since its introduction to North America in 2002 [18]. Unlike the ALB, the EAB can be effectively lured or trapped as a method for detection. Detection surveys rely on sticky prism traps made from purple or green coroplast and suspended high into ash trees [19]. These traps are either placed near the base of the tree, or pulled up into the tree by a line throwing apparatus [20]. An AMP could help bring lines into target trees, or use a camera to check traps in dense canopies without removal.

Many other animals inhabit trees in a less destructive manner. For those that nest or otherwise occupy sections of the tree that are difficult to access, observation by researchers quickly becomes impossible using conventional methods like binoculars. The Osprey, for example, constructs large nests, typically in high places, like on the tops of utility poles or in large, tall trees [21]. Ospreys mate for life, and a single family occupies the same nest for several years. The conventional observation method of these types of nests is to affix a camera apparatus (shown in Figure 2 to the tree that the bird is nesting in, mounted such that it is looking down into the nest [2].

To install these cameras, the target tree must either be stable enough to handle the

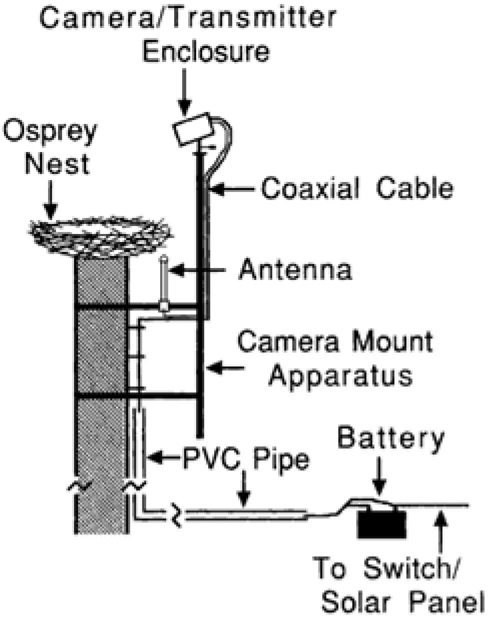


Figure 2: Video camera system for observing Osprey Nests [2]

weight of a human climber, or exposed enough to use a crane. Researchers also run the risk of damaging the nest during the installation process. Unmanned multi-rotors (drones) have been used to survey Osprey nests as well, but these solutions do not allow for long-term observation [22]. In any case, having a platform that could safely deliver a camera payload to an observation site without putting the observer or the observed at risk would be a great asset to researchers.

2.1.2 Collecting Samples from Trees

Currently, there is no substitute for tree climbers when collecting samples from trees. This is a long and potentially dangerous process for the climbers, and an expensive one for scientists, municipalities or organizations trying to inspect trees. One of the key reasons for sample collection in trees is to study lichen. Lichen can act as a gauge for the state and health of the canopy, particularly in large, old-growth forests [23]. Tree climbers typically use a bow and arrow to launch their first line high into the tree, then winch themselves into branches, launching and winching subsequent lines until they have scaled the full height of the tree

[24]. An arboreal mobility platform could give climbers another tool to increase productivity and safety while collecting these samples, or even replace the need for humans to scale trees in this application.

2.1.3 Problems With Alternate Methods For Tree Exploration

Naturally, comparisons are drawn between an AMP and other, more straight-forward methods to get into a tree such as a UAV or devices like pole-mounted cameras. The team has identified several key disadvantages that these alternate methods may have when compared to an AMP.

Disadvantages of a UAV

- Complexity for operator
- Short mission time
- Can't be used in windy conditions
- Difficult to operate at night
- Difficult to navigate though obstacles like branches

Disadvantages of a Pole

- Difficult to transport
- Mission specific-tree height
- Require physical strength and dexterity to carry the pole and inspect the tree
- Difficult to complete complex sample retrieval mission
- Cannot navigate dense branches

While these alternate methods may seem more intuitive, their key disadvantages give way to a need for more research into an AMP.

2.2 Current Solutions

This section discusses each of WPI's five previous robotic AMP projects, as well as four non-wpi robotic AMP projects. It is worth reviewing the current state-of-the-art in robotic arboreal mobility to gain an understanding of how others have approached the problem.

2.2.1 WPI AMP Projects

There have been several Major Qualifying Project (MQP) and graduate level projects that involve tree-climbing robots at Worcester Polytechnic Institute (WPI). It is useful to review the current state of the art of the technology at WPI.

2.2.1.1 Design and Construction of a Tree Climbing Robot (2012) [25]

WPI's first MQP attempt at a tree climbing robot, shown in Figure 3 occurred in 2012. In coordination with the USDA, the team conducted significant research into the requirements of an arboreal robot specifically tailored to inspect trees for ALB infestations. Despite significant progress in other aspects, the team was not able to meet most of their intended goals. The proposed design included a camera and six legs, each comprising three servos for articulation, and weighing just over 1.5 kg. The robot held onto the tree by holding around a sufficient radius to pinch the tree between toes and legs on opposing sides of the chassis. Unfortunately the final design iteration was a power-hungry, tethered device that was only able to hold on to the given tree, not climb it. In addition to their valuable research and experience, the team succeeded in creating a basic User Interface (UI) to show the camera feed and allow smooth theoretical control.

2.2.1.2 Design and Construction of a Tree-Climbing Robot (2013) [3]

WPI's second team took the opportunity of a new project to build off of the previous team's research while pursuing a different mechanical approach. The team carried on the

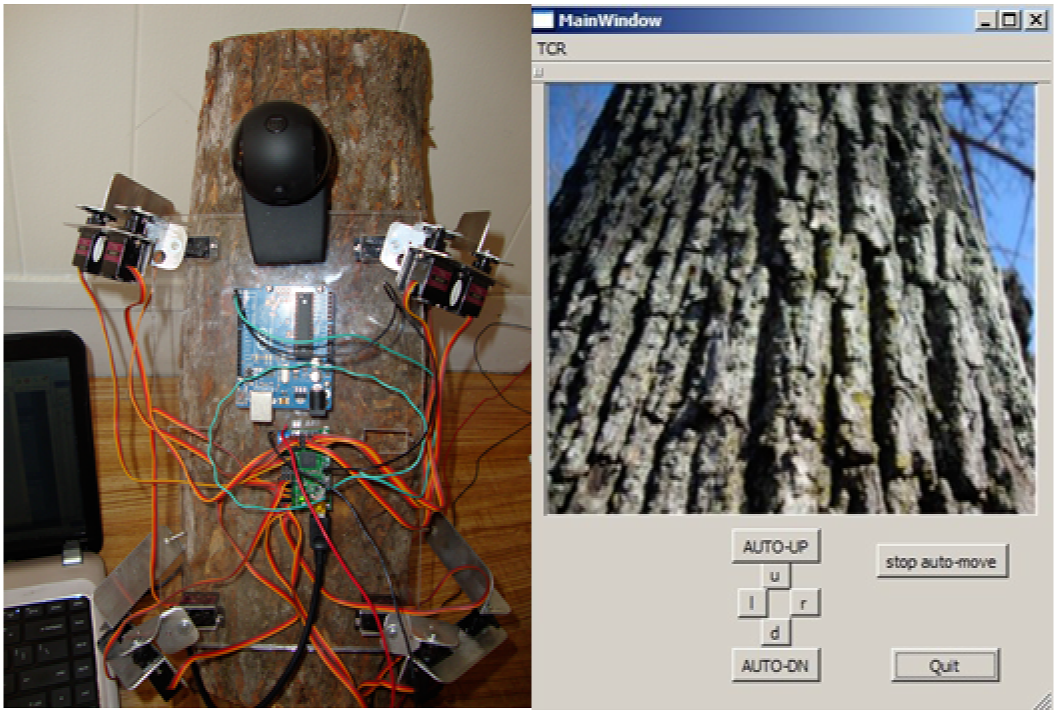


Figure 3: WPI's 2012 AMP MQP [3]

mission of creating an inspection robot to meet the USDA's requirements for an inspection robot for ALB detection. In order to expand research, the team looked heavily into more generic climbing robots including Boston Dynamics' RiSE robots. The team's research and criteria led them an inch-worm style robot with a large, 4 fingered gripper on either end. The robot moved rigidly by actuating 5 servos connecting the structure between the grippers to bend its mid-section much like an inchworm. The resulting robot, shown in Figure 4 weighed under 3lb, but was unable to fulfill the prescribed requirements. The group were successful in their gait but were unsuccessful in the use or design of their gripper, which required too much force to engage the tree meaningfully.

2.2.1.3 Project Squirrel (2014) [5]

WPI's Project Squirrel was a re-branded tree-climbing robot MQP, functionally the third installment. Squirrel, shown in Figure 5 incorporated the idea of legs and spiked attachment from the previous teams, but in new ways. For the legs, the team reduced the degrees of freedom from three to two, using a leadscrew to move vertically and springs to allow

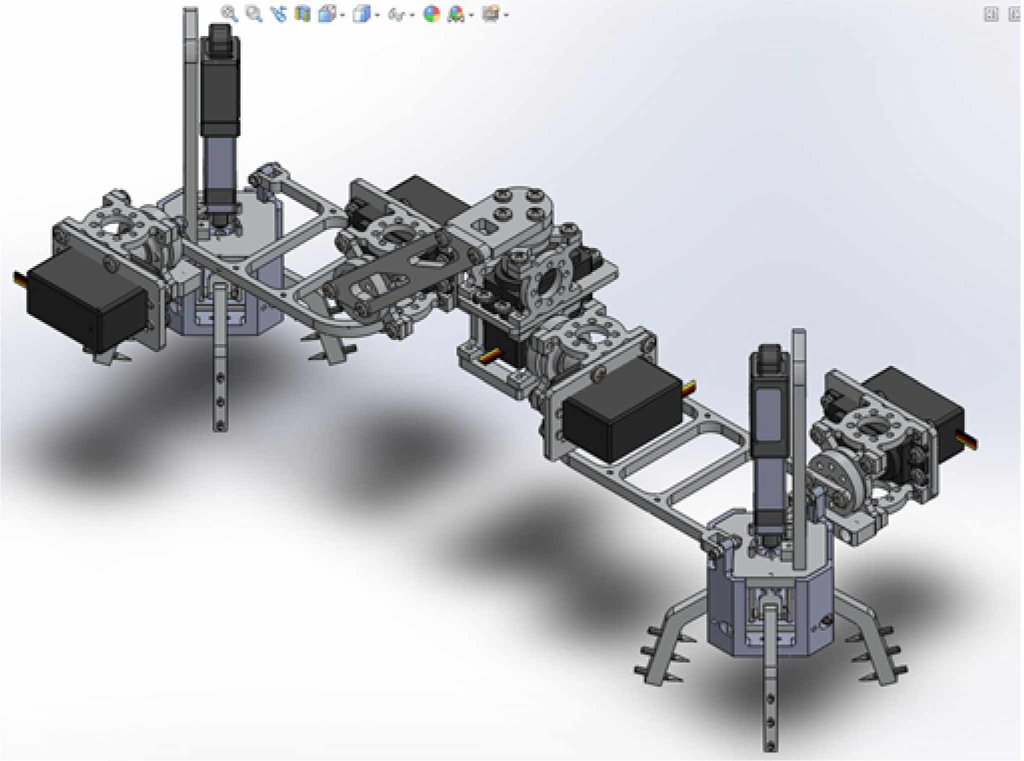


Figure 4: WPI's 2013 AMP MQP [4]

zero power draw when static on the tree. As for the spikes, the team used surgical needles with precise attack angles to launch the needles into the tree. One separate addition was a tail which greatly reduced the resulting forces on the spikes. Their method of locomotion was to move one spike at a time while using the other three and the tail for stability. The team was successful in their requirement of completing two full gaits up a tree, however encountered an issue: They steadily and uncontrollably walked off of the tree by falling farther out from the tree with every gait.

2.2.1.4 Project Squirrel 2.0 (2015) [6]

WPI's Project Squirrel 2.0 was the latest MQP working toward a tree-climbing robot. This team combined the successful ideas from the previous teams. In general they decided that the locomotion of 2013's inchworm chassis was a good idea, but did not like the power-hungry nature of the servos used. Instead they opted to use a leadscrew like the previous project and connected it to the grippers using a universal-joint shoulder with four winches

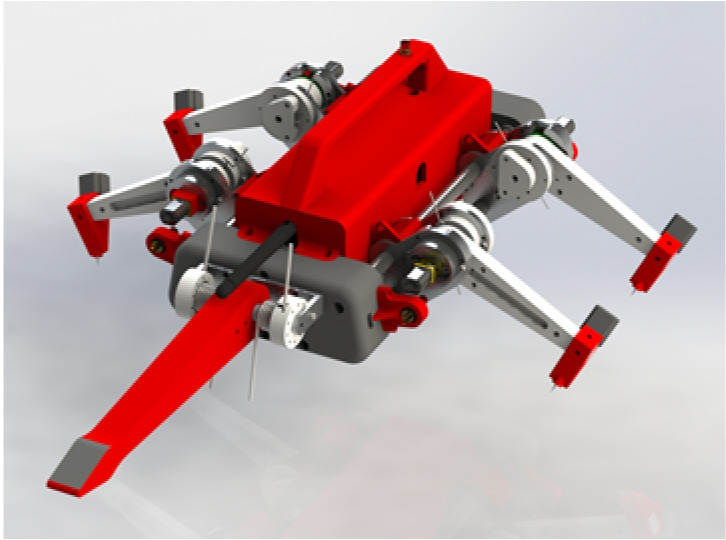


Figure 5: WPI's 2014 AMP MQP - "Squirrel bot" [5]

for actuation. For gripping they decided that 2013's four-fingered gripper was a good idea, adding the use of surgical needles and spring-loaded momentum like Project Squirrel. The resulting robot was successfully able to solve 2013's gripper issue, resulting in a fairly reliable gripper. Despite the success of the gripper, the implementation of the leadscrew did not account for torques sufficiently, and so was unable to climb. Additionally, there were concerns of damage to the tree with such a forceful gripper. Although unable to be fully tested or implemented, the team developed a fairly comprehensive and intuitive Graphical User Interface (GUI), shown in Figure 6.

