The Thesis Committee for Patrick Wayne Pace
Certifies that this is the approved version of the following thesis:

Development of a Design Methodology and Application to Advance the Field of Highly Mobile Robotics

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________
Kristin L. Wood

____
John J. Wood

Development of a Design Methodology and Application to Advance the Field of Highly Mobile Robotics

by

Patrick Wayne Pace, BSME

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Abstract

Development of a Design Methodology and Application to Advance the Field of Highly Mobile Robotics

Patrick Wayne Pace, M.S.E.
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Supervisor: Kristin L. Wood

Developing innovative ideas as part of engineering design can be limited by the field of technology and the engineer's or design team's understanding of the field. Without sufficient understanding of an emerging technical field, ideation may be hampered by reinventing the proverbial wheel or by a lack of knowledge of the underlying physical principles and state of technology. The research presented here seeks to develop a tool and methodology intended to strengthen a designer's or design team's understanding of a field and relevant technologies in order to foster creative and innovative solutions. The presented inductive methodology consists of conducting a thorough review of existing relevant developing or commercially available technologies in order to obtain characteristic property data to be used as a basis of understanding. Analysis of the plotted data may lead to understanding existing trends, identifying voids

where opportunities exist to expand the design space and general insights into the field. The effectiveness of using empirical data to look for innovation is investigated in the domain of highly mobile robots. Senior cadets from USAFA and UT Austin perform concept generation sessions before and after utilizing the proposed methodology to validate the effectiveness of the approach. The study at UT Austin validates the proposed methodology by measuring the quantity, quality, and novelty of the concepts generated before and after exposure to the methodology. These experiments demonstrate that state-of-technology design tools provide an effective foundation and platform for designers to generate a larger quantity of concepts.

To further investigate the effectiveness of the proposed methodology, it is used to develop a device within the field of highly mobile robotics. There exist applications of highly mobile robots which require innovative solutions with regard to overcoming obstacles, payload capacity, energy storage and minimizing power requirements. The methodology allows for the development of innovative concepts, and the embodiment and manufacture of a particular solution. The mechanical design solutions to multiple design challenges are presented, and the prototyped device proves capable of expanding the existing design space in terms of its performance with respect to the metrics mentioned above.

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INTRODUCTION

Chapter 1: Introduction

MOTIVATION

The modern designer's dilemma at this point in history is that there is virtually an incomprehensible abundance of manufactured products to accomplish virtually all humanly desired functions that are currently achievable with the state of scientific understanding, or within economic reach; though grand challenges still exist in the realms of healthcare, energy production and consumption, and sustainability [1]. This means one is unlikely to discover a common need, such as opening a can or means to boiling water, that an existing product does not already fulfill. The same can be said in the scientific world. The macro and microscopic observable world has been carefully studied for centuries, and theories that allow for practical understanding have held true and led to incredible advancements in society. From travel, communication, computing, and medical science, most "low hanging fruit" has been explored and refined Regardless, designers are faced with the challenge to make products bigger, smaller, better; to provide products at lower costs but provide more functionality, be it a portable phone or cancer screening device. This leaves a designer upon a road where making forward progress requires creativity, invention, and innovation

This reality of contemporary design leads to the increasing importance of creativity, invention, and innovation for new products if they are to be unique and successful. It is desirable for a designer to possess these creative skills, and for companies to encourage creative environments. Much work has previously been explored attempting to understand creativity and innovation, from a cognitive perspective to common methods such as Osborn's brainstorming [2], in order to create a systematic approach to being creative and innovative. It is imperative to continue the work of understanding what drives creativity, invention, and innovation, as well as methods that might develop these traits in designers or enhance the innate capabilities of designers so that they may succeed and continue to provide satisfying products in the increasingly complex world.

One such technological field that is well explored yet retains the opportunity for expansion should the appropriate innovation be discovered, is the field of highly mobile robotics. This field includes devices meant to negotiate rough terrain or work in hazardous or dangerous conditions. Devices might be intended for tasks ranging from intelligence, reconnaissance, and surveillance (ISR) and perimeter monitoring or security patrols [3] to aiding rescue, inspection, and cleanup of hazardous sites such as the collapsed World Trade Center collapse following the foreign terrorist attack in New York City [4] or collapsed mine sites such as witnessed in Chile in 2010 [5].

This field represents a prime proving ground for methods to enhance creativity and innovation. Expansion of the field could easily make significant impacts on everything from human safety, disaster assessment and relief, search and rescue, more advanced and effective devices for the military, to both terrestrial and extraterrestrial exploration. The field has applications in exploring manmade and naturally dangerous areas, allowing for the removal of personnel from dangerous situations including building collapses [4], the presence of hazardous materials [6], war torn regions, or, notably for 2010, disasters in underground mines [5]. Other applications may even include running subterranean piping and cabling, to spelunking or exploration of extraterrestrial bodies such as planets, moons, or asteroids. For these reasons, a proposed concept generation methodology is applied to this field in order to evaluate its usefulness in finding new innovative solutions in a well developed area in an attempt to uncover unexplored opportunities and expand the field to significantly affect the said application domains.

RESEARCH PROBLEMS ADDRESSED

This work seeks to first develop a methodology that may be used in conjunction with existing concept generation methods to enhance the overall creativity, inventiveness, and innovation skills of a designer in order to increase the likelihood that their work will be successful; with particular awareness of the existing literature and an understanding of the state-of-the-art of the given technological field. Additionally, the methodology seeks to advance a technological field in order to aid the evaluation of the methodology.

Challenges lie in collecting information about a given technical field, as well as analyzing and condensing the data into a design methodology that is meaningful and helpful to a designer. Additional challenges lie in both disseminating the methodology effectively that a designer will desire to use it, and in determining the most appropriate and accurate assessment of the proposed design methodology in order to measure its impact on the designer or its potential benefit.

In applying a proposed concept generation methodology to highly mobile robotics, there are challenges in expanding an already developed field. Should an innovation be discovered, there are also challenges in applying the potential innovations and embodying them for practical and meaningful use, i.e., creating a physical design that is feasible and practical to develop and useful for deployment. To aid this process, many design aids (new or existing) are implemented in order to increase the likelihood of success of an embodied innovation. Specifically, the functions desired to innovate upon within the field of highly mobile robots are increasing obstacle capabilities while maintaining or increasing payload capacity and providing maximum mission deployment times. Whether traversing wooded areas or collapsed buildings, a suitable device must possess an ability to surmount or otherwise negotiate obstacles such as ledges and crevices, whether they be formed from crumbled concrete or ditches created from running water. Also, carrying additional payload may provide relief to victims instead of simply providing location information. Increased deployment time (requiring energy storage and usage innovation) might increase the effectiveness and likelihood of success of a given mission.

The work presented here will explore the current state of design methodologies intended to enhance creativity and innovation. An empirical based methodology is developed to further enhance creativity and innovation and then evaluated to determine effects on the said traits. Evaluation of the methodology is performed with a study exposing participants to the methodology while working on a design problem related to highly mobile robotics. Finally, the research team uses the proposed methodology to both test its effectiveness and aid the design and manufacture of a new highly mobile robot in an effort to expand the field and design space.

THESIS ORGANIZATION

Chapter 2: Literature Review

Chapter two explores prior work in the area of cognitive psychology research exploring what enables individuals to be creative, inventive, and innovative, as well as research developing and evaluating methods to enhance such traits, namely, concept generation methods. Much work has focused on understanding the thought process in order to benefit the designer, such as the work to understand causes and solutions to design fixation. Exploring this work gives direction to the current research and motivation to help develop and further the field.

Applying concept generation methods to real world design problems is one method to test the effectiveness of developed methods, so the developed and proposed design methodology is applied to the field of highly mobile robots. There is a current need to improve the obstacle negotiating capability along with the controllability of such devices in order to progress their effectiveness. Devices that currently define the existing design space are reviewed below.

Chapter 3: Development of a Supplementary Design Methodology

It is hypothesized that a thorough and visual evaluation of the current state of technology would greatly aid a designer in his or her efforts to generate effective solutions and expand the current boundaries of the design space. The development of an empirical method to build a repository of performance data and its proposed use in concept generation methods are detailed.

Chapter 4: Validation of Design Methodology

The evaluation of the proposed methodology is documented in Chapter 4. The methodology is presented to two groups of participants, i.e., graduate-level engineering students, working on the same highly mobile robotics design problem; one group is selected from the United States Air Force Academy (USAFA), and the other group from The University of Texas at Austin (UT Austin). The influence the methodology has on the two groups of designers is evaluated and discussed.

Chapter 5: Mechanical Design of a Highly Mobile Robot, Application of Proposed Design Methodology

To further evaluate the effectiveness of the methodology, it is used to as a design aide in the design of a highly mobile robot. The insights and influence the methodology had on the design process is documented. The mechanical design of the device is likewise documented in detail, including design for manufacturing, design challenges, and engineering design tools applied or developed to assist solving specific challenges.

Chapter 6: Prototyping and Testing

This chapter includes highlights of the prototyping process, and the formal testing procedures followed to systematically evaluate the overall performance of the design. The device performance is evaluated against the original performance goals as well as the metrics presented with the design problem in Chapter 3 and 4 to compare the new device performance against the previous state of technology.

Chapter 7: Research Summary, Conclusions and Future work

Summaries of the successes, surprises, and future direction are included here. The design methodology proves to be a viable and beneficial process. A discussion summarizes the researcher's perspective on the results and beneficial future work. The subsequent discussion focuses on the capabilities of the developed highly mobile robot. This robot demonstrates performance that expands the previous design space in a manner that is expected to benefit the field as well as direct and distant analogous fields. Future work and improvements to the robotic system are presented.

Chapter 2: Literature Review

INTRODUCTION

Much previous work has been performed and documented in areas that the current efforts encompass. The current work seeks to build upon existing research of design methodologies, innovation, concept generation as well as the validation of ideation techniques. A large portion of the current work also depends on studying existing physical solutions relevant to highly mobile robotics. A review of these physical devices and systems serves to build a repository of knowledge that may lead to innovation in future designs and are discussed below.