2.2.2 Non-WPI AMP Projects

Outside of WPI, AMP projects have been completed with significant successes. These projects are discussed in this section, so that the team may better understand the limitations of today's AMPs.

2.2.2.1 Treebot [7]

Treebot comes from the Chinese University of Hong Kong as its answer to the need

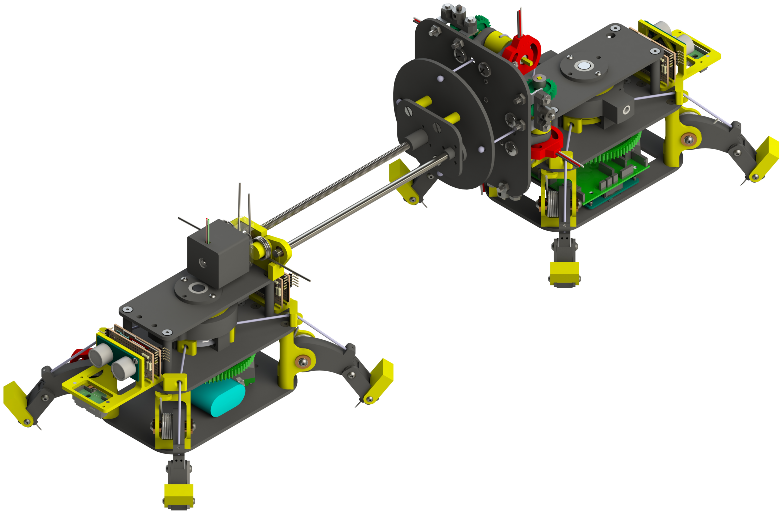


Figure 6: WPI's 2015 AMP MQP - "Squirrel bot 2.0" [6]

of a truly successful tree-climbing robot. The robot operates by extending, retracting, and flexing its continuum manipulator body and gripping with a large, four-fingered gripper at each end. The robot was extremely successful in its ability to vertically lift a 1.75kg payload while weighing itself only 0.6kg. Additionally it demonstrated ability to climb many tree types, operate quickly, and navigate around and onto branches. Yet another advantage of the Treebot, shown in Figure 7 is that the body is inherently compliant, allowing it to conform to a wide variety of surfaces and situations.Lastly, since every part of the robot is spring-loaded or non-backdrivable, no power is required to maintain any given position, even if only one gripper is attached. Treebot is impressively versatile, however it is not inherently designed for a payload, and has only demonstrated the ability to lift a non-functional payload perfectly vertically. Additionally the payload was weights attached directly to the lower gripper, causing no significant moment to the robot.

2.2.2.2 RiSE [26]

RiSE is a series of climbing robots developed by Boston Dynamics. To date there have been three iterations of the project, V1 (shown in Figure 8), V2 (shown in Figure 9), and V3 (shown in Figure 10). RiSE V1 was a hexapod robot with a tail that uses micro-spines

Figure 7: Treebot [7]

in order to attach to surfaces. It adopted a gait where three alternating legs would advance at the same time, relying on the remaining three and the tail to maintain stability. Each leg was driven by two actuators.

RiSE V2 is nearly identical in concept to V1 with the main difference being upgraded microspine grippers allowing RiSE V2 to scale rough, hard surfaces like the sides of buildings. RiSE V3 is Boston Dynamics latest version and a drastic departure from the previous concepts. While RiSE V3 does use two-actuator legs, it has only four legs and functionally runs up telephone poles as compared to the slow, methodical pace of V1 and V2. Boston Dynamics' RiSE robots represent important strides in organ climbing methods, however each iteration has limitations. RiSE V1 and V2 are both very slow while V3 is not well suited for diverse terrain. A common limitation for all versions is a lack of integrated payload accommodation.

2.2.2.3 Uncle Sam [11]

CMU's Uncle Sam is a tethered snake robot, as shown in Figure 11. It was originally created to study and mimic the motion of snakes. In addition to its other impressive abilities,

Figure 8: Boston Dynamics' RiSE V1 [8]

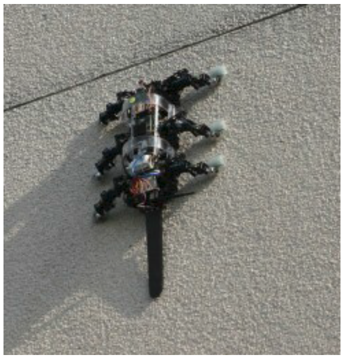


Figure 9: Boston Dynamics' RiSE V2 [9]

Figure 10: Boston Dynamics' RiSE V3 [10]

it has demonstrated the ability to gracefully and elegantly scale trees and poles. It does this by flexing its multitude of universal joints in order to roll itself up the tree. The robot uses force-feedback to help it conform to the tree with consistent pressure that is uniformly distributed. Uncle Sam also boasts a robust camera in the head of the snake backed up by a simple and intuitive GUI. Its final advantage is its repeated use of identical components, making designs, repairs, and alterations very straight-forward. In lieu of its impressive resume, it also has significant downsides for tree-climbing applications. First, it can only climb certain diameter trees and cannot navigate branches easily as it climbs. Next, it has no intuitive or logical payload attachment since the entire exterior is used to climb, with the insides packed full of electronics. Lastly, the snake is heavy, requiring more power than other designs and requiring a tether; adding additional weight and limiting height.

2.2.2.4 DIGbot [12]

DIGbot (Distributed Inward Gripping Robot), shown in Figure 12 was created at Case Western University as an attempt at a more universal climbing robot. Its basic design featured six legs with three servos each. Each leg ended in a foot designed to be pulled inward against feet on the other side of the robot. The feet were interchangeable to enhance climbing on different surfaces from screens to fences to trees. Some of the successful feet

Figure 11: Carnegie Melon University's "Uncle Sam" AMP [11]

incorporated individual compliance, allowing them to conform to their surface without the need for precise mechanical control. While impressive, DIGbot suffered some limitations. First in testing it did not demonstrate robust climbing on natural surfaces such as trees or telephone poles. Secondly it required a large number of motors, complicating control and adding weight. Last, the use and design of the legs required constant current draw, limiting climb duration, distance, and static power efficiency.

Figure 12: Case Western University's "DIGbot" [12]

3 Design Requirements

An Arboreal Mobility Platform is useful if it can carry a functional payload, climb up and down a tree, and navigate branching and complexities. Previous projects have proven these goals to be aggressive and ambitious, therefore it was the specific goal of the CHAMP to further the current technology, facilitating further development of a useful AMP at WPI.

To do this, the set of design requirements outlined in this chapter (and summarized in Table 1) were carefully chosen to represent this iteration's minimum, practical performance to be a useful AMP. The chosen requirements were used to guide the CHAMP's physical design and implementation. Each requirement is further elaborated in the proceeding sections of this chapter.

Design Aspect		**Requirement**
Arboreal Mobility	Climb Distance	Move up and down *at least* 3 non-branchy meters of Tree A
	Tree Branches	Navigate through *at least* 1 vertical meter of branched trunk of Tree B
	Tree Complexity	Navigate 2 different complexities of Tree C
Payload	Payload Moment	Supports *at least* 1.25 kg of payload at 10 cm away from the robot origin in any direction
	Payload Communication & Power	Power connections off of main system power
		Serialized high-speed data bus to interface with the main system
Portability	On-tree Mass	System on tree is *at most* 3 kg, without payload
	Full System Mass	Full system (including extra payload) fits on the back of a human and is *at most* 8kg
Climb Duration	Constant Climb Time	Maintain constant climbing motion for *at least* 5 hours at 1 m/min
	Static State Time	Stay static on the tree for *at least* 24 hrs

Table 1: CHAMP Design Requirements

3.1 Arboreal Mobility

To evaluate the tree navigability of the CHAMP, three trees were selected to represent a broad range of targets for arboreal mobility. Tree A, shown in Figure 13, was an Oak tree, and was used to evaluate the CHAMP's climb duration. It was chosen because it has a long straight section with no branches or complexity. Tree B, shown in Figure 14, was a Spruce tree, and was used to assess the CHAMP's branch navigability. It was chosen because of its evenly spaced branches, but it also has rather "scaly" bark, and is likely the most difficult surface of the three trees to grip to. Tree C, shown in Figure 15, was a Maple tree, and was used to assess the CHAMP's complexity navigability. It was chosen based on its consecutive, even forks. Each of the three trees provided their own difficulties, and represented a ranges of applications to help evaluate the usefulness of the CHAMP. An example of a complexity is given in Figure 16.

Figure 13: Tree A

Figure 14: Tree B

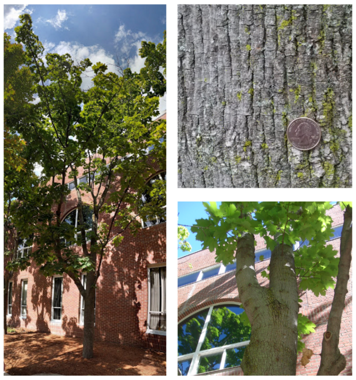


Figure 15: Tree C

Figure 16: Example Complexity

3.2 Payload Support

Additionally, the CHAMP was evaluated on its ability to transport a mission-relevant payload. The applications delineated in sections 1 and 2 of this document serve to define "mission-relevant;" for example the CHAMP might be used to place a CO_2 sensing package in the canopy of a tree. Based the sources from the aforementioned sections 1 and 2, most mission-relevant payloads for current applications fall under 1 kg. The CHAMP was evaluated under a 1.25kg payload, which was chosen assuming that most future use cases of the CHAMP will fall within 1 kg.

CHAMP was meant to navigate trees in three dimensions; as such it was important to limit the worst case moment created by the payload. Otherwise the gripping force could be overcome by the payload moment. For the payload moment, the "origin" of the CHAMP is defined as the projection of the center of mass of the robot, without payload, onto the tree. The CHAMP was designed to support a 1.25kg payload at a maximum of 10cm from the CHAMP origin, or a total of 1.23Nm of moment caused by payload weight.

Most applications of an AMP imply the ability to interface with custom payloads. To interact with a payload, the CHAMP was required to have power and data connections to a payload, as well as a series of standard physical mounting points.

3.3 Portability

The mass of the robot, operator interface (OI), and payload were selected based on the applicable situation that the CHAMP will be used in. The eventual goal was to be able to use the CHAMP system, which consists of the robot, the OI, and two payloads on a one day backpacking trip. According to REI [27], a "lightweight" backpacking load should not be more than 30lb, or 13.6kg. Also, conventional wisdom [28] states that a conservative weight for the supplies required for a one day backpacking trip is 13lb, or a mass of 5.9kg. Therefore, the entire CHAMP system must be less than 7.7kg.

An AMP's main purpose is to transport a mission-specific payload up the tree. The maximum mass requirement for payload support was 1.25kg (see Section 3.2) or about 2.5kg for two. This left about 5.2kg for the robot and the OI. If the OI consists of a laptop and a generic gaming controller or a hardware equivalent, it will be about 2.2kg. This leaves 3.0kg for the robot itself. Table 2 outlines the mass distribution of the hiker's pack when traveling to a tree designated for a CHAMP climb.

	Quantity	**Weight (kg)**	**Weight Totals (kg)**
Supplies	1	5.9	5.9
Robot	1	3.0	3.0
Payload	2	1.25	2.5
OI	1	2.2	2.2
		Total:	**13.6**

Table 2: One Day Backpacking Trip Weight Allocation

3.4 Climb Duration

The duration of climb requirements were selected based on the weight requirements discussed in sections 3.2 and 3.3, and a reasonable usability of the CHAMP. These requirements were generated in Phase One (discussed in Section 6.2 prior to the CHAMP's implementation, most values are reasonable estimates based on research into other AMP projects, and reasonable usability for the CHAMP. Additionally, a safety factor of 2.0 was applied to reduce the possibility that the CHAMP would run out of battery while in the tree.

The system's moment, and therefor the mass was one of the most important factors contributing to the CHAMP's ability to hold onto a tree, so ideally the battery mass would have been on the lower end of 10% to 20% of the robot's total mass, or 0.43 kg to 0.85 kg. Many batteries in this weight range are around 5.0 Amp-hours. Assuming the use of a one of these batteries, and that the CHAMP would use a nominal voltage of 12V, that puts the CHAMP's power capacity at around 60 Watt-hours. If two batteries are used, the CHAMP will have about 10 Amp-hours or 120 Watt-hours at 12V. For the purpose of this proposal, however, a single battery (5Ahr/60Whr) will be assumed.

The orange line in Figure 17 shows the early estimated power requirements for the CHAMP at different overall climb efficiencies, assuming it weighs 4.25 kg and travels at a conservative 1 meter per minute, or 1.7 cm per second. For estimation purposes, the climb efficiency was considered to be the same when travelling up and down the tree. The green line in Figure 17 shows the early estimated climb duration at different climb efficiencies, given a 60 Watt-hour battery and a 4.25 kg robot.

To generate the final “Constant-Climb-Duration” figure, an early estimate of 10% overall climb efficiency was generated. This estimate was intended to conservatively include the power requirements of electronics, sensors, payloads, and climbing in all directions.

From these considerations (an overall climb efficiency of 10%, with a 60 Watt-hour battery, 4.25 kg robot climbing at about 1.7 cm per second, and a safety factor of 2.0) the early estimated minimum required constant climb duration of the CHAMP was determined to be about 5 hours. This figure is a reasonable duration that falls within the range of most previous AMP projects.

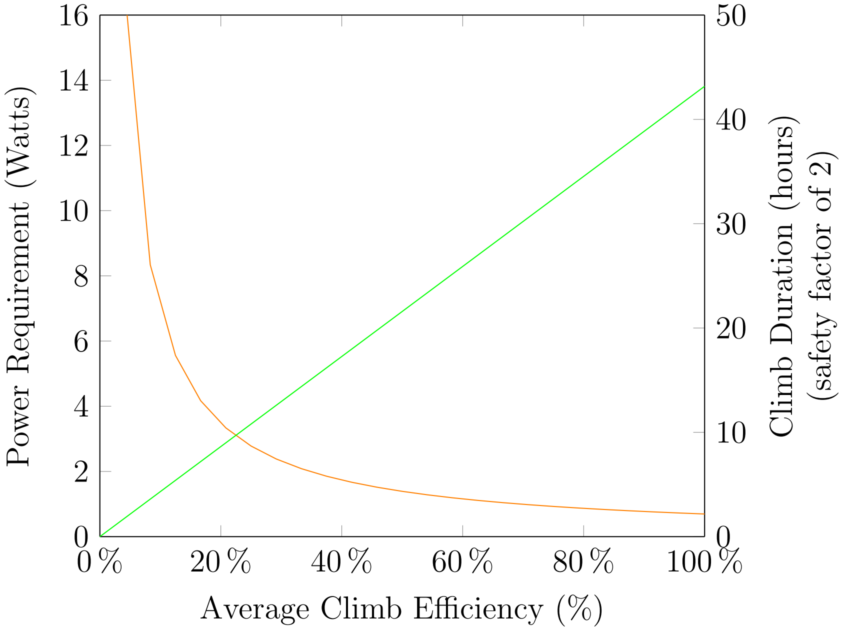


Figure 17: Average Estimated Climb Efficiency vs. Power Consumption and Climb Duration

4 Design & Analysis

Tree traversal is a complex mechanical challenge; to validate our mechanical concepts, the CHAMP was developed in three major phases, the first of which was general research. The second phase, completed over the first few months of the project, was the development of a complete mechanical proof of concept, and was a culmination of many rounds of analysis, prototyping, and testing. The proof-of-concept was designed to meet the "Arboreal Mobility" design requirements as discussed in Section 3.1. The second phase, completed over the last several months of the project, was a final design of the fully implemented CHAMP. This phase was meant to implement the concepts from the proof-of-concept with improved robustness and reliability, and meet the remaining requirements discussed in Section 3.

Figure 18: CHAMP Proof-of-Concept

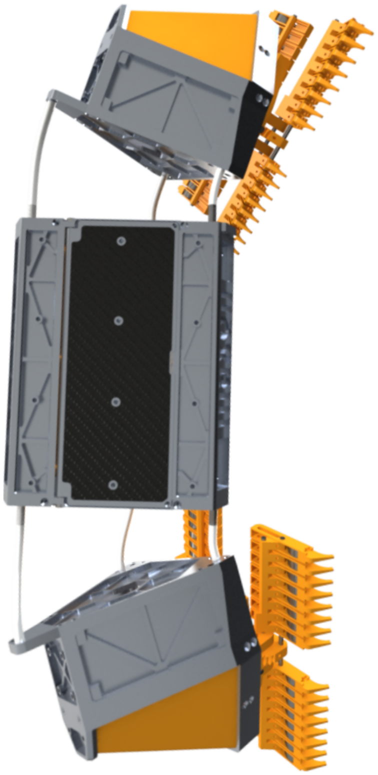


Figure 19: CHAMP Final Design

This chapter discusses the design decisions completed to implement the full CHAMP system. Design and analysis from both the proof-of-concept (shown in Figure 18) and the final implementation (shown in Figure 19) of the CHAMP are compiled here. The implementation of the CHAMP was approached in the context of the complete system, while design and analysis was completed at the component, subsystem, and system levels to ensure completeness.

4.1 Locomotion Mechanisms

This section discusses the three main subsystems that allow the CHAMP to maneuver a tree with only seven actuators. Two grippers allow either end of the CHAMP to attach to the bark of a tree. Between the grippers there is a three Degree of Freedom continuum manipulator which allows the placement of the grippers relatively to each other. Each gripper has a gripper rotator that allows for 370° of bi-directional rotation.

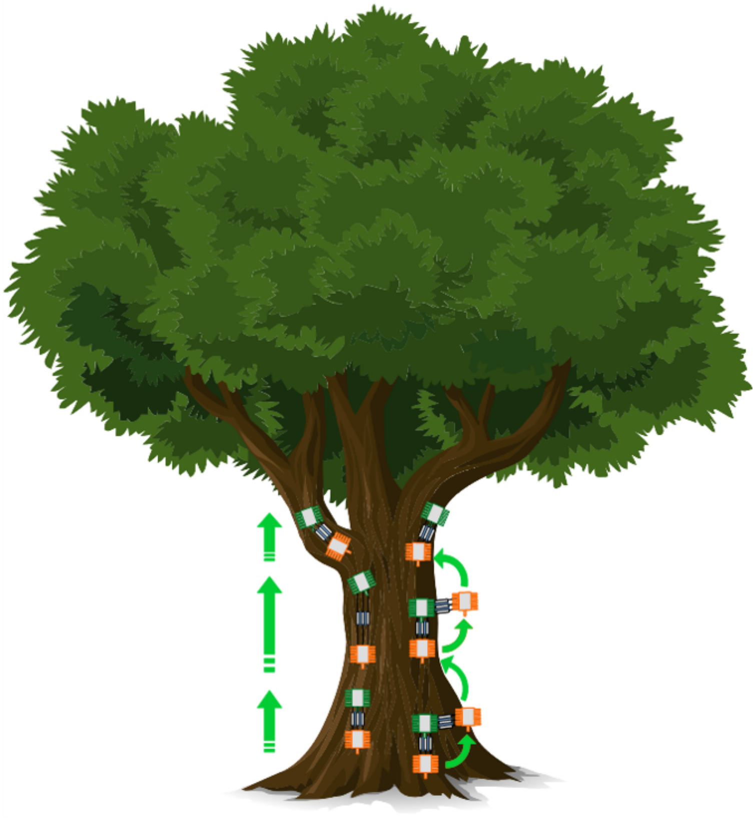


Figure 20: Inchworm Gait (Left) and Rotating Gait (right)

The many degrees of freedom and compliance of the CHAMP allow two primary locomotion strategies. The first strategy is the Inchworm Gait. As the name implies, the robot moves along a path by releasing the foremost gripper, moving it to a more forward position by stretching the abdomen, and gripping again. The same process is then repeated by the trailing gripper, alternating between grippers from then on. The Inchworm Gait is very conservative in the forces and moments applied to the grippers and also allows it to navigate spaces between obstacles the same width as the robot. The disadvantages of the Inchworm Gait is that it requires significantly more grips and releases, decreasing efficiency, needle life, and speed.

The other primary locomotion strategy is termed the Rotating Gait. It involves releasing the trailing gripper and then using its gripper rotator to rotate the entire robot end-over-end. This results in the trailing gripper becoming the foremost gripper and vice versa. This gait is useful in that it is faster and more efficient than the Inchworm Gait because it involves the fewest required grips and releases. However this is offset in that the Rotating Gait requires a large, open section of tree to avoid obstacles and also imparts large forces and moments on the grippers.

4.1.1 End Effectors

The end effectors used by the CHAMP are compliant-hook grippers. Each gripper consists of a number of individually compliant hooks split into two opposing, synchronized racks of hooks. These grippers connected to the robot through the to the gripper rotators.

Grippers

The Grippers allow the robot to attach to the tree and provide all reaction forces and torques of the robot's weight and movement. This is accomplished by using a large number of individually compliant hooks, each providing a small amount of force. Additionally hooks are set up in pairs so that the force to dig into the tree is provided by another hook, allowing secure attachment in any orientation.

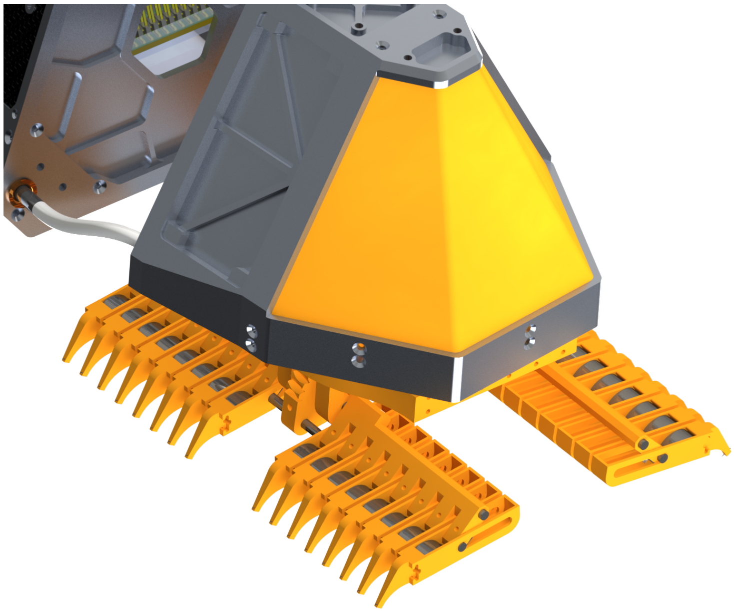


Figure 21: Gripper

The proof-of-concept employed a single worm gear as the output of the gearmotor. This drove two helical gears on opposite sides of the worm. This setup was simple and compact, however it resulted in the hooks colliding in the middle if they did not immediately dig into the surface. As such this needed to be revised in the next iteration by further separating the axles of the hooks.

The final design employed four separate racks of hooks which are driven by pairs of axles acting to transmit force rather than torque. Each pair of axles connects through the racks of arms, acts as the sliding pin joint for the hooks, and connects to the work gear. The worm gears are driven by worms directly above them, which join the gripper motor in the center of gripper as a set of 3 miter gears. This configuration allows simple, wide spacing of the hook pivots as well as an anti-backdrive power transmission. Lastly it also allows the gripper motor to remain stationary within the non-rotating part of the gripper assembly, simplifying wiring greatly.

Compliant Hooks

The proof-of-concept individually compliant hooks required the most iterations of any

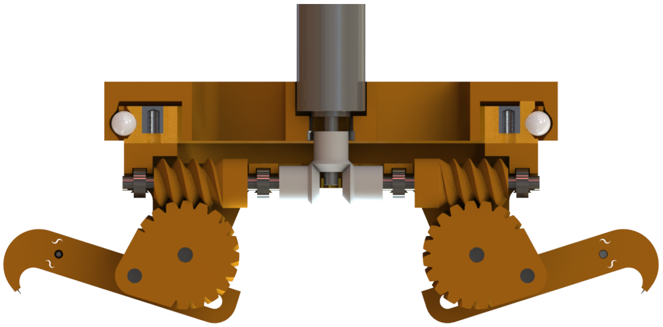


Figure 22: Gripper Gearing

component. The final proof-of-concept hooks consisted of an arm which ended in a pin joint into a slot in the hook itself. This allowed the hook to pivot and slide independently. Two 3D-printed springs applied a pulling return force as well as a twisting return torque. Each hook terminated in a single acupuncture needle which protruded about 1.5mm, preventing damaging penetration into the tree.

The individually compliant hooks required the most iterations of any component. Each hook has a constant force spring allowing two degrees of compliance. The lower part of the hook is free to slide in and out as well as rotate around its pivot. This allows the claw to swing down and inward until it contacts the surface. Once in contact, the claw is pulled along the surface until the needle digs into the surface or catches on an edge. Finally, the constant force spring applies a nearly constant load on the needle or needles. The pulling force is accomplished by doubled 1.5N springs, totaling around 3N. Additionally the torsional return force is accomplished by permanently back-bending the springs around the arm pivot. Each spring applies a return torque of about 25mNm. Combined this torque and force total around 55mNm of maximum torque required to actuate each hook. Figures 24 through 25 show the iterative design process of the hooks. In those figures, the leftmost hooks is the newest and rightmost is the oldest.

Gripper Rotators The gripper rotators on the proof-of-concept consisted of a ring with spur gear teeth recessed into the side. This was powered by a small pololu gearmotor, which was only marginally able to rotate the robot at full sideways extension. The ring was

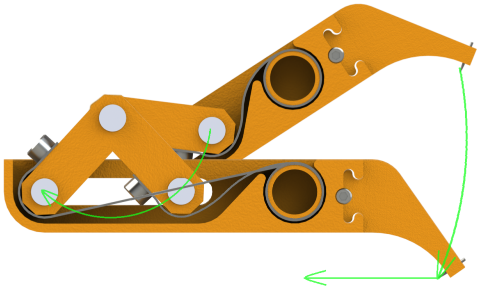


Figure 23: Hook and Illustrated Path

Figure 24: Iterative Hook Designs Side View

hollow to allow wires and the gripper motor to pass through the middle.