DESIGN METHODS

Much research has investigated innovation and creative thinking, including research ranging from the psychological level to empirical studies evaluating ideation activities meant to increase the quantity of ideas, innovation, and creativity. Psychology has sought to learn how creative thinking occurs, including memory storage, recollection, and overcoming impasses (fixation) when problem solving [7-14]. Gentner develops a structure-mapping theory to understand and define analogies. She defines analogy as "characterized by the mapping of relations between objects, rather than attributes of objects…" Also, particular relations are often governed by "higher-order relations" that depend on syntactic properties of knowledge representation, and not on the content of the domain [15]. The work is continued by Gentner and Markman showing comparison processes lead to insight, highlight commonalities, and relevant differences while inviting new inferences and promoting new ways of interpreting situations [16]. Moss et al. investigates the role open goals have on problem solving with respect to acquiring information. He defines an open goal as "…a goal that has been set but for which the associated task has not been completed." He suggests, referencing other work, that unsolved problems are recalled better than solved problems. Important findings from the study of open goals include more information is gathered on unsolved problems, even if the information is noticed unconsciously. They propose this knowledge should make opportunistic tasks, such as setting up subgoals to a larger overall goal, observable and explainable. Open goals may be behind insights people obtain during the incubation period, leading to creative and innovative ideas [17]. Schunn investigates the correlation between lower level cognitive processes and higher level reasoning. Notably, he finds that experience with one problem may assist solving a different problem without the subject realizing one problem helped with another; proving the hypothesis that "even when subjects do not spontaneously make an analogy between two domains, knowledge of one domain can still spontaneously make an analogy between two domains" [18]. Michelene et al. study not how to increase knowledge or recollection, but how the structure and networking of knowledge is utilized in recalling information, in a continued search to understand human knowledge. Their work is performed by studying the patterns of children's knowledge of forty dinosaurs [9]. Michelene et al. also document findings that support the hypothesis that experts tend to understand fundamental ideas, and derive second level equations while novices rely on known particular solutions, instead of the underlying principals. Their work is performed by examining the manner in which experts and novices solve physics problems [8].

Techniques to foster creativity have long been researched. One of the most popular methods is Osborn's brainstorming [2] though hundreds now exist [19], and existing research examines supplementing the ideation process seeking creativity using analogies or newer methods such as examining transformation principals in order to achieve greater innovation [15], [16], [18], [20-40]. These mentioned studies cover important topics and are shown to assist designers in achieving improved innovation. One large portion of efforts to increase innovation includes the studying of the impact on problem representation. McKoy et al. study the effect of representation, and among other results, demonstrate the evidence that pictorial representations have a much better effect on spawning creative ideas over textual representations [41]. Jensen et al. formally present and evaluate a combined suite of ideation methods, including 6-3-5, morphological analysis, transformational design, mind mapping, design by analogy, word trees, far field analogies, historical innovators, and TIPS [42], presenting the results of each method and combination of methods on the ideation process. Transformation principles and how they might be applied in ideation in order to increase innovation is also documented and explored by Singh et al. [43]. A virtually complete set of transformation principals and facilitators are identified and methods to implement them into ideation are explored. Other approaches, such as compiling data into a design repository have also been explored, based on the idea that if empirical data is gathered, it might serve to guide designers in necessary or innovative directions since present capabilities and limitations may be identified and linked to particular solutions [44].

One particular approach to increasing creative ideation is the use of analogies, both explored psychologically (as discussed above) and within the realm of the design process as explained here. Much work seeks to understand analogies and to define and measure the similarity between objects and analogous entities. It is found that both near and far field analogies play important roles in the design process, but that far field analogies may lead to more novel and creative solutions [21], [22], [25], [45]. The application of analogies have even been explored and implemented into autonomous design software. Goel et al. uses it to explore the role analogies might play in architectural software, computationally arriving at solutions through using analogies [30]. Linsey et al. study the different roles metaphors and analogies play in design. They find metaphors more often serve to understand design problems, while analogies are beneficial in actual concept generation processes. Another notable finding is that the use of analogy is very universal, discovered through observing nearly identical experimental results worldwide [29]. Linsey et al. also develop and present a "wordtree design-by-analogy" methodology to capitalize on the use of analogies. They promote first re-representing the problem, then searching for analogies, especially in analogous domains, which serves to dramatically increase the solution space to a design problem. For example, folding towels, or storing soft material might seek a solution through an analogous domain of dousing a ship's sail, a seemingly obscure analogy that actually lead to creative solutions [20]. One important finding is how exploring near field analogies early in the design process can be hindering as it may lead toward fixation, despite the commonality of the practice- better known as benchmarking [34]. Many researchers also promote seeking solutions through analogous biological systems; the concept being that many designs found in nature have had many millions of years to evolve and become rather efficient at their functions. One prime example is typical bone structure, comprising of strong material around the perimeter where stresses are high, but having lower density inner portions (the bone marrow) where high strength is not required [26-28], [35], [40].

One hindrance to innovation is when a designer becomes fixated or reaches an impasse. Thus, it is beneficial to study fixation so that it may be understood as well as avoided. Jannson and Smith repeatedly demonstrate the existence of design fixation, showing that designers who are given sketches of design solutions become fixated on those solutions [46]. Linsey et al. continues the study of fixation and its mitigation [47]. Kaplon and Simon determine that a change of representation of the problem is important to avoid fixation. They also show that it takes few constraints to narrow the range of solutions from hundreds of thousands [12]. Ohlsson also demonstrates that reframing and relaxing constraints of a design problem allow for the breaking of impasses, while seeking to determine why fully competent designers often encounter such impasses, unable to solve solutions that have solutions within reach [13], [14].

Concept Generation Validation

Testing proposed or existing studies requires a standardized and commonly utilized metric system to measure the results of the proposed design methodology or ideation method. Such metrics have been proposed by Shah et al. [48], [49]. Due to a suggested large amount of anecdotal evidence that ideation methods serve useful purposes, Shah et al. experimentally evaluate the effectiveness of the methods for various design problems [48]. The authors continue research and develop four objective ideation effectiveness measures to determine the value of concept generation methods. Proposed metrics include novelty, variety, quality, and quantity. They propose novelty may be determined by counting the total quantity of ways a particular attribute may be satisfied, and by counting the number of instances a concept generation session finds the particular method. Then, the ratio of a particular solution to the total number of solutions determines the novelty; the lower the number of occurrences, the higher the novelty of the particular method. Variety indicates how well the design space has been explored, thus, quantifying the variety is beneficial. It is completed by collecting similar ideas into groups, and then observing the total number of groups resulting from a concept generation method. Since the goal of product development is to obtain a marketable, profitable product, the quality of the ideas are of interest. Conceptual quality is typically able to be inferred from the rater even if it's not analytically obtainable [49], [50]. Quantity of conceptual ideas also has been previously linked to the success of a product, and would also tend to indirectly measure the extent of the design space explored [51]. Justification for the quantity metrics can also measure an individual's creativity and increase the occurrence of better ideas [2], [52-57].

Highly mobile robots

For reasons discussed in Chapters 1, 3, and 4, existing mobile robots and devices are examined, documented and researched. The primary motivation is to build a repository to utilize in a manner that may increase innovation. A thorough search attempts to find all possible persons and efforts involved in the specific technical field and its respective applications; exemplar devices and research efforts are documented and references to additional literature are presented in this chapter. For succinctness in presentation, current research in the arena of mobile robots and devices is grouped into categories of jumping, tracks, segments, wheels, legged, whegged, airborne, and other.

Jumpers

One solution to overcoming obstacles is to "jump" over them. Allowing a device to jump may be accomplished through striking the ground, pushing on the ground analogous to a frog, or by rapidly changing linear or angular momentum. Designs primarily utilize springs [58-66] and pneumatic systems [66-69], or specialty applications of pneumatics such as combustion [70]. Some of the devices are driven more by a minimalistic goal, and may serve "swarm" robotic needs quite well, but can be limited in payload capacity or simple locomotion, such as the work of Burdick et al. [64]. Their work capitalizes on spreading the work of jumping over a longer period of time, by winding a spring; this allows for a much smaller motor than would be needed to drive the jumping process directly, and dramatically increases the height to mass ratio. Their device is shown in Figure 1. Other research has lead to the developments of a hybrid type device utilizing whegs for locomotion and a bio-inspired flea type leg for clearing obstacles, also in Figure 1 [63]. Pneumatic devices typically have a cylinder and piston, and utilize the piston to strike the ground and send the device airborne over obstacles, as pictured in Figure 2 [67], though other configurations exist.

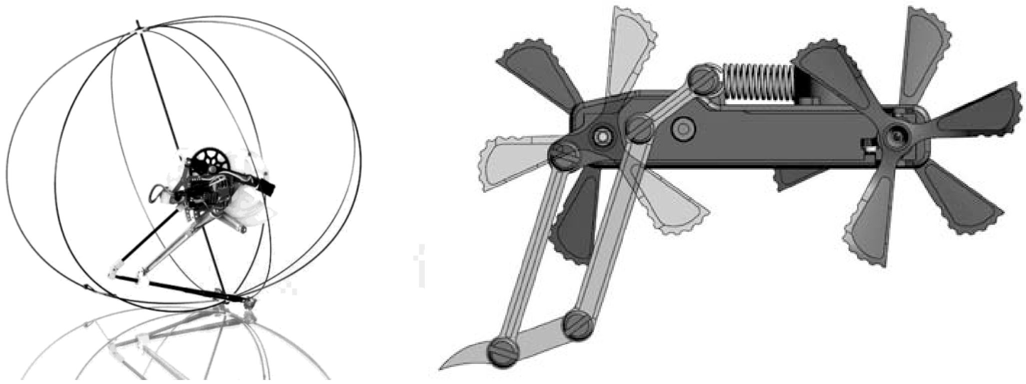


Figure 1 – Minimalistic approach to jumping devices (left) [64], flea type device (right) [71]

Figure 2 – Piston striking pneumatic design [67]

Segmented

The segmented group incorporates snake type devices and devices with multiple segments, linkages, or arms that may be manipulated in order to overcome obstacles, which have been developed by many different research groups and commercial establishments [3], [72-82]. Snake devices have the advantage of a small cross section, as to fit through small holes, but lengths that may enable overcoming ledges, or climbing onto ledges or up trees and poles. Often, they lack payload capacity and can be difficult to maneuver precisely in non-controlled environments. One exemplar hybrid of technologies, pictured in Figure 3, highlights the capability of segmented devices to capitalize on multiple technologies. The omnitread design allows for simplified locomotion through the utilization of tracks, allows for payload and energy storage with the compartments in each segment, and the segments allow for overcoming obstacles [76], [77].

Figure 3 – Omnitread design [76], [77]

Other designs in the segmented category utilize linkages to create multiple segments which can be manipulated for obstacle negotiation, as pictured in Figure 4.