The final design gripper rotator is a ring with mount holes. The rotator's rotor rides on 16 delrin ball bearings held in a bearing cage. It is powered by a Maxon DCX motor through a ring gear printed inside of the bearing race and re-enforcement ring. This motor and transmission allow the rotator to easily move the robot to any position and hold it with minimal effort. Additionally the transmission is nearly entirely anti-backdrive, further reducing (and usually eliminating) the torque required to hold position. The rotor also has

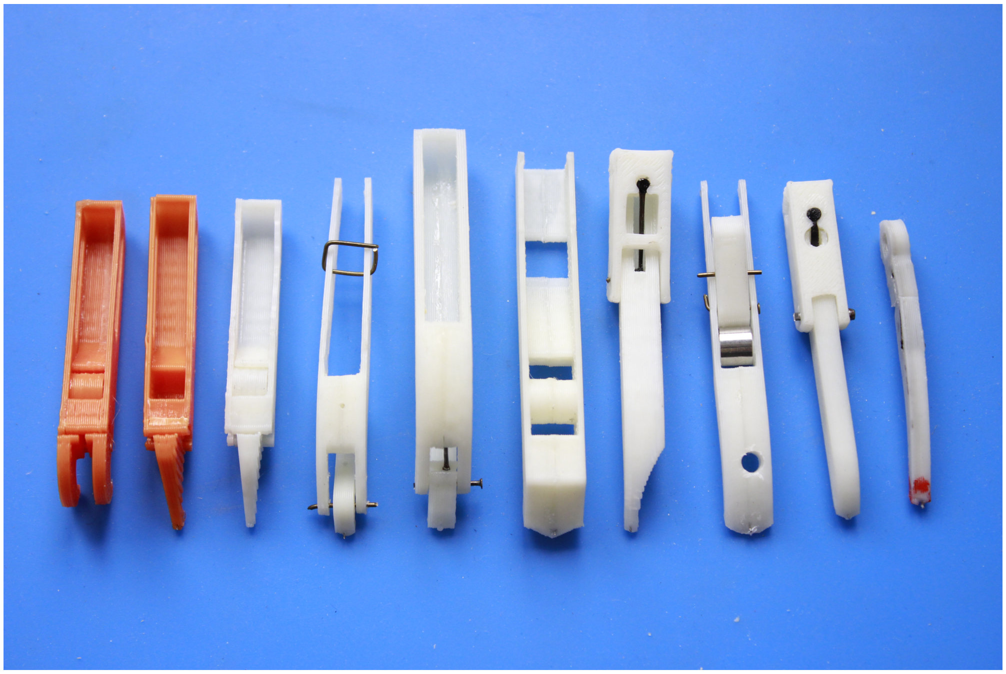


Figure 25: Iterative Hook Designs Top Down

an aluminum re-enforcement ring at its core to maintain rigidity and provide metal threads for gripper mounting. Finally, the gripper rotator allows 370° of rotation in either direction. This was chosen because it means that there is always an orientation which will not need to rotate more than 180° to achieve a target rotation. In practice this means the robot can reset each gripper to a position near zero in order to ensure it does not run out of travel.

Motor Selection

The opportunity to be able to use Maxon motors, regarded as the highest quality motors available, enabled the project to be completed but also was a point of difficulty. With complete control of the motor parameters, many calculations were done to determine the necessary torque curves and speeds required of each motor. This required the team to gain a full working knowledge of each of these parameters, something that was beyond their classroom experience. Using these calculations as starting points, a numeric thermal simulator was programmed using constants derived from Maxon's catalog. This simulator took in torque curves as well as motor and gearbox selections as inputs. The simulator then reported the resulting speed, current, efficiency, and temperatures curves over short- and

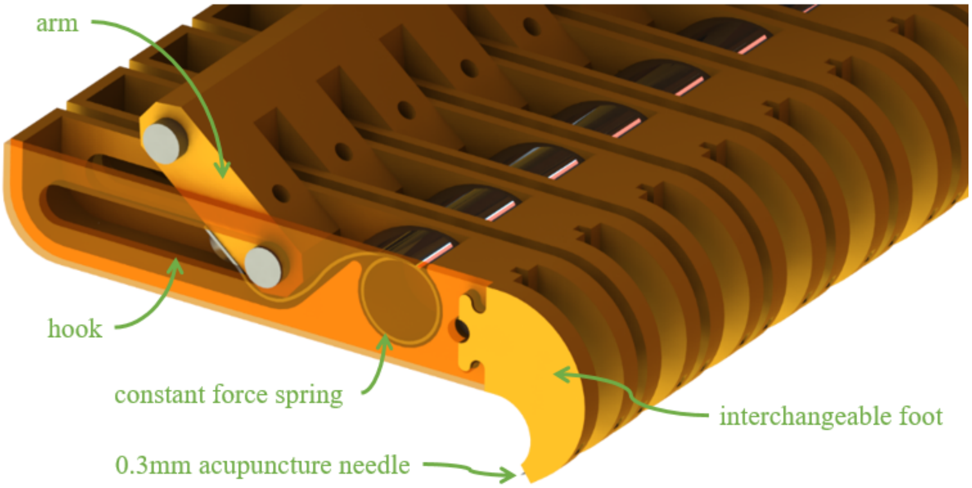


Figure 26: Rack of Hooks

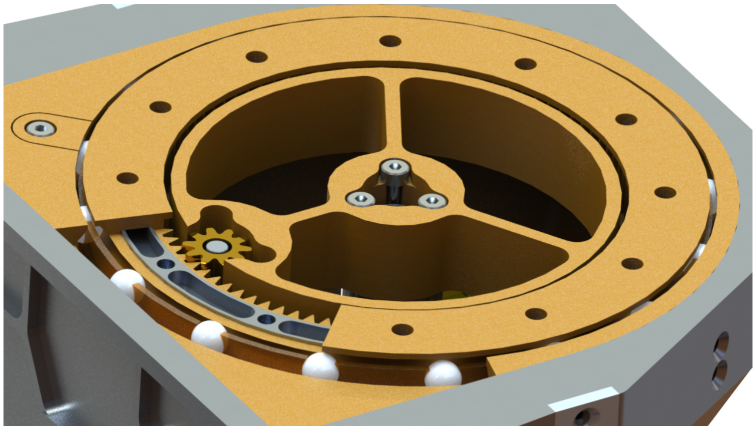


Figure 27: Gripper Rotator Underside

long-term operation. The resulting long-term output data for the gripper motors is shown in Figures 28 and 29, respectively. The results for the girpper rotator are shown in Figures 30 and 31.

Modularity

Since this robot is intended for a variety of tasks and missions, it is important that the robot be both modular and serviceable. For these reasons both the gripper and hook feet are modular and interchangeable. The gripper mounts to the gripper rotator using a 72mm m3 bolt pattern, allowing the grippers to be an interchangeable component which can be any compatible device. Similarly the ends of the hooks terminate in a lockable dovetail,

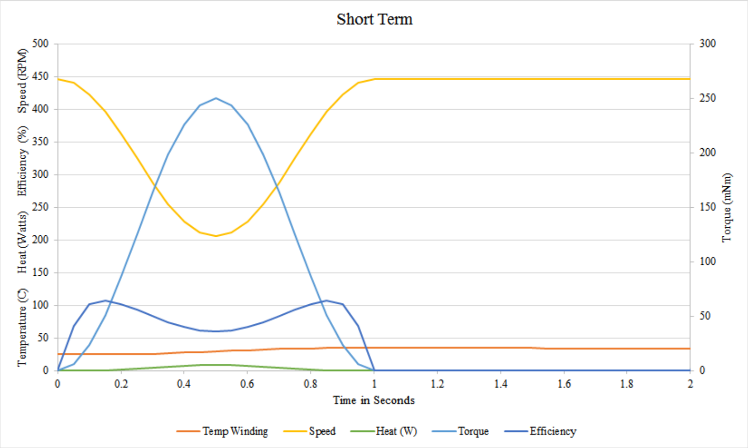


Figure 28: Gripper Motor Numeric Simulation Outputs for Short-Term Operation

Figure 29: Gripper Motor Numeric Simulation Outputs for Long-Term Motor Heating

allowing any foot with compatible geometry to be mounted and dismounted quickly, easily, and accurately. This allows the replacement of damaged feet or the addition of feet for gripping surfaces other than trees or be otherwise task-specific. In the final design, this is demonstrated in that each hook has two separate feet attached simultaneously.

4.1.2 Abdomen

The abdomen, shown in Figure 32 houses the mechanisms that actuate the continuum manipulator, and most of the major electronic components such as the battery and main computer. It also serves as a rigid mount point for the linear slides that form the continuum

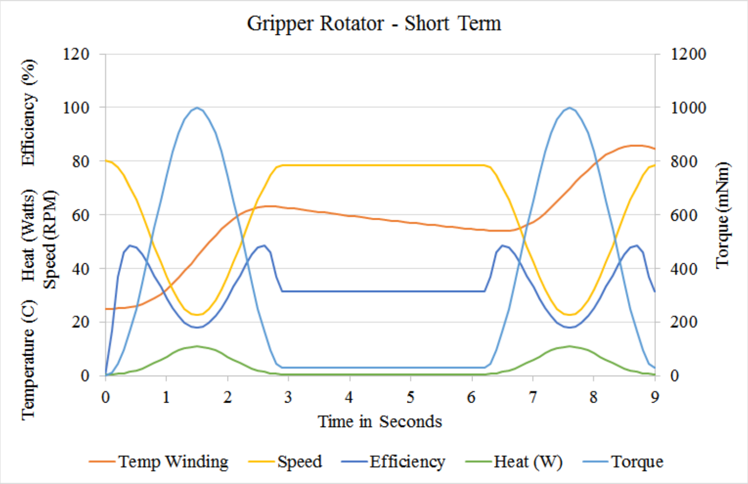


Figure 30: Gripper Rotator Motor Numeric Simulation Outputs for Short-Term Operation

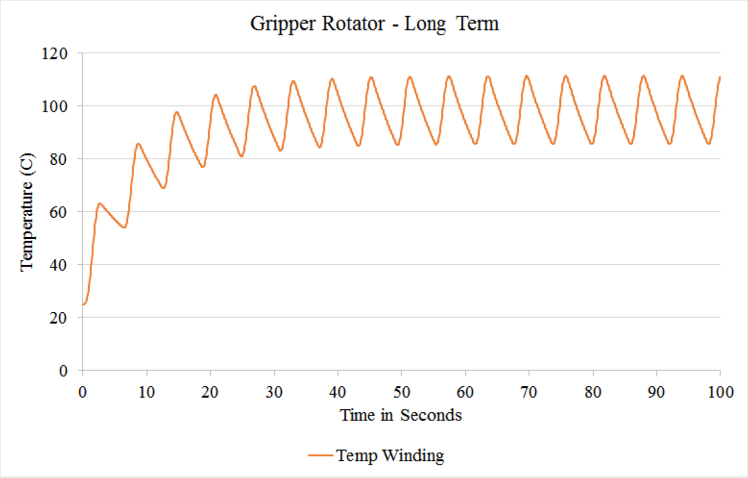


Figure 31: Gripper Rotator Motor Numeric Simulation Outputs for Long-Term Motor Heating

manipulator, and for multiple payloads.

Symmetrical Continuum Manipulator Actuation

Three linear slides at each corner of the triangular abdomen form the continuum manipulator that positions the grippers. In the proof-of-concept the push-pull rods were actuated with a discontinuous motion belt-and-pulley system. This system functioned properly on limited use, but it fell short in several important aspects. Most importantly, the system was large and heavy, and the belts were improperly tensioned; implementing a proper tensioner in the engineering prototype CHAMP would have increased the size and weight of the

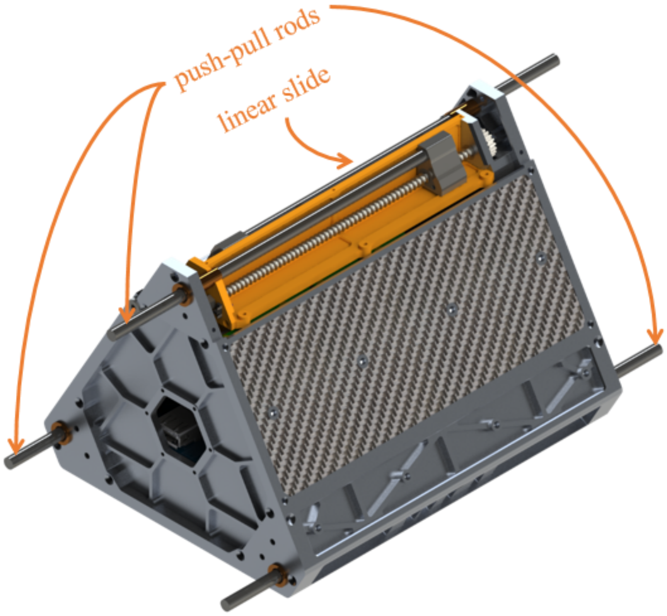


Figure 32: Abdomen

mechanism. Secondly, the energy stored in the deformed push-pull rods caused the mechanism to back-drive when the motors were unpowered; this required continuous power draw for the CHAMP to hold position. To mitigate these problems, the engineering prototype CHAMP employed counter-rotating lead screws for continuum manipulator actuation.

Each linear slide assembly in the engineering prototype CHAMP is actuated by a single DCX 16L Maxon Motor and gearhead, which counter-rotates two lead screws in opposite directions through a custom, single-stage gearbox. The position of the push-pull rods is controlled using absolute Maxon encoders, zeroed limit switches mounted at either end of the linear slide assembly. The lead screws have an anti-backdrive transmission angle allowing the abdomen motors to consume minimal power while the CHAMP stays static on the tree.

Axial Load Mitigation

The lead screws are supported at each end of the linear-slide assembly with 6mm OD, 3mm ID ball bearings, shown in Figure 33 so that they can spin at up to 3500rpm. The linear slides can apply a load of up to 90N axially on the bearings, which they are not rated for. The wear on these bearings at such high loads and speeds was a concern, so they were tested in a custom built fixture, pictured in Figure 34.

Figure 33: Abdomen Ball Bearings

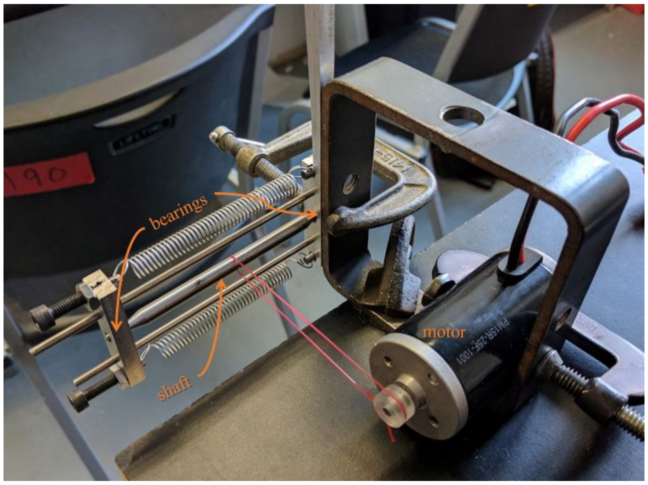


Figure 34: Custom Bearing Test Fixture

Results of the tests run on this fixture showed that with regular use, the bearings that we planned to use in the abdomen would indeed wear to the point of breakage. Larger bearings could not be used as this would increase the size and weight of the entire assembly. Instead, to mitigate the axial loading on the bearing, the ends of each lead screw assembly stack (shown in Figure 35) holds a single 3mm steel bearing ball. The ball spins against a set screw that can be adjusted such that it touches the bearing ball when an axial load is applied to the lead screw. This removes the axial load from the inner race of the ball bearing, and puts it on the minuscule surface between the set screw and the ball bearing, therefor minimizing wear.

Push-Pull Rod Material Selection

Many materials were considered for the material of the push-pull rods. The material of the rods was selected based on (1) material properties, and (2) availability of material. The material that was chosen needed to be able to deform elastically over a large range of bending forces, and store energy, but not easily stretch axially, or deform plastically in any direction. The proof-of-concept used ABS push-pull rods; these were undesirable because ABS reached its plastic deformation range too early upon bending. Polycarbonate was used for the final continuum manipulator are because its material properties follow the requirements most

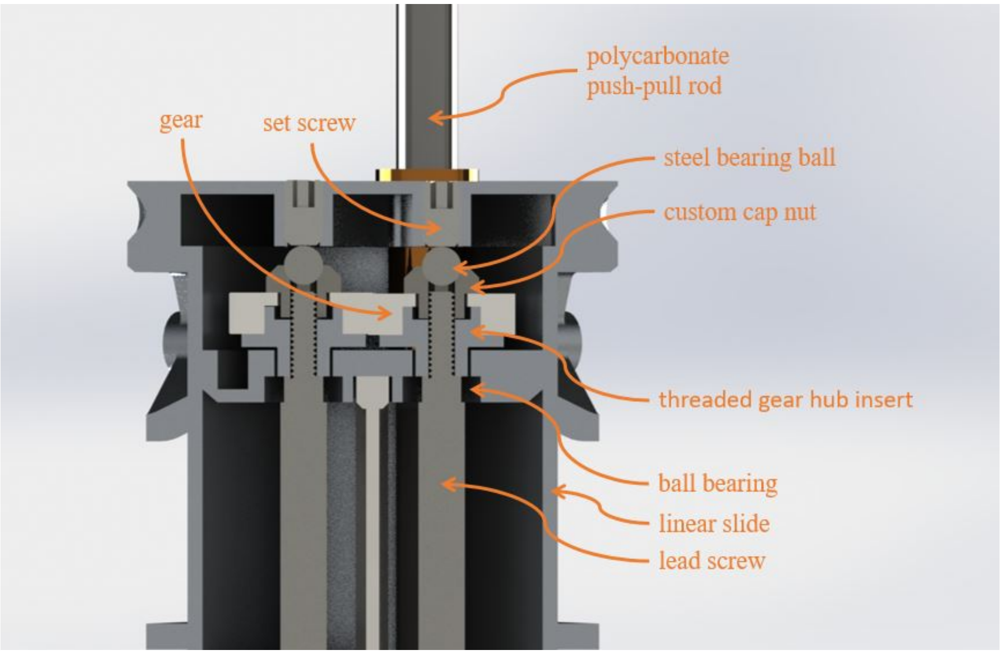


Figure 35: Lead Screw Stack Cross Section

closely, and were readily available in the necessary form factor at a price that fit out budget.

The force required to bend the push-pull rods was determined experimentally. Multiple diameters of rod were procured and tested in the same way. A 4.8mm, or 3/16” diameter polycarbonate rod was chosen because it requires approximately 20N applied at the linear slide to bend. This value was used for motor selection, as well as for the design of the linear slide mechanism and the abdomen.

Motor Selection

The continuum manipulator actuation motors were selected based on power requirements for the task, and the thermal properties of the motors. From the testing and analysis outlined in Section 4.1.2, the force required to bend the push-pull rods at the linear slide is approximately 20N. Analysis of forces using the Free Body Diagrams shown in Appendix A, the worst case axial loading on the push-pull rod due to mass and moment of the robot is 57N. While the robot cannot possibly experience both of these forces at the same time, 77N was used as the worst case scenario for protection of the motors and continuum manipulator components.

MathCAD was used to calculate the maximum power requirement for the abdomen motors, which was 12.5W. The worst case torque profile for these motors was plugged into the numerical simulator described in Section 5.4, and the plot shown in Figure 36 and 37 was output. From this analysis, the DCX 16L Maxon Motors with a 6.6:1 gearhead were chosen for the linear slide actuator motors. The motors output a maximum of 18W, which is 44% more than is required. The chosen gearing, however, causes the motors to operate in their most efficient range (approximately 85% motor efficiency, and 35% overall efficiency) during regular operation (not the operation range shown in Figure 36.

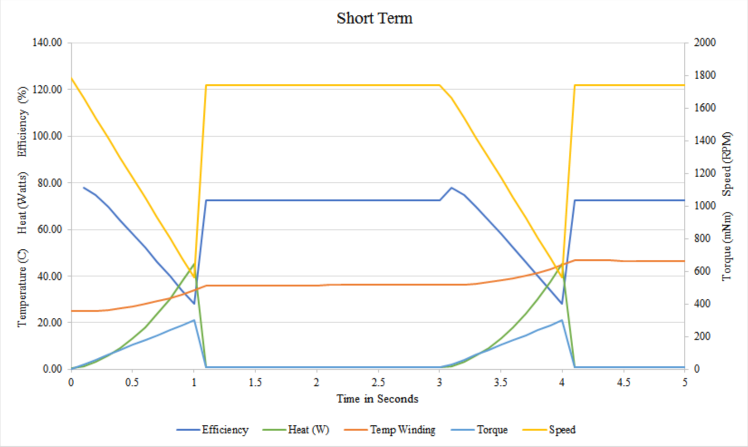


Figure 36: Motor Numeric Simulation Outputs for Short-Term Operation

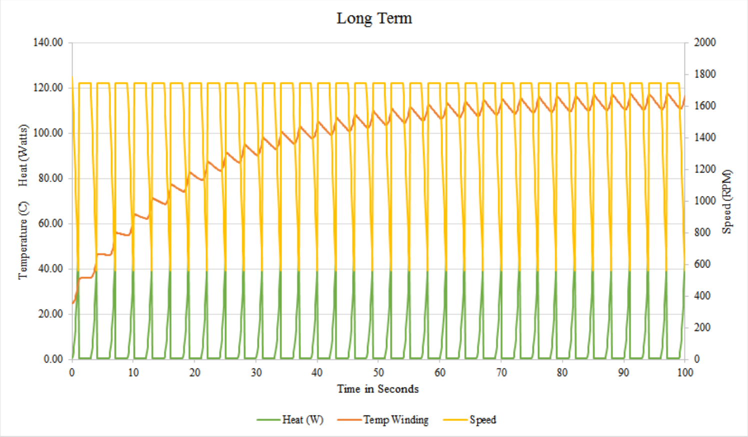


Figure 37: Motor Numeric Simulation Outputs for Long-Term Motor Heating

Physical Payload Support

The abdomen for the engineering prototype CHAMP not only serves as a rigid housing for the continuum manipulator, but it also supports payloads for many use cases. The final abdomen has a standard 43mm M3 bolt pattern that can be used to mount custom payloads. There is also a set of standard connectors that can be used by the payload to access the CHAMP's main power and communications bus.

4.2 Electrical System

4.2.1 Sensing & Control

The CHAMP uses a series of sensors to be able to determine the position, angle and velocity of each of the modules relative to each other. Sensors are also used to ensure proper operation. Figure 38 illustrates what kind of sensor is used where. The Table 3 specifically lists and describes each of the sensors used.

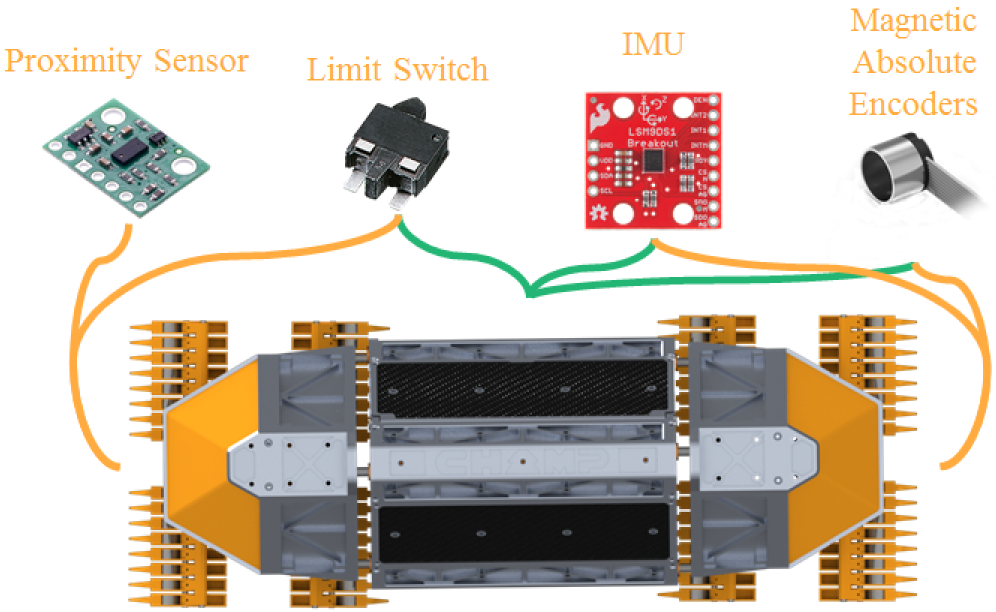


Figure 38: Sensor Placement On Robot

For the IMU, a wrapper library was written on top of the given Sparkfun library, to abstract out the relevant and important technology to this project, making using the sensor much less complex.

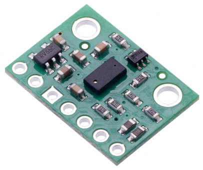
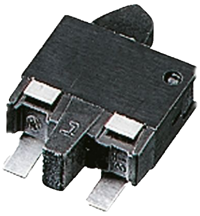
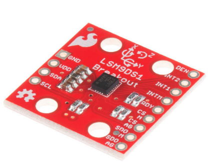
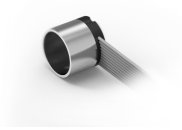
	Sensor Name	Part Number	Locations on Robot	Specifications	Connectivity
	Proximity Sensor	VL6180X	Grippers	Detect up to 20cm away at 1mm resolution	I2C
	Limit Switch	ESE22MH23	Grippers, Abdomen	5.7mm x 5mm x 1mm	Digital Pin
	IMU	LSM9DS1	Grippers, Abdomen	9 Degrees of Freedom	I2C
	Encoder	ENX16 EASY Absolute SSI	Grippers, Abdomen	Magnetic Encoder,	SSI

Table 3: Sensors

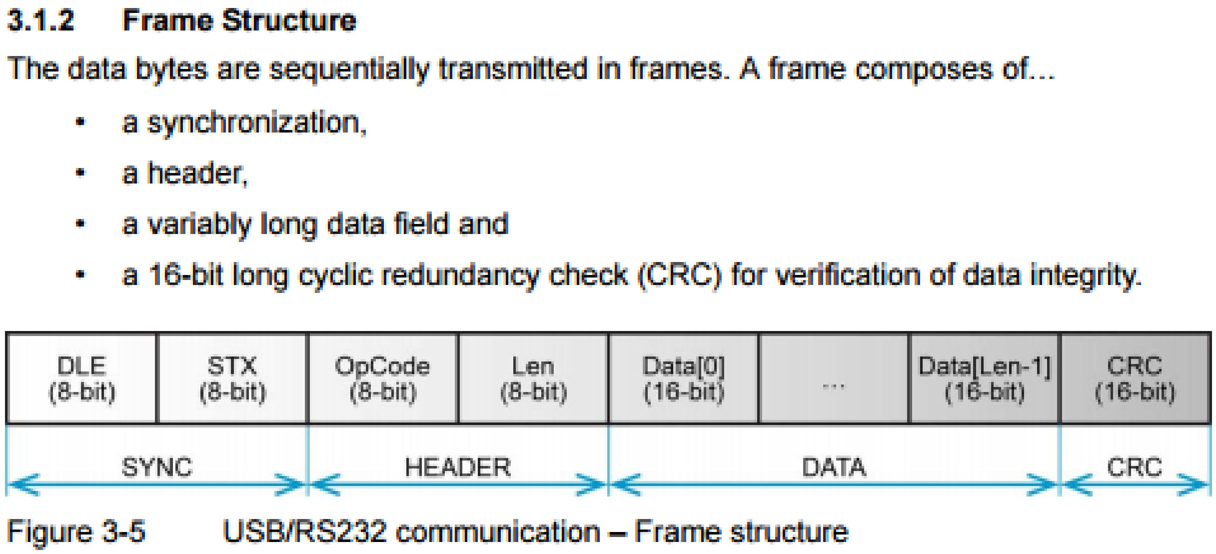
4.2.2 Implementing Maxon Communication Over RS232

In order to drive the motors, the Maxon serial communication protocol was implemented. This process required an in depth knowledge of the Maxon firmware and communication objects. Interfacing with the EPOS4 motor controllers is relatively straightforward, once the basic principal behind doing so is understood. There is a table kept in memory inside the processor on the EPOS4 Controller known as the object dictionary. This object dictionary contains all of the parameters about the motor it's attached to, as well as serves as the place where new commands are set. As an example, this project used profile position mode (PPM) to rotate the motors to the exact desired position. To set the position, three commands must be passed:

1. The ControlWord entry must be set such that the operating mode is changed to PPM.
2. The ControlWord entry must be set such that the motors is enabled.