Figure 4 – Segmented designs using linkages (left) [74] and “flipper” arms (right) [83]

Tracks

Devices that solely utilize locomotion for obstacle negotiation also exist, but are typically limited in obstacle performance; these include tracks, wheels, and legs. Despite having restricted obstacle height performance, they can still overcome measureable obstacles. Tracked devices tend to have large payload mass to device mass ratios and benefit from contact along the length of the device serving to reduce the chances of high centering, requiring less ground clearance. Tracked devices that also contain an obstacle negotiating technology are documented in its respective category. Several tracked devices are recorded in the repository [84-86]. An example device utilizing tracks is shown in Figure 5 [86].

Figure 5 – Tracked device [86]

Wheels

Wheeled devices included in the design repository include 2 to 6+ wheeled devices, as well as centimeter scale devices to multi-meter scale devices ranging in weight from ounces to tons [84], [87-89]. Typically wheeled devices are limited to obstacles measuring equal to the radius of the wheel or tire, but some exemplar devices can negotiate taller obstacles, even larger than the diameter of the tire as demonstrated by the “crusher” developed by CMU [87] shown in Figure 6.

Figure 6 – Crusher developed by CMU [87]

On the opposite end of the spectrum, there are small two wheeled cylindrical devices. The “throwbot” is built robustly and intended to be thrown through windows or onto rooftops for ISR. The device is shown in Figure 7 [90]. Larger versions of the two wheeled cylindrical devices with larger diameter wheels allow for increased obstacle capabilities such as the “MegaScout” [89].

Figure 7 – Recon Robotics throwbot [90]

Legged

Some legged devices include legs to overcome obstacles, as pictured above in Figure 1, while others utilize legs primarily for locomotion, while still retaining an inherent maximum obstacle height [91-96]. Perhaps an engineering marvel of its time of development is the “Big Dog” device from Boston Dynamics utilizing decades of research on legged devices lead by researcher Martin Buehler. Legged devices are shown in Figure 8.

Figure 8 – Big Dog device hauling cargo (left) [96], Legged device climbing wall [95]

Whegged

Whegged devices were initiated through Case-Western University, and are a hybrid design suitable for rough terrain and have proven performance [92], [97-100]. They have also been commercialized through Boston Dynamics. Devices utilizing whegs are shown below in Figure 9.

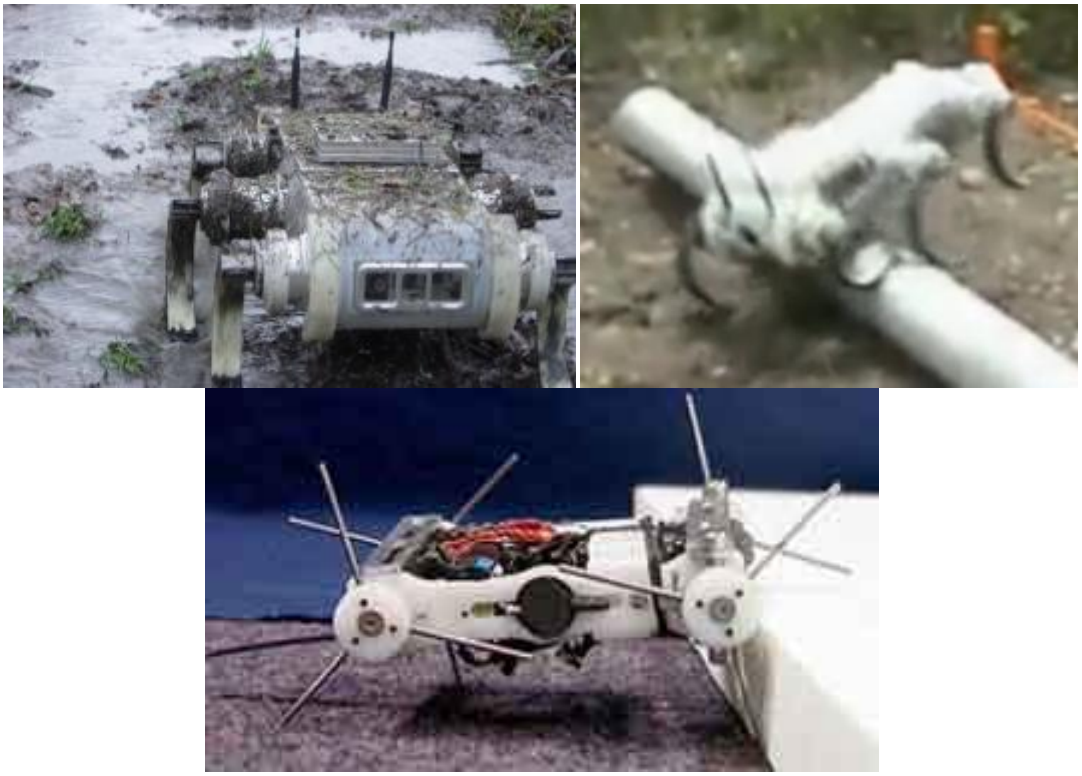


Figure 9 – Whegged devices [97], [101]

Airborne

Airborne devices, including devices that utilize thrust and buoyancy are included in this section, and in the repository and include small to large scale unmanned aerial vehicles and ground based designs that utilize thrust to overcome obstacles [84], [102]. Many of the devices were located through Clapper, in his collection of devices in a presentation to the U.S. Department of Defense [84]. Figure 10 shows two sample airborne systems.

Figure 10 – Airborne unmanned systems [84]

Other

Many other devices utilizing novel concepts exist, typically at much lower quantities and tend to exist in experimental stages. Such devices use pressure differentials, Van der Waal forces, adhesion, or grasping techniques to allow the negotiation of obstacles [95], [103-107]. Work has expanded knowledge on how geckos are able to climb smooth surfaces, such as glass, utilizing the Van der Waal force, and through careful manufacturing, have duplicated fine synthetic fibers effectively duplicating the geckos foot [95], [108]. Other devices simply rely on vacuum forces, or pressure differentials, to generate a normal force and navigate vertical surfaces [106], [107].

DESIGN METHODOLOGY

Chapter 3: Development of a Complementary Design Methodology: Use of Repository for Innovation

INTRODUCTION

Developing innovative ideas as part of engineering design can be limited by the field of technology and the engineer's or design team's understanding of the field. Without sufficient understanding of an emerging technical field, ideation may be hampered by reinventing the proverbial wheel or by a lack of knowledge of the underlying physical principles and state of technology. When starting to solve design problems, designers may not fully benefit from ideation methods alone due to problems such as design fixation [17], [45-47], [109], [110]. Pursuing flawed designs or designs that will underperform existing solutions may likewise occur from the lack of understanding of the field.

Existing research examines supplementing the ideation process as well, such as seeking and using analogies, fostering creativity and examining transformation principals in order to achieve greater innovation [15], [16], [18], [20-40]. These mentioned studies cover important topics and are shown to assist designers with achieving improved innovation.

The research presented here seeks to develop a tool and methodology intended to strengthen a designer's or design team's understanding of a field and relevant technologies in order to foster creative and innovative solutions. A relevant finding in the psychological literature is that individuals who acquire experience with classes of information and procedures tend to represent them in relatively large, holistic "chunks" in memory, organized by deep functional and relational principles [7-9]. Many researchers have argued that this ability to "chunk" underlies expertise and skill acquisition [10], [11]. However, if the task at hand requires the individual to perceive or represent information in novel ways, e.g., to stimulate creative ideation in design, representation of that information in chunks might become a barrier to success, particularly if processing of component parts of the information chunks helps with re-representation [12-14].

To accomplish the goal of this research in the context of these findings, first a thorough search must be performed to collect all possible information in a technical field. Data is consolidated in an electronic spreadsheet programmed to ease data management and provide the ability to efficiently analyze design solutions. Critical metrics for the given application are generated and comparative results are plotted. Analysis of the plotted information may lead to understanding existing trends, identifying voids where opportunities exist to expand the design space, as well as general insights into the field leading to more beneficial concept generation sessions and effective use of concept selection tools. Design fixation is expected to be avoided through presenting designers with a broad spectrum of solutions that encompass the entire design space, to prevent fixation on a particular solution for a particular function.

The effectiveness of the stated design methodology and tool are investigated for the problem domain of developing a mobile cave and tunnel exploration type robot. Senior cadets from the U.S. Air Force Academy (USAFA) perform concept generation sessions before and after utilizing the presented tool to understand the existing technology, where the results are examined to determine the impact and utility of the tool in design and as part of engineering design curricula. A second experiment is also conducted with graduate students from The University of Texas at Austin (UT Austin) to further analyze the effectiveness of the tool on quantity and quality of the concepts generated. These experiments aim to demonstrate that state-of-technology design tools provide an effective foundation and platform for designers to generate a larger quantity of concepts, with higher quality and novelty. There exist significant implications on engineering design education from this process. For example, the systematic mapping of the state-of-the-art in a field is an important learning objective and skill to be nurtured in our engineering students as they explore and solve design problems.

Background

As discussed in Chapter 2, techniques to foster creativity have long been researched. One of the most popular methods is Osborn's brainstorming [2] though hundreds now exist [19]. Another pioneering technique is Brainsketching, attributed to Rohrbach [111]. Both these techniques aim to aid individuals or groups to generate the largest quantity of ideas so that solutions may be pulled from as large a solution space as possible, which is crucial to the designer as the quantity of initial solutions to a problem is correlated to the success of a product [51]. In addition to the fundamental ideation methods, much study has been focused on how to properly administer and supplement ideation. One large area of research is the use of analogies to increase innovation [20], [41], [42]. Analogies allow connections to be drawn that are otherwise much harder to generate, thus, understanding the psychology behind how persons conceive analogous solutions is beneficial. More specific approaches to supplementing ideation have been examined as well, such as utilizing transformational design principals to increase innovation [43]. The research at hand seeks to understand the influence of a thorough examination of a particular product field on the ideation process. Namely, understanding where current technologies perform, in general and relative to each other, as well as identifying insights, gaps in technologies, and current technological limitations allows designers to see opportunity for new combinations of existing solutions, new applications, or otherwise positively affect ideation.

DEVELOPMENT OF DESIGN TOOL AND METHODOLOGY

Application to Highly Mobile Robotics

In order to test the proposed methodology of systematically collecting and reviewing existing technology in a field, the proposed methodology is applied to solving a robotic design problem. Among the many uses of robotic systems, there is an increasing demand for them to both increase accessibility as well as remove humans from hazardous or toxic environments or situations. Often applications require robotic systems to possess high traversing mobility. Such applications include search and rescue robots for manmade and natural disasters, ISR, and exploration (terrestrial or extraterrestrial). These environments provide for challenging mechanical designs for the robotic systems, often with conflicting objectives. Low mass is desirable for portability as well as lower energy consumption, thus lower energy storage requirements which is often a limiting factor. Size may also influence portability, where smaller is desirable but may negatively affect the maximum obstacle size a robot can surmount. This application is thought to serve as a practical, interesting and challenging area, ripe with opportunity for innovation, making it an ideal test bed for the methodology validation. A summary of the derived performance requirements for such applications follows, which sets the goals for participants to try to meet during the validation process documented in chapter 4.

Design Problem

The specific design problem presented to the student participants from each institution. The problem deals with the design of a robot to explore an underground cavity such as a cave or tunnel. The access to the cavity will be through a bore hole 8 inches in diameter. Once in the tunnel, the robot must traverse up to 450 yards along the tunnel, be able to negotiate rubble, rocks, water and mud. Expectedly, the most challenging requirement is for the device to negotiate a two foot shear ledge as well as traverse across a two foot crevice. The robot should also be able to return to the point of insertion for retraction to the surface. Additional requirements include a payload carrying capacity volume of 4in x 4in x 5in, use a minimum amount of energy and have a low mass to aid portability and energy consumption.

Empirical Study and Search Techniques

The proposed methodology requires the collection of data for a particular field best accomplished through an empirical study of the field. A summary of the research methodology is shown in Figure 11. Advantages of studying the current state of robotics include minimizing the duplication of previously established technology and identifying gaps in current technology that is yet to be explored. The study of exploration type robotic systems begins by obtaining data from multiple sources including databases of professional societies such as ASME and IEEE and their respective journals and conferences, other scientific journals or journal hosts such as Elsevier, as well as robot manufacturers. Additionally, contacting research organizations seeking initial or additional data helps expand the knowledgebase. Querying the sources to obtain relevant results was done by searching the following categories and keywords: robots and robotic systems relating to ISR, search and rescue, defense applications such as room clearing and perimeter monitoring, obstacle capability and avoidance, climbing, stair climbing, jumping, hopping, and mobility. Interchanging the keywords allows for a larger quantity of search results. For example, results are increased by searching each database for "hopping OR robot", "hopping robot" and similar searches and combinations for the remaining keywords: climbing, jumping, search and rescue, etc. Typically, the first 100-200 hits are scanned manually for relevance to the problem, and the relevant articles saved for review. Due to obtaining a large amount of information, it became necessary to systematically record the gathered information in a useful means, which lead to the development of an electronic repository.

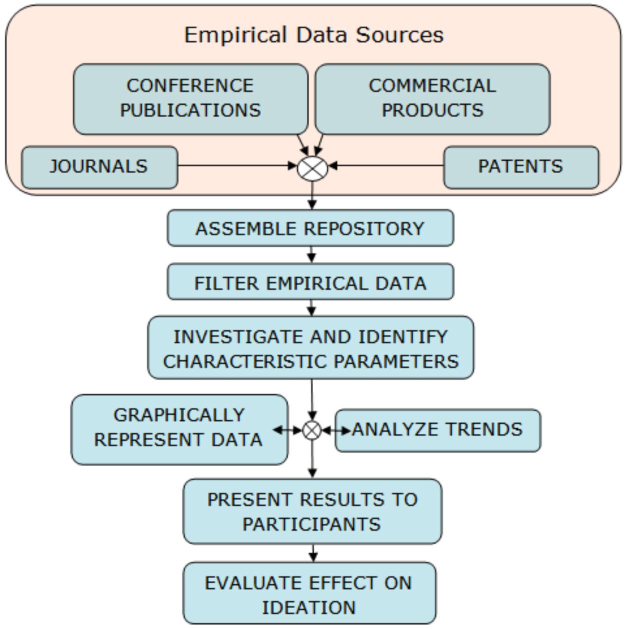


Figure 11 – Research methodology process

Repository Creation

From the results, a software based repository of information is built which aides in the analysis of the information [44], [112], [113]. The repository includes robot performance specifications, the enabling mobility technology, and people and places involved with the work as well as dates. Additions to the repository continue with the discovery of new information or when researchers or developers release new information.

Contents

On reviewing the field, the repository holds data from approximately 75 robotic platforms and consists of the data mentioned above as well as ten raw performance metrics for each device (where available) as well and another twenty derived metrics useful for comparison. The existing design space explored results in a collection of robots spanning one legged hopping robots to six wheeled all terrain systems, as well as combustion powered jumping to using momentum to assist climbing. The repository includes a number of plots as they allow for the visual comparison of particular metrics in order to assess the data and gain insights into the field, and will be discussed below. After the creation of several plots, it became clear that organizing the data into two main categories is beneficial: the locomotive technology and obstacle negotiating technology. Allowing for the separation of this information suits the review of metrics that are linked more directly to one metric over the other. For example, desiring to review energy consumption while traversing would apply to the locomotive technology while one would conversely be concerned with the particular obstacle negotiating technology to review how high an obstacle robotic system's technology can surmount. These two main categories consist of 6 and 16 various technology subcategories, respectively, listed in Table 1.

Pictures of representative devices in each category are shown in Chapter 2 and "Appendix C: Photographs of Representative Technologies" to help visualize the type of systems comprising each group and to understand particular technology groups. For example, a wheg may be unfamiliar to most and can best be described as a rotating leg but easier to understand visually. Firstly, it is necessary to note that in some instances, the locomotive technology doubles as the obstacle negotiating technology. This is because most locomotive technologies have an inherent ability to surmount obstacles up to a limit. In the case for wheels, the typical limit would be the radius, for legs or for whegs it may be one half to twice the height of the leg or wheg, for example. The locomotive technologies are the technology a system utilizes for traversing and are self explanatory. Tracked robots are those that use a tread system, similar to a tank, the snake subcategory is for systems that mimic snakes in appearance and motion, VTOL represents vertical takeoff and landing systems (such as a helicopter), thrust devices utilize thrust for locomotion and/or obstacle negotiation, buoyant systems separate systems that are buoyant in air. Systems that have portions that expand, such as a telescoping portion, are categorized together; segmented systems have multiple segments, which may rotate, but if they are able to separate further or closer to each other it would be labeled an expanding technology. Springs and pneumatics systems use a spring and/or a spring with linkages or a pneumatic system as an energy system to surmount obstacles. The grasp category is for technologies that can grasp in order to assist surmounting obstacles, whether by grappling, hooking, or grabbing similar to a human hand. The adhesion category houses systems that adhere to a surface to surmount obstacles; similarly vacuum systems use suction. Van der Waals systems use the said force in order to overcome obstacles, such as natural or synthetic materials mimicking gecko's feet.

Table 1 - List of technologies captured in repository

Locomotive Technologies	**Obstacle Negotiation Technologies**
Wheel	Wheel
Wheg	Wheg
Leg	Leg
Track	Track
Snake	Snake
Thrust	VTOL
	Thrust
	Buoyancy
	Expand
	Segment
	Spring
	Pneumatic
	Grasp
	Adhesion
	Van der Waals
	Vacuum

Metrics

As mentioned above, the repository holds approximately ten metrics representing raw collected data as well as twenty representing derived values based on raw data, such as the cross sectional diagonal length or power to weight ratios. The majority of the listed metrics relate strongly to the counter tunnel robotics scenario, however, to broaden the applicability of the research as well as for potential future use, commonly reported data is also collected, such as the maximum speed of the robots which is not critical for the research on hand. Not all data sources provide information for all 10 raw metrics, but all available information is recorded when reviewing a particular robotic system. Recording the mobility metrics is critical in order to later compare the relative performance of the technologies and a list of the metrics collected and derived is shown in Table 2.

One approach to increase insights while comparing metrics is to normalize the metrics. For the given research problem, simply having a high payload capacity, large obstacle height capability or low power requirements is not sufficient to guarantee an acceptable level of performance. For example, even if a particular design overcomes tall obstacles, it is not of use given the specific requirements unless it also has a small cross sectional diagonal. Again, the ability to carry a large payload mass may not be useful if the system itself has a very large mass. Therefore, the goal is to seek systems or technologies that perform *relatively* well as a ratio of their metrics, such as a high obstacle height to cross sectional diagonal ratio. Though utilizing normalized metrics is a sound idea, due to holes in the collected data from unavailable information, plotting normalized metrics against one another may reduce the information on the charts as well as making interpretation of the information ambiguous and difficult to understand. Working around the lack of plots utilizing normalized metrics is accomplished by examining additional plots that would have otherwise been condensed to a single plot. For example, only one chart is required to analyze mass normalized payload versus size normalized obstacle height, but four may be required with standard metrics including mass versus payload, mass versus obstacle height, payload versus size and payload versus obstacle size.

Table 2 - Recorded performance metrics

Performance Metric	Definition
Locomotion Technology	Key technology allowing robot to traverse horizontally
Obstacle Navigation Technology	Key technology allowing robot to traverse vertically
Year	Year the robot was published / made available
Obstacle Height, m	The maximum height of a vertical object a robot can traverse
Speed, m/s	Maximum locomotive speed
Mass, kg	Mass of robot
Payload, kg	Maximum additional mass a robot can carry
Original Dimensions, (various)	Dimensions of the smallest rectangular prism that can enclose the robot
Minimum Cross Sectional Diagonal, m	Length of diagonal across the minimum cross section of the enclosing rectangle
Locomotive Power Consumption, W	Power consumed for horizontal motion
Vertical Power Consumption, W	Power consumed for vertical motion

Analysis of Graphical Data Representation and Insights

The creation of plots allows the visualization of the collected data stored in the repository. Plots may compare any of the metrics against one another and may be used to observe limitations and relative performance against various technologies. Studying the plots and performing trend analysis allows for insights to be made about robots and the associated technologies involved such as current limitations, areas in need of improvement, unexplored design space and the reasons behind the limitations or opportunities. They may also indicate the relationship or lack thereof between particular metrics, and identify expected or unexpected trends within metrics or certain technologies relative to another. Ultimately, study of the data, plots, and trend analysis should lead to the insights that may advance the field. Several specific plots lend themselves to the observation of beneficial insights, which are listed in Table 3. A representative plot is shown in Figure 12, the additional features of the plot are discussed below in the graduate student experiment training session section.