3. The Target position entry must be set to the targeted position.
4. The ControlWord entry must be set to do the operation.

Each one of these communication frames are formatted as follows in Figure 39 from the Maxon documentation:



3.1.2 Frame Structure

The data bytes are sequentially transmitted in frames. A frame composes of…

- a synchronization,
- a header,
- a variably long data field and
- a 16-bit long cyclic redundancy check (CRC) for verification of data integrity.

DLE (8-bit)	STX (8-bit)	OpCode (8-bit)	Len (8-bit)	Data[0] (16-bit)	…	Data[Len-1] (16-bit)	CRC (16-bit)
SYNC		HEADER		DATA			CRC

Figure 3-5 USB/RS232 communication – Frame structure

Figure 39: Maxon Command Frame Structure

Data structures like C unions had to be used to pass the 64 Byte data values of this frame on the 8 bit Atmel 328p. This processor architecture meant that the checksum algorithm given in the docs could not be implemented as given. These two things slowed down progress on the development of the electronics significantly and should be avoided in future projects using these very powerful motor controllers. Again, once these problems were solved, building a control architecture on top of the motor controllers was painless.

Commands are passed to the co-processor, parsed, and then converted into commands to be passed to the Maxon motor controller as seen in the following figure:

The way these commands flow is further explained later in the report.

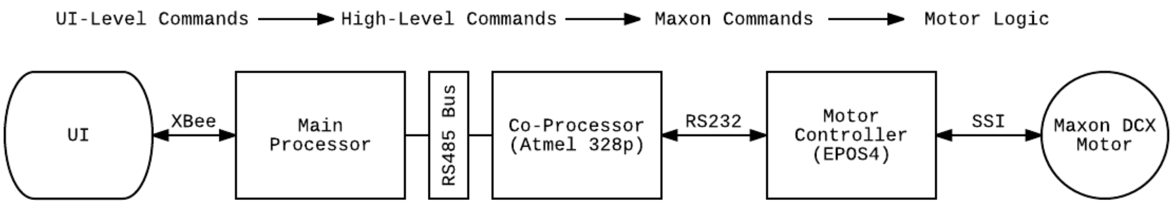


Figure 40: UI To Maxon Command

4.2.3 Power Management

The main power source on the robot is a custom designed 14.4V, 3.5AH (50.4W) Lithium-Ion battery pack sourced from BatterySpace. It is about 0.22 kg, which is about half of the weight of the original estimate, yet it has more than 80% of the capacity.

Figure 41: Robot Battery

The EPOS4 motor controller boards are all powered directly from the battery as they have the capabilities to step the voltage down. There is a single switching regulator housed in the abdomen which provides a 5V signal to the other modules on the robot.

4.2.4 Distributed Computing Network

The CHAMP implements a distributed computing network inside the robot to handle all controls. This means that there is a series of co-processors governed by a single main processor distributed through the robot. There are three co-processors, one in each of the two grippers, and one in the abdomen. These co-processors handle:

- Reading in sensor data
- Processing sensor data
- Communicating with motor drivers
- Applying sensor data to motor position

This frees up the main processor to do more computationally intense tasks. As an example, when the operator wants to grip one of the grippers, the grip command gets sent from the OI to the main processor, and then from the main processor to the desired gripper. The gripper co-processor handles actually moving the motors, and motoring the current draw to detect that the motor is indeed gripped. This data does not have to leave the coprocessor, so it can be executed very quickly and accurately. The conventional way of doing this would be to have the main processor read in the data from the proximity sensor and IMU, and then send the grip commands all while simultaneously managing the other modules on the robot (making sure the other gripper is sill gripped, making sure the abdomen motors are in the right position etc). If the designer wanted the main processor to have the capabilities to do computer vision calculations, or do analysis on some data in real time, it would not be possible as the main processor would be bogged down with the other computations. The other option would be to increase the speed and power of the main processor to handle all of this, but that would cause significant losses to climb time.

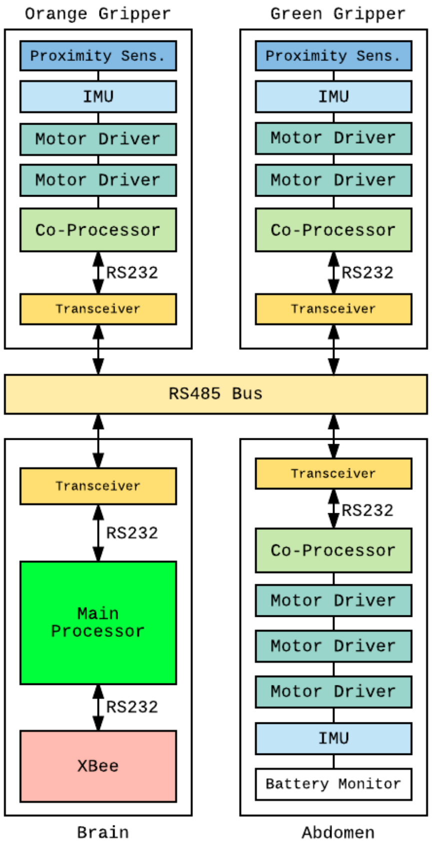


Figure 42: Distributed Computing Network

Using a distributed computing network also means that the number of wires passed between the different modules is minimized as well. There are only four essential connections:

- Battery +
- Battery -
- Bus high
- Bus low

RS485 was selected to implement the hardware layer of the distributed computing network. The following characteristics led to this decision:

- Simple to go from RS232 to RS485, only a level shift operation. All of the processors could already speak RS232
- Inexpensive, fully assembled transceiver modules can be purchased on eBay for as little as $0.79
- Fast, the bus can operate at the upper limit of the baud rate of our co-processors, 115k bits/second
- The team had prior experience working with the technology.

4.2.5 Electrical Payload Support

Since the electronics in the robot are based around a bus model, in order for the a payload to gain access to all of the sensors and components on the robot, all it needs to do is tap into this bus. Additionally, a payload could also be modeled as a module as well if the user wanted it to be driven by the brain. The battery is also more than capable of applying power to a potential payload as well given it's nominal voltage.

4.3 Software

4.3.1 User Interface

The principal purpose of the user interface is to form and pass high level commands to the main processor on the robot over the XBee. The CHAMP's UI, shown in Figures 43 through 45 was designed in QT and implemented in python through the pyQT library.

Controls on the UI are linked to methods that send commands to the robot. For example, if the user scrolls one of the trackbars on the advanced operating mode page, it sends that value to the designated gripper module on the robot. One of the novel features of the UI is the different control modes. If the user selects standard mode, they can prompt

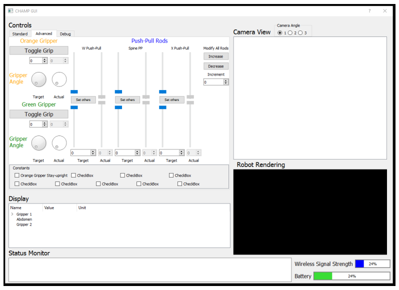


Figure 43: Advanced Mode

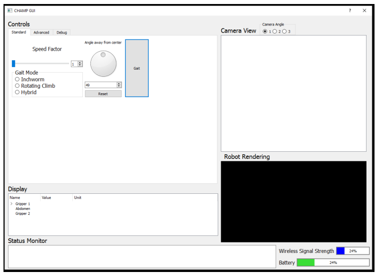
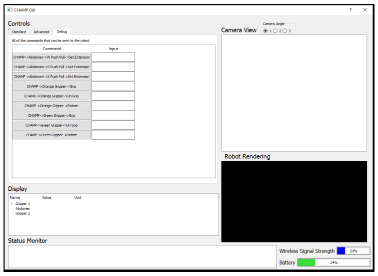


Figure 44: Standard Mode


All of the commands that can be sent to the robot.

Command	Input
CHAMP->Abdomen->W Push Pull->Set Extension	
CHAMP->Abdomen->S Push Pull->Set Extension	
CHAMP->Abdomen->X Push Pull->Set Extension	
CHAMP->Orange Gripper->Grip	
CHAMP->Orange Gripper->Un Grip	
CHAMP->Orange Gripper->Rotate	
CHAMP->Green Gripper->Grip	
CHAMP->Green Gripper->Un Grip	
CHAMP->Green Gripper->Rotate	

Figure 45: Debug Mode

the robot to gait at a given angle relative to their current position. The idea here is that this would be given to operators who only want the bare minimum of functionality. If the user selects advanced mode, they are given the ability to graphically control any element on the robot. The can modify the extension of each of the push pull rods, they can rotate the grippers or toggle a grip. This is for operators executing complex maneuvers that require a great deal of precision and control. Lastly, the user can select debug mode. In this screen a list of all possible commands are presented to the user. As the name implies, this is designed to help with debugging the robot if something goes wrong. While switching between these three modes in the controls panel, other UI elements are constantly displayed to the operator. Things like the battery indicators, camera feed etc persist through mode switches.

4.3.2 Robot Software Modeling

The UI interacts with the main processor on the robot though a set of messages. Each message has a set of prefex bytes that uniquely define it. Messages are modeled as a part of a tree of Containers. Each Container has a set of messages associated with it, and then a tree of sub-containers to form a hierarchy of messages. Figure 46 is a visual representation of this arrangement, and Figure **??** is an instantiation of the tree in python.

This tree is how the prefex is generated. For example, if the operator wanted to set the extension of the S Push Pull rod, the prefex would be 020, as shown in Figure 47.

The robot object is instantiated on the UI as well as the main processor, so all messages with have identical signatures. This is refereed to in the code as the robot topology.

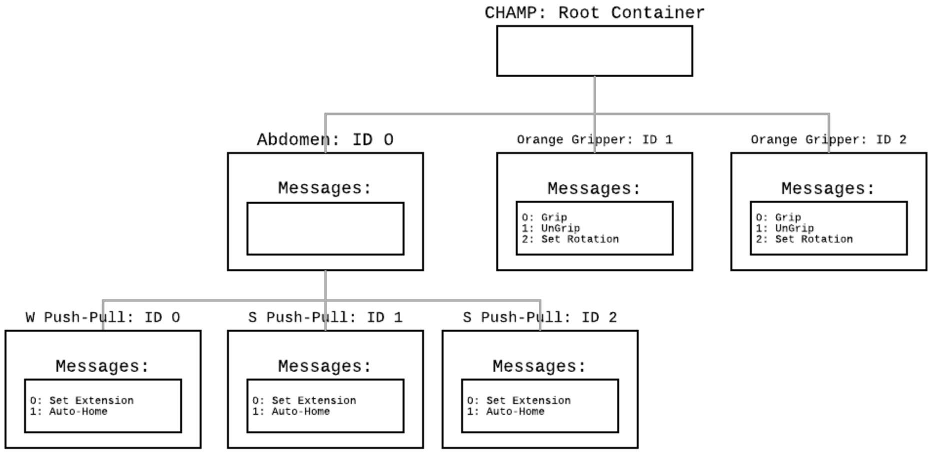


Figure 46: Section of the CHAMP's container model

It allows messages to be passed by signature.

4.3.3 Message Passing

Message passing occurs in multiple places through the robot's codebase. Messages are retrieved from the robot topology file by the UI, serialized, and then sent to over the air over the air by the XBee to the main processor on the robot where they are reformed into message objects, interpreted, and then sent over the RS485 bus to the co-processors. To handle all of this communication, an object called the SerialPortController is implemented as seen in Figure 49.

The programmer only has access to the outgoing and incoming message queues. To send a message over the port (it could be to an XBee or an RS485 bus) all one has to do is put it into the outgoing message queue, and the SerialPortController will handle serializing and sending it. Conversely, to receive a message, the SerialPortController reads in bytes from the port until the number of bytes per message is read in. It then uses the decode method supplied by the designer to checksum and then reform the message into a message object. It is then placed in the incoming message queue to be handled by the rest of the application. Both queues are thread safe, and supplied by python3's Queue module.