Table 3 – Plots and gained insights

Plot	Insights
Obstacle Height Vs. Minimum Diagonal	1. Springs produce high obstacle height to size ratios, but limited to small designs
	2. Pneumatics designs can be independent of robot size, i.e. large and small design can be made to surmount large obstacles
	3. Wheels and tracks have small increases in obstacle height capability with increase in size
	4. Some Segmented designs can be made to have high obstacle height to size ratios
	5. Wheels / Whegs / Tracks require additional or complementary technology to surmount relatively large obstacles
Obstacle Height vs. Mass	1. Thrust, Springs, Pneumatics have high height to mass ratios, i.e. can get a given mass over taller obstacle than other technologies
	2. Segmenting can result in >2x higher obstacle/mass ratios
	3. Legs have low obstacle height to mass ratios
	4. Springs are not currently suitable for larger mass applications
Obstacle Height vs. Vertical Power Consumption	1. Instantaneous power can be reduced by spreading work over time
	2. Thrust based designs have large power requirements
Payload vs. Mass	1. Springs have very low payload capacity - innovation required
	2. Tracked vehicles have large payload capacities
	3. Legged designs have high payload to weight ratios
	4. Trust designs have low payload to weight ratios - innovation required
Locomotive Power vs. Mass	1. Tracks use locomotive energy efficiently
	2. Whegs are highly dependent on design, but can be efficient

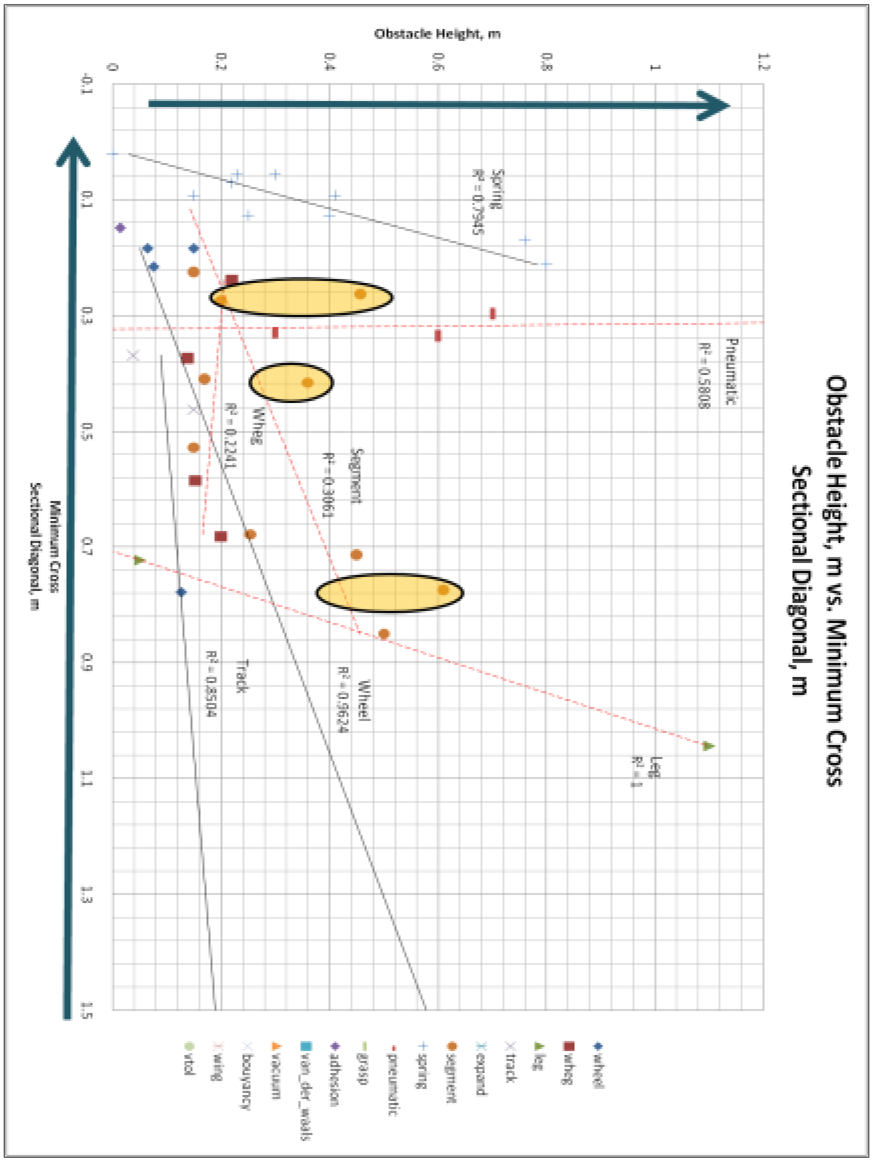


Figure 12 – Representative plot for training sessions

SUMMARY

A need to systematically approach visualizing a technical field is identified, and a method to do so proposed and expected to enhance concept generation and innovation. An electronic repository is programmed to allow technical data to be quickly organized and graphically represented, allowing a channel to gain and apply insights into the field.

The field of highly mobile robotics is used to apply the method, and insights resulting from using the method are discussed.

Chapter 4: Validation of Design Methodology

INTRODUCTION

Three efforts are made to determine the value, effectiveness, and potential for the proposed methodology of studying empirical data in search of insights and innovative ideas. The methodology is presented to two groups of students, graduate mechanical engineering students at UT Austin and senior cadets of USAFA. The effect on ideation is measured after exposing students to the methodology. The methodology is also utilized to design, prototype, and test a new design of a highly mobile robot (Chapter 5), and the performance of the device is compared to existing data to determine the effect on the existing design space (Chapter 6).

GRADUATE STUDENT EXPERIMENT

Hypothesis

The expectation is that when a designer follows the developed methodology in order to understand the relevant technologies, observe the trends and existing design space, and analyze general relative positions of the technologies against critical design metrics, she/he will be able to generate a larger quantity of solutions, be more likely to combine technologies in new ways or otherwise generate novel solutions, and by understanding practical limitations, will generate higher quality solutions.

Participants

The participants for the experiment are master's and doctorate students from UT Austin. All participants have previously been exposed to design engineering concepts either in their course work and/or their research. In particular, most participants will have previous experience with mind mapping and the C-Sketch methods discussed in the background. To encourage participation a light meal is provided during each session and the three one hour sessions are conducted the same evening over three weeks.

Experimental Method

An experiment is conducted to compare the impact on designers who are exposed to the design tool and methodology. A group of twelve designers is assembled and given a design problem to solve over the course of three sessions. The first session collects solutions that participants form without exposure to the design tool and methodology, the second session familiarizes participants with the design tool and methodology and the third session collects the impact the design tool and methodology has made on the group. For the first session, all participants perform a mind mapping session [114] in the same room so that there is a common starting knowledge of potential design solutions. After the mind mapping session, the group is split into two groups to have 6 members each for the 6-3-5 sessions. Participants will meet only with their respective group for the remainder of the experiment. During the next portion of the first session, the individual groups perform an initial C-sketch session [48], [115], [49] intended to serve as the baseline performance expectation. The second session requires thirty minutes and consists of informing the groups of the design methodology to be evaluated and training them in its use. Groups are given a one week break before rejoining for the third session to perform another C-sketch session to capture the impact the design methodology has had on the participants. The performance of the groups will be determined through examining and comparing the results of each group's first C-Sketch results to their final C-Sketch results.

Procedure

First Session – Combined

For the first session all participants meet together for an introduction to the design problem and to perform a mind mapping session. The facilitator describes the design problem to the participants and distributes a figure (Figure 13) to each participant to help solidify the requirements of the design problem. The facilitator leads the group in attempting to find all possible technologies available to solve the design problem through populating the mind map, to broaden the design space participants draw solutions from, or expand upon. To reduce the amount of time the mind mapping session requires, but to allow the participants to ponder solutions, a partially completed mind map will be distributed on a sheet of letter paper (Figure 14). The facilitator will then lead the group and encourage ideas to be added to the mind map; when an idea is suggested by a member, the facilitator will interpret the idea and suggest the location for all participants to write down the idea or solution on their copy. These activities will be completed in the first twenty minutes of the session and are intended to form a common knowledge base for all participants. The group then divides into two individual groups for the first C-Sketch sessions. The group is split by each participant taking a sheet of butcher paper from a back table in the room randomly labeled with either "A" or "B", done to ensure similar group dynamics. Before breaking the assembly into the individual groups, the facilitator reviews the rules for the C-Sketching sessions, which will be identical for both sessions and are: (1) criticism is not allowed, (2) "wild ideas" are welcomed, (3) build off each others' ideas; similar rules to Osborn's brainstorming [19], [2].

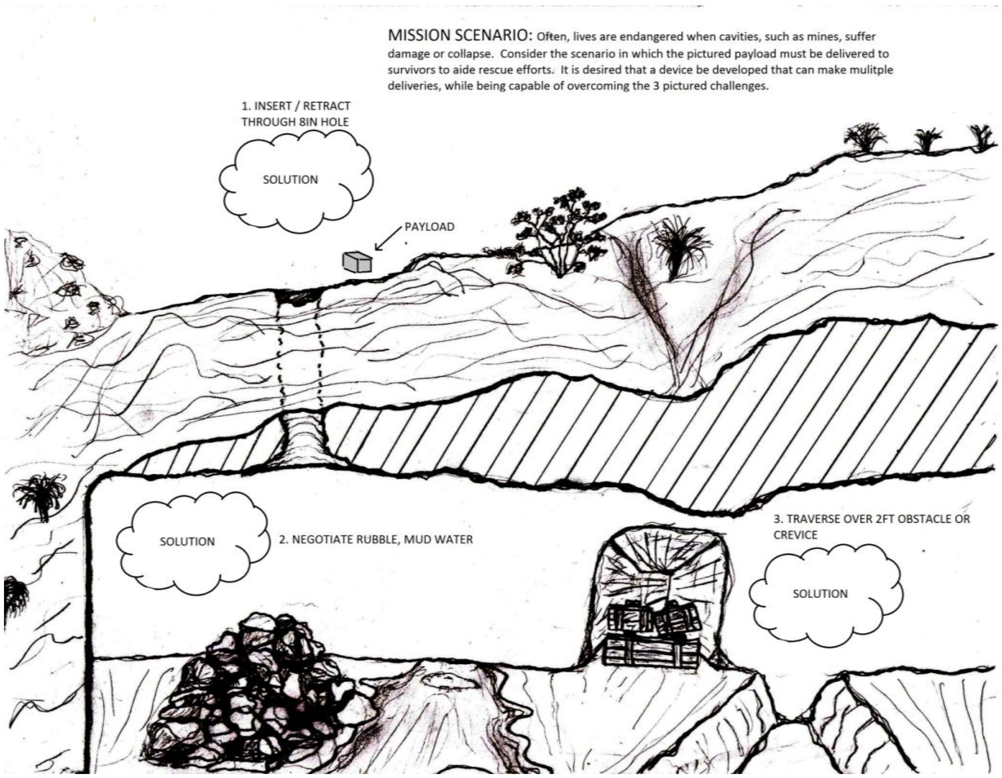


Figure 13 - Figure depicting the design problem

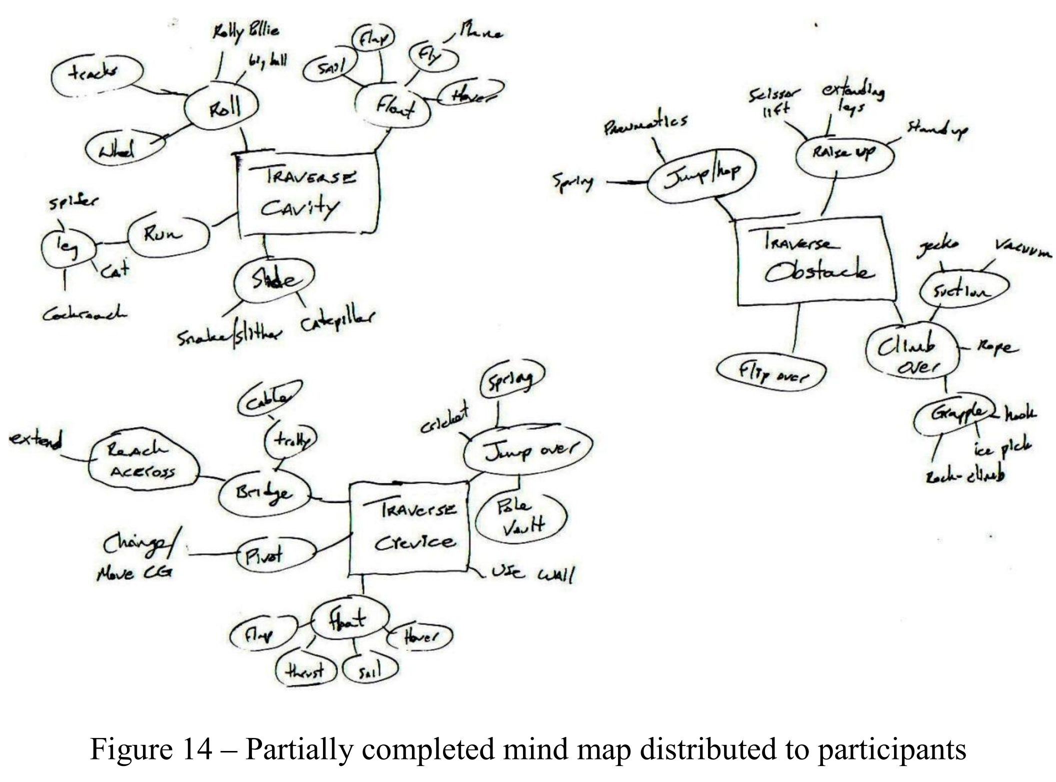


Figure 14 – Partially completed mind map distributed to participants

First Session – C-Sketch

After establishing the two groups, and after they move into different rooms, the first C-Sketch session begins. Short annotations to help clarify a concept will be an allowed variation to the C-Sketch method. To ensure participants understand the level of detail as well as the overall expectation of the session, a printout of a model C-Sketch session is distributed to each participant. Butcher paper is provided as well as flow ink pens for the participants to sketch their ideas. Additionally, each participant has a unique color pen to ease tracking the origin of ideas as well as separating original concepts from addition. The session is run as follows: participants are given 12 minutes total to sketch their three original concepts. The sheets of butch paper are then rotated 5 times, with 6 minutes per rotation for participants to add onto the original concepts. The facilitator collects all the materials at the conclusion of each session.

Second Session – Training

The second session aims to help the participants understand the technological field and equip them with both tools and an approach intended to increase their quantity, novelty, and quality of solutions. The training session is designed to take half an hour to complete and includes four main foci, discussed below in terms of training session and materials.

Training Sessions and Materials

As the methodology consists largely of examining the collected robotic performance information, it is crucial to present the information in a manner that is intuitive to understand as well as accurately represent the relative performance of competing technologies as well as the voids in the design space. Plots were created with several features to ease the interpretation of the information. Trends identified on the plots show where a technology would likely lie across the design space. Trends are shown on the plots as solid lines for R^2 values greater than 0.75, and as red dashed lines for lesser R^2 values in order to indicate their unreliability; however, they are included to indicate a possible trend. Ovals highlight instances where the expected trend was broken. Highlighting the trend breaking technologies is meant to illustrate that novel solutions usually break trends, and are due to new combinations of technologies or redesigns of existing technologies. Lastly, arrows along the axis indicate which direction along the axis represents increasing performance. A representative plot is shown previously in Figure 12. Additionally, including photos of each technology category is meant to help participants visually solidify the nature of each category since the written labels may be difficult to accurately interpret. See Appendix C: Photographs of Representative Technologies.

The first five minutes are used to reiterate the design problem along with encouraging the participants to find innovative solutions, mentioning design conflicts found in the design problem and introducing participants to the proposed design methodology. The emphasis on innovation is to help stimulate original thought among the participants, but is also true of the design problem as no known solution fulfills the requirements of the design problem to an acceptable level. Mentioning key design conflicts is done to help participants seek innovative ideas to solving the conflicts when plots are reviewed. The conflicts include two size conflicts, as well as an energy conflict. The first size conflict is that the robot must surmount vertical obstacles and crevices up to three times higher or wider than the allowable maximum cross section diagonal of the robot. The second size conflict is that when the payload is placed in the bore hole, there is little room for supporting structure to be placed around the payload. Lastly, there is a conflict with the energy requirements. Maximum service or deployment time requires an increasing amount of energy storage which means an increasing amount of mass. However, decreasing the mass of the robot will reduce power requirements and increase the deployments time. It is also mentioned that increasing the efficiency of the device is crucial in order to reduce power requirements and therefore increase deployment time. Toward the end of the five minute introduction, the proposed design methodology is briefly described.

The second focus of the training takes ten minutes and is meant to review the collected data relevant to the design problem and serve as an introduction to the plots. Participants are introduced to each of the five plots, reasoning for their inclusion, and the use and distinction of log and linear scale. Next, participants are asked to seek certain information found on the charts to increase familiarity. As the trainer and participants review the included plots, questions are presented to the audience for them to ponder and verbally respond. The questions mainly center on asking the participants to review the plots and identify which technologies perform well or poorly against certain metrics, and about apparent limitations of certain technologies.

For the third focus, also ten minutes in duration, the participants are introduced to how the methodology and training materials are intended to be used to increase the quantity, novelty and quality of solutions to the design problem. The two main techniques discussed are seeking combinations of technologies from the data and combining personal knowledge or intuition with the data to form new ideas. The third focus is concluded with an example to show how the data may be applied to a practical problem. In order to showcase how combinations of technologies often results in innovation and in expanding the design space, exemplar combinations are discussed. These exemplar designs include an urban hopper that uses combustion to fill a pneumatic cylinder rather than a compressed gas, a device that utilizes ducted fans to fly over objects using short bursts of energy, and a track-snake hybrid that uses multiple segments to mimic snake-like motion, but utilizes tracks to drive eliminating the difficult control previously synonymous with snake like devices. Next, it is pointed out that including personal knowledge and intuition can be very helpful in interpreting apparent trends as not all trends are necessarily correct. It is also mentioned that there are holes in the data, and some technologies may be misrepresented or completely absent due to lack of data. By imagining where missing data may lie, or where a particular technology trend should lie, it may be possible to spark new ideas. To conclude the third focus, participants are given the following design problem and challenged to seek solutions using the plots and proposed method. The design problem is to seek combinations of technologies (presented or intuitive) that would make for a good bug squishing device which must be capable of jumping over walls as well as carrying a payload of insecticide. It is explained that extra mass is beneficial to ease squishing, and the environment in which it is to be used will have an uneven floor with walls or dividers that the device must overcome. Participants are encouraged to view charts relating mass to obstacle height capability and payload capacity to obstacle height capability in order to find combinations of technologies that would suit the design need.

The last focus is a five minute conclusion to highlight what is expected of the participants regarding the use of the tool for the third session and key points of the training. Participants are encouraged again to seek combinations of technologies shown on the chart as well as personal knowledge of shown or unrepresented technologies in order to form new solutions to the design problem. Additionally, participants are instructed to seek these combinations or new ideas instead of repeating ideas they recall from the first C-Sketch session on the second C-sketch, but that it is allowed to reuse an idea from the first session if they think of a way to alter or modify the idea in a way that significantly increases the performance of that idea.

Third Session – Final Mind Map and C-Sketch

The format of the third session is much like the first, but the groups are separated for the entire third session. There is a 20 minute mind mapping session for each individual group, followed by a 40 minute C-Sketch session with a 12 minute initial sketching period, and 6 minute rotations. A scan of the final mind map from the first session is printed and distributed on legal size paper to give participants more room to record new ideas. Participants are again led by a facilitator and are encouraged to completely verbally explore the design space. The facilitator again interprets the vocalized solutions and suggests a location for the participants to write the suggestion on their mind map. Upon conclusion of the mind mapping session, the groups perform the final C-Sketching session. Materials are then collected and analyzed by the primary researcher.

Evaluation of Results

Metrics

In order to interpret the results and determine the effectiveness of the design tool and methodology, the solutions are quantified in regards to quantity, quality, and novelty. Analysis techniques are similar to Lindsey's adaptation of several methods as previously developed by Shaw. [49], [50].

Quantity

Measuring the quantity of ideas serves as a useful means to determine the tool and methodology's effectiveness as the quantity of unique solutions has been shown to be crucial in the success of product development [51]. Defining the total number of single ideas based off hand drawn sketches can be a difficult task to standardize. Utilizing a method adapted from Shah et al. [48] by Linsey et al. [19] allows for the quantity to be defined. The rules for defining a single idea are summarized in Table 4. Prior to evaluating the C-Sketches for quantity, a function list is generated, and, in general, the number of functions a given concept fulfills represents the number of ideas that the concept represents. The list may be modified as reviewing the concepts may lead to a more comprehensive list than initially created.

Table 4 – Rules for counting single ideas [19]

1. An idea solves one or more functions in the functional basis
2. The same idea (or component) being used in multiple places counts as one idea
3. Each idea counts as only a single idea even when solving more than one function
4. New Combinations of already-counted ideas are counted in a separate measure
5. Categories of ideas only count as ideas when no subordinates are given*
6. Ideas count even if they are not needed or cause systems not to function
7. Ideas must be shown and not implied
8. When an idea reframes the problem, they are placed in a category called "Problem Reframing" These ideas may not address the problem but meet higher level customer needs a. These ideas do not typically fit a defined function well b. They must add a function to the system c. They count as an idea if they produce a product different than the original customer needs
*If a general pulley and a timing pulley are given, it counts as one idea as one is a sub-type of the other

Comparing the quantity of ideas the teams produce before and after exposure to the methodology indicates whether or not the method has a positive impact on the participant's ideation process.