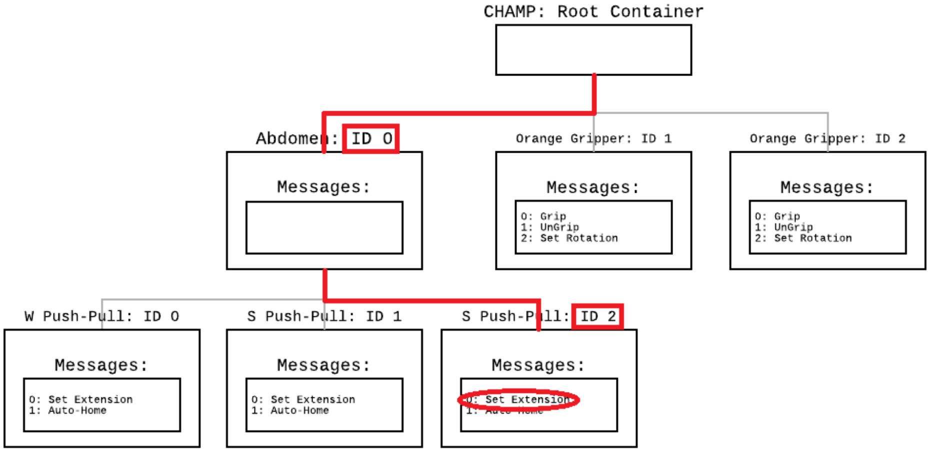


Figure 47: Determining prefex of S Push Pull Extension

This relatively simple object is a fast and easy way to move message objects through a serial port.

```
robot = RootContainer("CHAMP", 5)

robot.abdomen = robot.add_sub_container(MessageContainer(0, "Abdomen"))  # high level add
robot.abdomen.w_pp = robot.abdomen.add_sub_container(MessageContainer(0, "W Push Pull"))
robot.abdomen.w_pp.set_extension = robot.abdomen.w_pp.add_message(Message(0, "Set Extension"))
robot.abdomen.s_pp = robot.abdomen.add_sub_container(MessageContainer(1, "S Push Pull"))
robot.abdomen.s_pp.set_extension = robot.abdomen.s_pp.add_message(Message(0, "Set Extension"))
robot.abdomen.x_pp = robot.abdomen.add_sub_container(MessageContainer(2, "X Push Pull"))
robot.abdomen.x_pp.set_extension = robot.abdomen.x_pp.add_message(Message(0, "Set Extension"))

robot.orange_gripper = robot.add_sub_container(MessageContainer(1, "Orange Gripper"))  # high level add
robot.orange_gripper.grip = robot.orange_gripper.add_message(Message(0, "Grip"))
robot.orange_gripper.ungrip = robot.orange_gripper.add_message(Message(1, "Un Grip"))
robot.orange_gripper.rotate = robot.orange_gripper.add_message(Message(2, "Rotate"))

robot.green_gripper = robot.add_sub_container(MessageContainer(2, "Green Gripper"))  # high level add
robot.green_gripper.grip = robot.green_gripper.add_message(Message(0, "Grip"))
robot.green_gripper.ungrip = robot.green_gripper.add_message(Message(1, "Un Grip"))
robot.green_gripper.rotate = robot.green_gripper.add_message(Message(2, "Rotate"))
```

Figure 48: Example Code

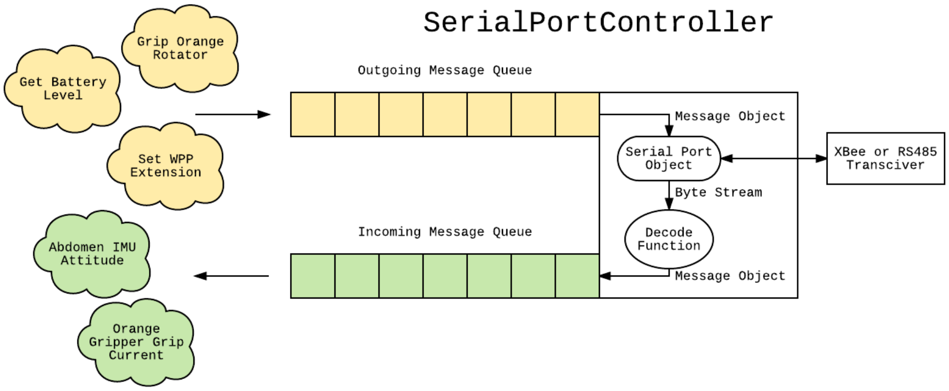


Figure 49: SerialPortController Explanation

5 Evaluation & Results

Testing and evaluation of the CHAMP was split up by the design requirements discussed in Section 3. This partitioning of evaluation made it simple test the CHAMP thoroughly against each requirement requirements. Each of the following sections summarizes the evaluation methods used for each subsection of design requirements.

5.1 Arboreal Mobility Requirements

The CHAMP's arboreal mobility was evaluated throughout the implementation and after the completion of both the proof-of-concept and the engineering prototype versions of CHAMP. Throughout development, each hook and gripper prototype was qualitatively tested on the test trees in Figures 13 through 15.

Completion of the proof-of-concept in December marked the first full-system test of arboreal mobility. The general mobility of the proof-of-concept CHAMP was tested on Tree A, with resounding success. The tests of the proof-of-concept proved that the chosen climbing mechanisms would work, but in terms of durability, and ability to meet any other design requirements, left much to be desired.

Throughout the implementation of the final CHAMP, further prototypes of hooks were tested on various materials and surfaces including the test trees. Finally the professional-grade CHAMP prototype was tested on Trees A, B, and C during the final stages of assembly and refinement. Unfortunately only qualitative testing was completed, but based on the proof-of-concept's performance, and the promise of the gripper testing detailed in Section

5.2 Payload Support Requirements

The CHAMP's payload support was not tested on the proof-of-concept, as its main purpose was to prove arboreal mobility. The engineering prototype, however, was evaluated against the electrical and physical payload support design requirements from Section 3.2.

The CHAMP engineering prototype can easily support any reasonable payload electrically and through software. The CHAMP supplies electrical connections to main robot power and the distributed network via a standard connector. The software supports most reasonable payloads as it is easy to add custom commands, and expand the network to support more nodes.

Direction	**Tested**	**Robot Without Payload**	**Required Payload Support From Gripper**
X	41N	21N	20N
	5.1Nm	1.6Nm	3.5Nm
Y	41N	21N	20N
	6Nm	2.8Nm	3.2Nm
Z	41N	21N	20N
	9.5Nm	4.6Nm	4.9Nm

Table 4: Arboreal Mobility Test Results

To test the platform's physical payload support, a gripper was actuated against Tree A such that it gripped, then loads were applied in multiple directions. By testing the maximum allowable forces and moments about the X, Y, and Z axes, as shown in Figure 50, the maximum loading *per gripper* was determined experimentally. Using the Free Body Diagrams from Appendix A, and the known center-of-mass of the robot and payload, Table 4 was generated.

Figure 50: Distributed Computing Network

From the Free Body Diagrams in Appendix A, it was calculated that in order to perform the rotating gait with the minimum required payload, the gripper must be able to support 2.9 Nm contracted, and 5.5 Nm extended in all directions. For the inchworm gait, the robot must be able to support 1.23 Nm. From these values and the results listed in Table 4, the CHAMP *can* traverse a tree with the minimum required payload via the inchworm gait and the rotating gait, but *cannot* support the minimum required payload while hanging upside down, or fully extended outward.

5.3 Portability Requirements

The engineering prototype came in at under 2.1 kg, which is about 70% of the design requirement specification of . This was about a 400% increase in mass from the proof-of-concept. The majority of this mass increase was to add on-board electronics, more powerful motors, and more structure to accommodate mission specific payloads as well as to meet the rest of the design requirements.

With the robot at 2.1 kg, the full system not including additional payloads is 4.3kg. This is significantly less than the 8 kg design requirement. The remaining system mass could be used for extra batteries or payloads. The full system weight allows for comfortable transport of the CHAMP to almost any potential use case.

5.4 Climb Duration Requirements

Unfortunately, the CHAMP did not quite meet the static state time requirement of 24 hours. Every locomotion mechanism in the robot has anti-backdrive mechanisms in place, which allows the CHAMP to stay static on the tree without the motors drawing power. The electronics, however, do not have low power capability, so they draw power whether the robot is static, or moving. Through experimentation, it was determined that in a static state, the electronics drew 7 watts. With no low-power mode available, the CHAMP would only be able to stay statically in the tree for 7.1hrs Most of this was consumed by the motor controllers, where there were seven of on the final design.

From the expected torque curves and the numeric simulator described in Section , the expected current draw from the motors is 14.3W if all motors run at all times. The gaits performed by the CHAMP requires each motor to operate one third of the time, making the power draw about 4.8W. Combining this with the electronics power draw, the entire platform draws about 21.3W, and the operation time is about 4.25hrs. This, unfortunately, did not meet the 5hr operation time requirement.

Unfortunately the aggressive development time line of the project did not allow time for the physical testing and evaluation of this requirement. Therefor the accuracy of these results leave much to be desired. By these estimates, however, the CHAMP should meet the climb duration requirements.

6 Project Logistics

This project was completed over a period of four WPI academic terms, or 36 weeks, and was split into three unique phases. The first phase, outlined in section 6.2, is focused on researching the most effective method to traverse a tree. The second phase, elaborated on in section 6.3, was meant a first attempt at implementing the most effective full system level design. The third phase, outlined in section 6.4, was the final development of the CHAMP. The three-phase method helped to prevent unseen failures in the overall system design, and facilitated smooth development of the CHAMP.

6.1 Project Budget

WPI allocated \$250 for each of the three students on this project, and each student was expected to match another \$250. The total monetary budget for the project was therefore \$1,500. The budget accounted not only for the production of the professional-grade CHAMP, but also its research and development, and it did not include any items that were donated or procured for no cost. Figure 51 shows the original budget projection for the project, as well as the actual expenditures excluding sponsorships from Maxon Precision Motors and the WPI Robotics Engineering Department. Table 6.1 shows the total cost of the development and implementation of the robot, including the donated materials.

Source	**Budget Allocation**
Maxon Precision Motors	\$7050.00
Team Member Personal Expense	\$750.00
WPI RBE Department	\$530.00
WPI ECE Department	\$250.00
WPI ME Department	\$250.00
Total	\$8930.00

Table 5: Project Budget Allocation

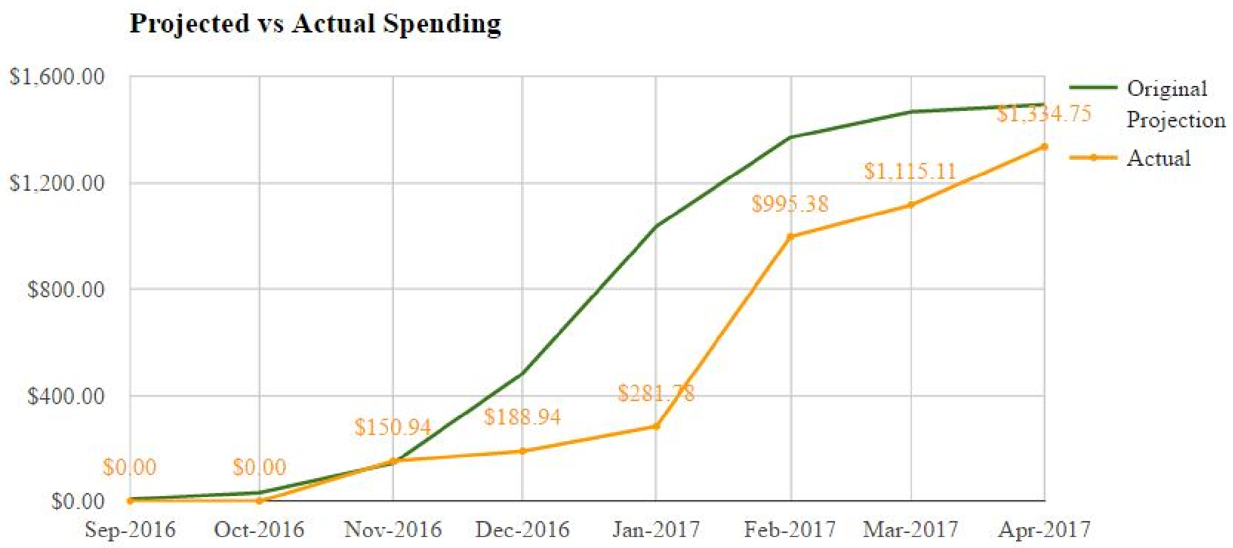


Figure 51: Project Budget Timeline

6.2 Phase One: Research and Subsystem Prototyping

Phase one of the project focused on broad research, and the narrowing of ideas to a reachable goal. The research done in this phase (which was compiled into sections 1 and 2 of this document) consisted of applications of an AMP, previous WPI and non-WPI AMP attempts, and tree-climbing methods. This research culminated to a more refined definition of a useful AMP, and subsequently defined the goals of the CHAMP. The requirements in section 3 were determined mainly from the research into various applications and previous AMP projects.

Concepts for tree navigation, including tree attachment and locomotion, were developed simultaneously with the development of the goals and requirements of the CHAMP. After thorough research into each of the five different tree navigation concepts, they were then narrowed using the design decision matrix shown in Appendix C. Based on a maximum "Σ" of 1320 and a minimum "Σ" of 264, the design decision matrix showed that the Compliant Hook concept is most likely to be best suited for arboreal mobility in the target application space. From the decision to pursue the Compliant Hook concept further, the project was named "the Compliant Hook Arboreal Mobility Platform (CHAMP)."

Finally, the chosen concept was pursued far enough to rule out the majority of possible failure points. More in-depth analysis and prototyping of the CHAMP attachment and locomotion methods, and investigation of electrical and software pieces of the design were conducted. These analyses explored the intricacies of the CHAMP design concept, and led directly into the development of the first CHAMP prototype.

6.3 Phase Two: Full System Prototyping

The second phase focused on refining the analyses and prototypes from phase one to produce a full CHAMP proof-of-concept. The results from the separate prototypes and analysis decided the overall concept of the CHAMP prototype, which was built to verify that fully-functioning CHAMP "proof-of-concept." The full mechanical prototype demonstrated the CHAMP's final mechanical systems and behaviors, but was not meant to be a final product, nor meet all the requirements in Section 3. After thorough testing, flaws in the prototype were noted for improvement in the third phase.

6.4 Phase Three: Full System Design and Manufacturing

Phase Three served to finalize all aspects of the CHAMP to meet the requirements specified in Section 3. Based on the results of the previous phase, several of the CHAMP's subsystems required a complete redesign. Improvements made during this phase focused on the following elements:

- Ability to meet the CHAMP design requirements outlined in Section 3
- Improved durability robustness
- Improved aesthetics

The purpose of this phase was to implement a fully functioning, *useful*, CHAMP prototype that meets the revised requirements from Section 3 of this documents.

7 Conclusion

The goal of this project was to design and manufacture a robot capable of scaling trees and carrying functional payloads. The majority of the project requirements as described in Section 3 were met over the course of the project. Countless engineering problems in an area of robotics that has not been thoroughly explored were solved. This task took immense effort, leading to the exploration of engineering methods and technologies that reached far beyond classroom experience.