Quality

One aspect of the hypothesis is that reviewing existing technologies, and seeing a physical comparison of their performance data relevant to the design problem will help designers generate new ideas that are of higher quality, thus, more useful to solving the problem. In order to measure an abstract idea quantitatively, quality is measured similarly to Lindsey [50] by applying a variation of a Likert scale summarized in the flow chart of **Figure 15**.

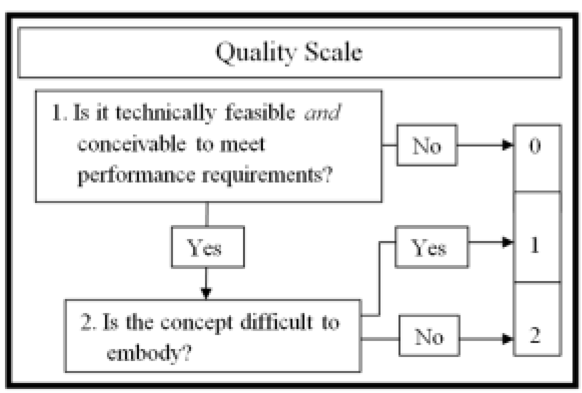


Figure 15 - Quality scale flowchart **[19]**

If the concept is thought to be technically feasible, meaning known to the designer to be both realistic in applications of known technologies as well as manufacturable (regardless of cost) then the concept receives a minimum quality value of 1 but possibly 2 if the concept does not seem overtly difficult to actually embody and prototype. If the concept is not considered technically feasible by the designer, the concept receives a value of 0.

Novelty

Often the trend breaking and high performing solutions are unique solutions, so another metric chosen to evaluate the effectiveness of the design tool and methodology is Novelty. Novelty is measured as a function of variety. As in Linsey's work [50], the variety is calculated by having a rater group similar solutions into bins, the more a group spans the total number of bins with their concepts, the higher variety score they receive. Calculating the novelty is completed by applying Equation 4.1 which is Jansson and Smith's measure of originality [46]. Novelty scores are calculated for each bin in which a concept lies, and averaged for each team and session.

$$Novelty = 1 - frequency = 1 - \frac{Number\_of\_Similar\_Concepts}{Total\_Number\_of\_Concepts} \qquad \text{Equation 4.1}$$

For this work, the total number of concepts is the number of bins created when all concepts from both C-Sketch sessions and both teams are sorted and grouped; doing this is meant to create the largest design space for the relatively small experimental population. The number of similar concepts is the number of bins the concepts from a particular session form. To evaluate whether novelty increased or decreased as a result of the exposure to the design methodology, the novelty value for a team's third C-Sketch session will be compared to each team's first C-sketch novelty value.

Cadet Exposure

Presentation of Design Tool

Cadet exposure to the design methodology follows an initial 6-3-5 concept generation technique to generate solutions to the robotics problem. Presentation to the Cadets serves to evaluate if detailed knowledge of the field, presented in graphical format to ease comparison of technologies and the design space, can increase the number of solutions as well as the quality of solutions. Cadets were given instruction to the use of the trends and insights from the data were discussed.

Cadet Use of Design Tool

When the tool was implemented, cadets had previously generated over 100 solutions through popular brainstorming as well as through building models of expected terrain to visualize required device capabilities and options to meet the design goals. The first use of the proposed design tool focused on allowing cadets to review the various technologies represented in the repository. Cadets were broken into groups to study technologies and each group reported on their respective findings and discussed what they thought would be beneficial to solve the design problem, and from these discussions the cadets discussed ideas that they would be interested in pursuing. Cadets also used the tool to research and expand on initial concept generation ideas by circulating existing sketched design solutions and adding new ideas which had resulted from reviewing the tool data. Using appropriate plots, cadets ranked technologies based on mobility capability by using tool data. The ranking served to rate existing conceptual solutions and assist in concept selection.

VALIDATION RESULTS

Graduate Student Experiment Results

The C-Sketching sheets from the graduate student experiment were examined and the quantity, quality, and novelty quantified based on the method presented above. Concepts capitalized on exiting technology, as well as creative solution to the specific design problem as shown in Figure 16. The concepts include a ball with treads, a walking segmented device, with function separation between each segment (ie, one houses payload, another energy or equipment), an inflatable wheel to cross crevices and a worm drive for locomotion.

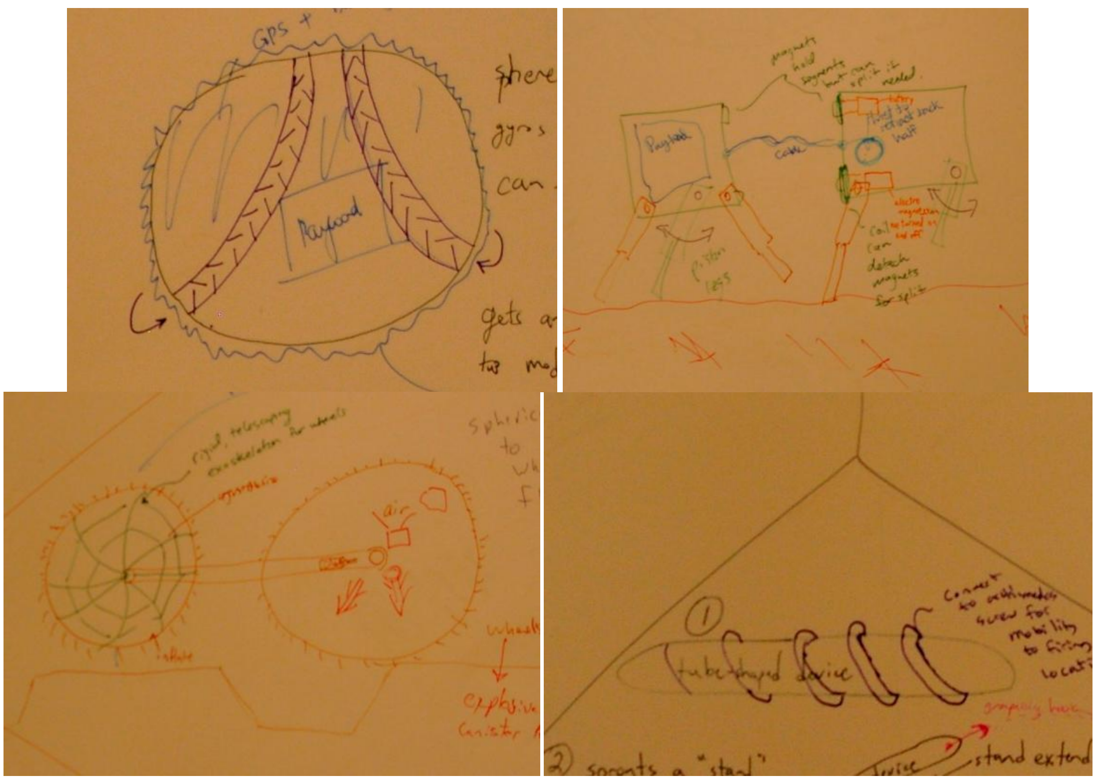


Figure 16 – Concepts from second 6-3-5 session

The numerical results are shown below in Table 5. Team A shows a 36% increase in ideas after exposure to the tool, a 17% decrease in the quality score, and a 17% increase in novelty. Team B's results conflict with team A's showing a 21%

decrease in ideas post tool exposure, a 10% increase in quality score, and virtually no change in novelty score.

Table 5 – Graduate validation experiment results

Team	Quantity		Quality		Novelty	
	Session 1	Session 2	Session 1	Session 2	Session 1	Session 2
A	42	57 (+36%)	1.28	1.06 (-17%)	0.830	0.971 (+17%)
B	57	45 (-21%)	1.17	1.28 (11%)	0.971	0.975 (+0%)

Cadet Exposure Results and Perception

Cadets developed a numerical ranking system for mobility, based on data represented in the plots, to assist in concept selection. Wheeled robots received a score of 0, whegs 1, treads -1, and airborne devices 2. Whegs had initially been an idea the cadets were pursuing, but reconsidered after concluding their inability to clear sheer steps would be problematic. Tracks, airborne, and extending push-rod type solutions for obstacle negotiation and mobility were ruled out as well after proposed solutions to increase their mobility were ruled infeasible or too unpredictable to provide reliable performance in the operating environment.

Cadets then narrowed their findings down to fourteen ideas they felt were best by reviewing relevant charts showing historical performance for the various technologies based on the proposed design methodology. Information from the tool was utilized again to determine the strengths and weaknesses of each concept, and the top three choices were chosen from the final fourteen. Cadets expressed the feedback the analysis led them to climbing type devices which would provide a more stable platform to pursue through prototyping and testing.

Based on the Cadet's evaluation, the tool was easy to use and the graphs provided good data analysis. The graphs helped optimize designs by selecting the best technology, as well as providing a feasibility analysis on how certain technology would perform. They did report that a lack of data may have hindered more detailed analysis. They also felt the tool did not promote innovation, but rather represented technologies as being pigeon-holed, instead of revealing limitations to be innovated upon.

DISCUSSION AND CONCLUSION

Graduate Study

Results from the experiment are mixed as quantity and quality are shown to both increase and decrease with exposure to the design methodology. Group A shows that exposure may lead to an increase in novelty, but group B demonstrates that it is also possible to produce good novelty without exposure. Several additional conclusions are drawn upon further non-quantitative analysis completed to help interpretation of the results. Since quantity only considers non-redundant ideas, the average ideas per sheet including redundancies is calculated in order to determine if exposure increases combinations of identical ideas on various concepts, or potentially more hybrid concepts. This was not found to be the case as the quantity of ideas per sheet follows the same trend as quantity of ideas. The number of ideas unique to the first and second C-Sketch sessions were also evaluated. Combining results from both teams and both sessions, there are 120 total ideas. Of these total 120 ideas, 31 relate to session 1 and 38 to session 2, and 51 were shared between both sessions meaning they are likely independent of the design tool. It is noteworthy that the majority of the unique ideas related to the 2nd session were refinements made to existing ideas in order to make them more feasible; this does not mean the concept as a whole increased in feasibility, however. For example, 10 of the 38 unique ideas were various refinements of the idea to transport or creating a portable bridge or ladder to traverse obstacles. It is difficult to attribute the refinements to exposure to the tool, idea loitering time, or other sources. The cause of a decrease in quality in team A was evaluated as well. It is concluded that the cause of the decrease is due to the complexity of ideas increasing in the 2nd session, thereby containing more concepts that earn a “1” quality score instead of “2” because they become considered difficult to embody, but not necessarily decreasing the likelihood the concept could lead to a successful product.