From the beginning, it was clear that this challenge would be no small task to complete. After five years and almost a dozen students attempting this project with varying degrees of success, it was clear that great engineering, creativity, and innovation would be required to solve this multidimensional, complex problem. In the end, the project was a success; the CHAMP can traverse trees and meet almost all of its design requirements. There are, however, a few shortcomings made throughout the project that should be echoed to subsequent projects. The first of these pitfalls was that an entire seven weeks was spent defining the specific design parameters, and measurements of success. The information obtained from this process proved invaluable to have, and generating it served as a way to understand the minds of this technology's potential end users. This process compressed the remainder of the project timeline for engineering work, reducing the time available for system testing and integration. Future teams are advised to use the research from Section 2, and adhere to our carefully laid out design requirements as found in Section 3 of this report to maintain their project schedule.

The CHAMP is designed to be a flexible platform capable of supporting a variety of payloads, and these should be developed to support the applications described in the early sections of this report. The most suggested projects are SLAM and navigation of a tree, design and implementation of an ALB inspection payload, or design and implementation of grippers for non-arboreal mobility. The CHAMP could also benefit from efforts put forth to increase manufacturability of various components. Lastly, many of the capabilities of the

EPOS4 digital position controllers are not taken advantage of, and could increase the overall quality of the robot if implemented.

References

[1] Ohio Department Of Agriculture, "Asian Longhorned Beetle," May 2013.

[2] D. M. Kristan, R. T. Golightly, and S. M. Tomkiewicz, "A Solar-Powered Transmitting Video Camera for Monitoring Raptor Nests," *Wildlife Society Bulletin (1973-2006)*, vol. 24, no. 2, pp. 284–290, 1996.

[3] T. G. Murray, M. A. Gennert, and Z. Hou, eds., *Design and construction of a tree-climbing robot.* Worcester, MA: Worcester Polytechnic Institute, 2013.

[4] W. C. Jones and M. A. Gennert, eds., *Project Squirrel 2.1.* Worcester, MA: Worcester Polytechnic Institute, 2015.

[5] M. J. Simpson, L.-J. V. Mistretta, D. C. Ilacqua, E. DeMaio, M. A. Gennert, and K. A. Stafford, eds., *Project Squirrel.* Worcester, MA: Worcester Polytechnic Institute, 2014.

[6] A. C. Stylos, D. C. Pounds, E. S. Brown, M. L. Strickland, M. A. Gennert, and K. A. Stafford, eds., *Project Squirrel 2.0 – A Tree Climbing Robot.* Worcester, MA: Worcester Polytechnic Institute, 2015.

[7] T. L. Lam and Y. Xu, "A flexible tree climbing robot: Treebot - design and implementation," in *2011 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5849–5854, May 2011.

[8] "Kod*lab : RiSEV2."

[9] "Kod*lab : RiSEV1."

[10] "Kod*lab : RiSE V3."

[11] D. Boroughs, "Come Slither," *ASEE Prism*, vol. 20, no. 9, pp. 41–43, 2011.

[12] L. R. Palmer, E. D. Diller, and R. D. Quinn, "Toward a rapid and robust attachment strategy for vertical climbing," in *2010 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2810–2815, May 2010.

[13] D. Y. Hollinger, “Optimality and nitrogen allocation in a tree canopy,” *Tree Physiology*, vol. 16, pp. 627–634, July 1996.

[14] E. A. Graham, S. S. Mulkey, K. Kitajima, N. G. Phillips, and S. J. Wright, “Cloud cover limits net CO2 uptake and growth of a rainforest tree during tropical rainy seasons,” *Proceedings of the National Academy of Sciences*, vol. 100, pp. 572–576, Jan. 2003.

[15] R. Nuwer, “Cool Jobs: Professional Tree Climber,” Jan. 2016.

[16] P. S. Meng, K. Hoover, and M. A. Keena, “Asian Longhorned Beetle (Coleoptera: Cerambycidae), an Introduced Pest of Maple and Other Hardwood Trees in North America and Europe,” *Journal of Integrated Pest Management*, vol. 6, p. 4, Mar. 2015.

[17] D. J. Nowak, J. E. Pasek, R. A. Sequeira, D. E. Crane, and V. C. Mastro, “Potential effect of Anoplophora glabripennis (Coleoptera: Cerambycidae) on urban trees in the United States,” *Journal of Economic Entomology*, vol. 94, pp. 116–122, Feb. 2001.

[18] USDA, “Emerald Ash Borer.”

[19] D. A. Herms and D. G. McCullough, “Emerald Ash Borer Invasion of North America: History, Biology, Ecology, Impacts, and Management,” *Annual Review of Entomology*, vol. 59, pp. 13–30, Jan. 2014.

[20] D. J. Crook, A. Khrimian, J. A. Francese, I. Fraser, T. M. Poland, A. J. Sawyer, and V. C. Mastro, “Development of a Host-Based Semiochemical Lure for Trapping Emerald Ash Borer Agrilus planipennis (Coleoptera: Buprestidae),” *Environmental Entomology*, vol. 37, pp. 356–365, Apr. 2008.

[21] “Osprey (Pandion haliaetus) - BirdLife species factsheet,” 2013.

[22] J. Junda, E. Greene, and D. M. Bird, “Proper flight technique for using a small rotary-winged drone aircraft to safely, quickly, and accurately survey raptor nests,” *Journal of Unmanned Vehicle Systems*, vol. 3, pp. 222–236, Sept. 2015.

[23] C. Jes, “Updates from the Field: Lichen it up in the trees,” July 2013.

[24] AoM Team, “How to Become a Professional Tree Climber,” Jan. 2014.

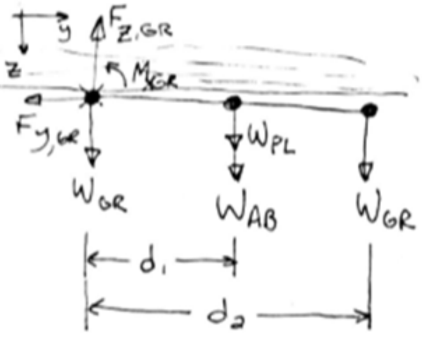
[25] E. T. Read, J. Gostanian, and M. A. Gennert, eds., *Design and Construction of a Tree Climbing Robot.* Worcester, MA: Worcester Polytechnic Institute, 2012.

[26] A. Saunders, D. I. Goldman, R. J. Full, and M. Buehler, “The RiSE climbing robot: body and leg design,” vol. 6230, pp. 623017–623017–13, 2006.

[27] REI, “Lightweight & Ultralight Backpacking Basics.”

[28] ppl, “backpacking - How much should your backpack weigh? - The Great Outdoors Stack Exchange.”

A Free Body Diagrams



$d_2 = 2d_1$

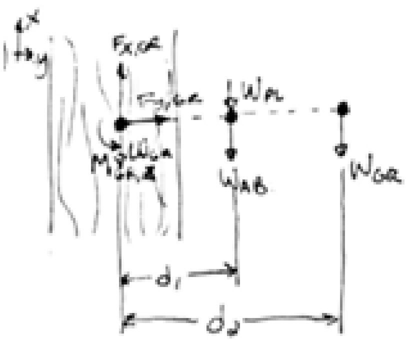
$$\Sigma F_y = 0 = F_{y,GR}$$

$$\Sigma F_z = F_{z,GR} - 2W_{GR} - W_{AB} - W_{PL} = 0$$

$$F_{z,GR} = 2W_{GR} + W_{AB} + W_{PL}$$

$$\Sigma M_o = M_{x,GR} - d_1 \cdot W_{AB} - d_2 \cdot W_{GR} - d_1 W_{PL} = 0$$

$$M_{x,GR} = d_1 (W_{AB} + 2W_{GR} + W_{PL})$$



$d_2 = 2d_1$

$$\Sigma F_x = F_{x,GR} - 2W_{GR} - W_{AB} - W_{GR} = 0$$

$$F_{x,GR} = 2W_{GR} + W_{AB} + W_{GR}$$

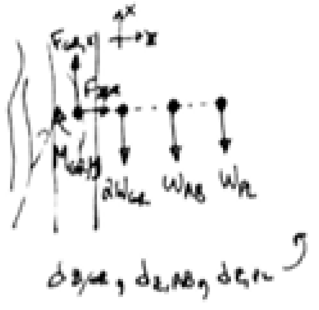
$$\Sigma F_y = 0 = F_{yGR}$$

$$\Sigma M_z = -M_{GR,z} + d_1(W_{PL} + W_{AB}) + d_2 W_{GR} = 0$$

$$M_{GR,z} = d_1(W_{PL} + W_{AB} + 2W_{GR})$$

M

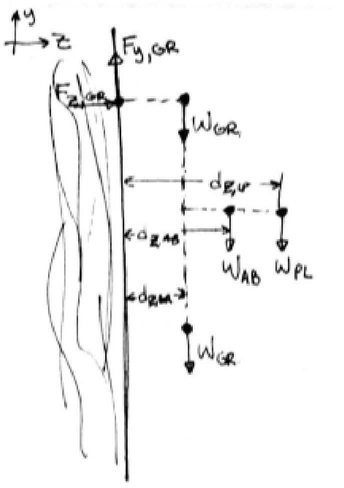
$M_{x,GR}$ IS SAME AS IN CASE #2



$$\Sigma F_z = F_{z,GR} = 0$$

$$\Sigma M_y = -2W_{GR} \cdot d_{z,GR} - W_{AB} \cdot d_{z,AB} - W_{PL} \cdot d_{z,PL} + M_{y,GR} = 0$$

$$M_{y,GR} = 2W_{GR} \cdot d_{z,GR} + W_{AB} d_{z,AB} + W_{PL} \cdot d_{z,PL}$$



$$\Sigma F_z = F_{z,GR} = 0$$

$$\Sigma F_y = F_{y,GR} - (W_{GR} \cdot 2) - W_{AB} - W_{PL} = 0$$

$$F_{y,GR} = 2W_{GR} + W_{AB} + W_{PL}$$

$$\Sigma M_x = M_{x,GR} - 2 \cdot W_{GR} \cdot d_{GR,z} - W_{AB} \cdot d_{AB,z} - W_{PL} \cdot d_{PL,z} = 0$$

$$M_{x,GR} = 2W_{GR} d_{GR,z} + W_{AB} d_{AB,z} + W_{PL} \cdot d_{PL,z}$$

B Glossary of Terms and Acronyms

Acronyms

ALB

Asian Longhorned Beetle. 3, 4

AMP

Arboreal Mobility Platform. 4, 6, 15, 17

CHAMP

Compliant Hook Arboreal Mobility Platform. viii, 15–17, 39, 40

DOF

Degree of Freedom. 20

EAB

Emerald Ash Borer. 4

MQP

Major Qualifying Project. 7

UAV

Unmanned Aerial Vehicle. 6

WPI

Worcester Polytechnic Institute. 7, 15, 39

C Design Matrix

Estimated Design Parameter	*x*	***Max***	Compliant Hook				Crab Bot				Snake Machine				Fan + Wheels				ES Adhesion				Coffee Ground			
			D	R	M	Σ $(D+R+M)\times x$	D	R	M	Σ	D	R	M	Σ	D	R	M	Σ	D	R	M	Σ	D	R	M	Σ
Tree Types (more is better)	*7*	*5*	5	5	4	98	5	4	3	84	5	5	5	105	5	4	5	98	5	3	5	91	5	2	2	63
Climbable Tree Radius (range)	*5*	*5*	3	5	5	65	5	4	3	60	2	3	2	49	5	3	3	77	5	5	5	105	5	5	5	105
Payload Capacity (more is better)	*9*	*5*	3	5	5	117	3	5	3	99	5	4	5	98	2	3	3	56	2	3	3	56	5	3	4	84
Payload Simplicity (more is better)	*9*	*5*	5	4	5	126	5	5	5	135	1	2	1	28	4	5	5	98	5	5	4	98	5	5	4	98
Mechanically Durable (more is better)	*4*	*5*	3	4	3	40	2	5	3	40	3	4	4	77	3	3	5	77	1	1	4	42	1	1	2	28
Mechanically Robust (more is better)	*4*	*5*	4	5	4	52	2	5	2	36	1	3	3	49	3	3	2	56	1	1	3	35	1	1	2	28
Overall Simplicity (more is better)	*5*	*5*	3	3	2	40	3	4	2	45	1	1	3	35	4	4	4	84	1	1	3	35	1	1	3	35
Overall Weight (less is better)	*8*	*5*	4	4	4	96	2	3	2	56	2	2	2	42	4	4	4	84	1	3	4	56	1	1	2	28
Speed (faster is better)	*3*	*5*	2	2	2	18	2	2	2	18	4	5	4	91	5	5	5	105	1	2	3	42	3	2	2	49
Branches (higher ability is better)	*9*	*5*	3	5	4	108	2	2	2	54	4	2	3	63	1	1	2	28	1	4	4	63	3	4	4	77
More than Just Trees/Poles	*2*	*5*	5	5	5	30	1	1	2	8	1	1	1	21	5	5	4	98	5	4	5	98	2	4	4	70
Project Cost (cheaper is better)	*6*	*5*	3	5	4	72	3	5	3	66	2	3	3	56	4	5	4	91	1	1	2	28	1	1	3	35
Passive, On-Tree Stabilty	*9*	*5*	5	5	5	135	1	3	3	63	1	1	3	35	1	1	1	21	1	1	1	21	1	1	1	21
Power Consumption (less is better)	*8*	*5*	3	5	5	104	2	3	4	72	2	3	4	63	1	1	1	21	1	1	2	28	1	2	2	35
	Final Scores:					1101				836				812				994				798				756