Most notable is the result on quantity. Lindsey shows that the number of ideas generated drastically reduces over time by tracking the generation of ideas during 6-3-5 sessions [19]. The effect of the proposed methodology on increasing the quantity of ideas and likelihood of success is very positive in that participants were able to match their number ideas in the second session, after exposure to the methodology. This strongly suggests that the methodology was successful in spurring a new surge of ideas to the same design problem, where typically, participants would be exhausted of ideas following a 6-3-5 session. Also, the relevance of this finding is supported by the emphasis given on quantities of ideas with respect to product development success [116] as well as implications associated with the presentation of analogies. Linsey finds that through presenting student designers with analogous solutions, the designers find solutions they are otherwise unlikely to realize [19], [29], [118], [117]. One conclusion about the results on quantity is that through presenting analogous solutions, the collection of robotic data as a whole, designers are able to generate more solutions to the design problem.

Cadet Work

Cadets found the tool to be useful as a means to compare and rank concepts to aid selection for further work, as well as bringing additional ideas to existing concepts after reviewing the field. However, the tool was not received as intended, as an aid to encourage innovation. This perception highlights the need for a more strategic approach to presenting a particular group with both the method and tool. Collected data can certainly show limitations for existing technology, as well as holes in the design space that will, if explored and filled, present breakthroughs for the current state of technology. However, the presented methodology may need considerable refinement to help serve as the connection between identifying the limitations and gaps and recognizing feasible solutions.

FUTURE WORK

A greater population of participants is necessary in order to verify or counter the results that have been observed and discussed so that the results would be more statistically significant and less ambiguous as to whether the particular method of reviewing the technical data of a field helps the ideation process. Further, there are a number of factors whose influence are difficult to isolate. One significant unknown is if having the design problem linger in participants minds for one week or more influences results as well as the presentation of new data. One way this unknown may be controlled in the evaluation of the design tool would be to utilize a control group who does not receive the tool data and training but has similar C-Sketch sessions as the groups who receive the training. This would allow for the observation of the effect time has on solving a design problem with respect to the mentioned metrics. Inter rater reliability analysis will also be conducted on existing and future data sets to provide a higher level of confidence in the results.

Additionally, the way in which the information in the electronic database is presented as well as the intricacies of the materials and presentation used in both training and introduction to the design problem can easily fixate or lead the participants and if a greater population will be utilized to examine the methodology these variables should be standardized and monitored closely. Also, for future experiments, it is preferable to eliminate the partially completed mind map and, instead, have participants generate a complete mind map from a clean slate for both the first and third sessions. Lastly, as with any human science experiment, effects such as social loafing, and personality dynamics, such as participants feeling they are performing better or worse than actuality [119], [120], may be beneficial to monitor.

SUMMARY

The proposed design methodology proposed in chapter 3 is evaluated for effectiveness and potential for future work. Through presenting the design methodology to cadets at the United States Air Force Academy and graduate design engineers at The University of Texas at Austin, positive preliminary results are discovered. Insights gained through graphical representation of the technical field and currently state of technology allow for an increase of design solutions, in part, due to existing devices to serve as analogous solutions to the problem, which has been shown to allow designers to generate solutions they would not have otherwise arrived upon.

PROTOTYPE

Chapter 5: Mechanical Design of a Highly Mobile Robot: Application of Proposed Design Methodology

INTRODUCTION

Highly mobile robotics encompass many interesting and challenging design aspects; in addition, they have much potential to increase in popularity in real world applications as technologies improve; applications range from assisting recreational spelunking to defense application such as perimeter monitoring or ISR. These reasons, as well as providing a fertile proving ground for the proposed design methodology discussed in Chapter 3, are motivation to develop a working prototype from the pool of concepts. Motivation for choosing the specific field is discussed in greater detail in the Application to Highly Mobile Robots in the mentioned chapter.

The design requirements, in brief, are that the design will be required to overcome two foot vertical shear ledges, as well as traverse across two foot crevices, that may arise from rubble, running water, or other means. The device must traverse rubble, rocks, and through mud and water. It must be insertable through an 8 inch bore hole, allowing for insertion and retraction into cavities such as caves or tunnels. The requirement of a small cross section to fit into the bore hole serves to increase its mobility through collapsed rubble, where there may not be large opening to explore the interior of the collapse. It is desirable that the design minimizes energy consumption, thus, reducing energy storage requirements, and maximizing exploration time. The device should be capable of housing a payload mass of dimensions 4 x 4 x 5 inches, which might be utilized for ISR equipment, or for delivering supplies. Lastly, a low mass is beneficial to both reduce energy requirements and increase portability.

Insights From Design Methodology and Concept Selection

Many insights were established through the thorough study of the current state of the art of highly mobile robots and analogous devices, which is expected to allow for an understanding of the field that aides the current design process and increases the likelihood of success. In terms of the insights and applications towards the creation of a new device, observations were focused on trends dealing with obstacle height versus size, obstacle height versus mass, obstacle height versus vertical power consumption, payload capacity versus mass, and locomotive power versus mass. Insights were mainly gained through analysis of the developed plots. A sample plot is shown in Chapter 3 in the "graphical representation of data and insights" section. A full collection of the plots created from the repository of data are included with and without trendlines and other features in Appendix D: Resulting Plots from Repository Data. A summary of the insights that were found are shown in Table 3. Some of the applied insights in the conceptual design process include rational in choosing a particular obstacle negotiation method, energy consumption insights, and payload insights.

It is observable from the plots that jumping designs have several limitations. Designs utilizing springs are capable of surmounting large obstacles relative to their size, but are difficult to control and often lack suitable methods for effective and controllable locomotion. One exception of this limitation is the miniWheg device [121] which utilizes a hybrid design with a sprung leg mechanism, similar to a flea, which allows jumping and employs whegs for locomotion and smaller obstacle negotiation. However, the jumping devices universally tend to lack significant payload capacity. Similarly, devices utilizing thrust suffer from large energy consumption during obstacle negotiation and also have small payload capacity. Segmented devices are one design that has potential for increasing obstacle height capability without hindering payload, as well as proving suitable for devices with too much mass to utilize current jumping technology. Utilizing segments in tracked devices is shown to allow for a two fold increase in obstacle height over tracked devices without segments, as shown in the plots 2 and 4 of Appendix D: Resulting Plots from Repository Data. It is also notable that legged devices do not have large obstacle clearance with respect to size or large payload capacity, and currently, are a much more difficult method of locomotion due to the large number of degrees of freedom. Tracked devices are shown, in general, to have larger payload capacities relative to device mass, as well as having an innate benefit of being harder to high center since the tread runs the length of the chassis, as opposed to wheeled devices which may be caught by rough terrain. It is also found that tracks and whegs can be designed for relatively high locomotive efficiency over other locomotion methods, as shown in the last two plots of Appendix D.

Considering the maximum cross-sectional diagonal and the required payload volume, it is anticipated that it will be difficult to design for significant ground clearance. Since treaded designs inherently are less prone to high centering, thus, requiring less ground clearance, a treaded design is selected. As mentioned, treaded designs also handle payload well, however, they suffer from low obstacle clearance requiring a novel solution to provide a significant improvement towards the challenging design requirement to overcome a two foot shear ledge or crevice. Inspiration is drawn from the observation that hybrid designs often significantly increase performance related to the functions of the combined technologies. For example, devices that combine one technology for locomotion, and another for vertical obstacle negotiation perform far better, as expected, than devices that rely on their locomotive technology for obstacle negotiation. Noting segments can increase obstacle height significantly, yet also allow for higher device masses and payload mass, it is decided to pursue a hybrid conceptual design utilizing extendible segments.

A full mind mapping and brainstorming experiment is carried out in Chapters 3 and 4, and many resulting concepts are included in Appendix B: Experiment Validation C-Sketch Sheets. Many of the resulting concepts may perform equally as well as the selected conceptual design, but as often is the case for designers, there is not time nor budget to fully explore each idea, so after a careful selection process is performed, as presented by Otto and Wood [114], a design must be chosen and concentrated on full time, keeping in mind options and new ideas for future iterations.

CONCEPT EMBODIMENT

As mentioned above, the selected concept is a device that utilizes segments to climb over tall obstacles and negotiate crevices, and uses treads for locomotion as well as negotiating small obstacles. The first rendition of the concept is shown below in Figure 17.

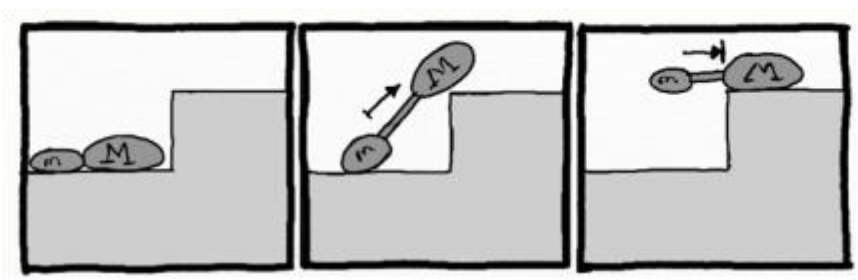


Figure 17 – First rendition of the conceptual device

The idea is that a two-segment device would drive up to a ledge, and driving tracks on both segments might start to drive up the ledge slightly. When the device reaches an appropriate angle, the two segments might extend from one another, and if the leading segment is sufficiently more massive than the rear, the device might pivot onto the top of the ledge when the leading segment reaches a height clear of the edge. If a shifting mass is employed, such that either front or rear segment might be more massive than the other, the light front segment could be extended across a crevice, the mass shifted, then the rear segment retracted, effectively crossing the crevice.

Due to concerns that it may be impractical for the leading tread contact to have enough friction to initiate climbing vertical obstacles, and too dependent upon the particular surface encountered, a modification to the concept is made in which the leading segment might be rotated up, analogous to a fire truck's ladder, and placed on the ledge's corner. After this modification was made, it can be realized that the rear segment might be unnecessary, and if so, there only need be one set of tracks for locomotion instead of both segments including driven treads. In fact, it is possible to accomplish the same maneuvers with only one driven segment, and a second segment consisting of only a telescoping ladder. Progressing with the concept above, through several embodiment stages, results in the modified concept shown in Figure 18 and Figure 19 below.

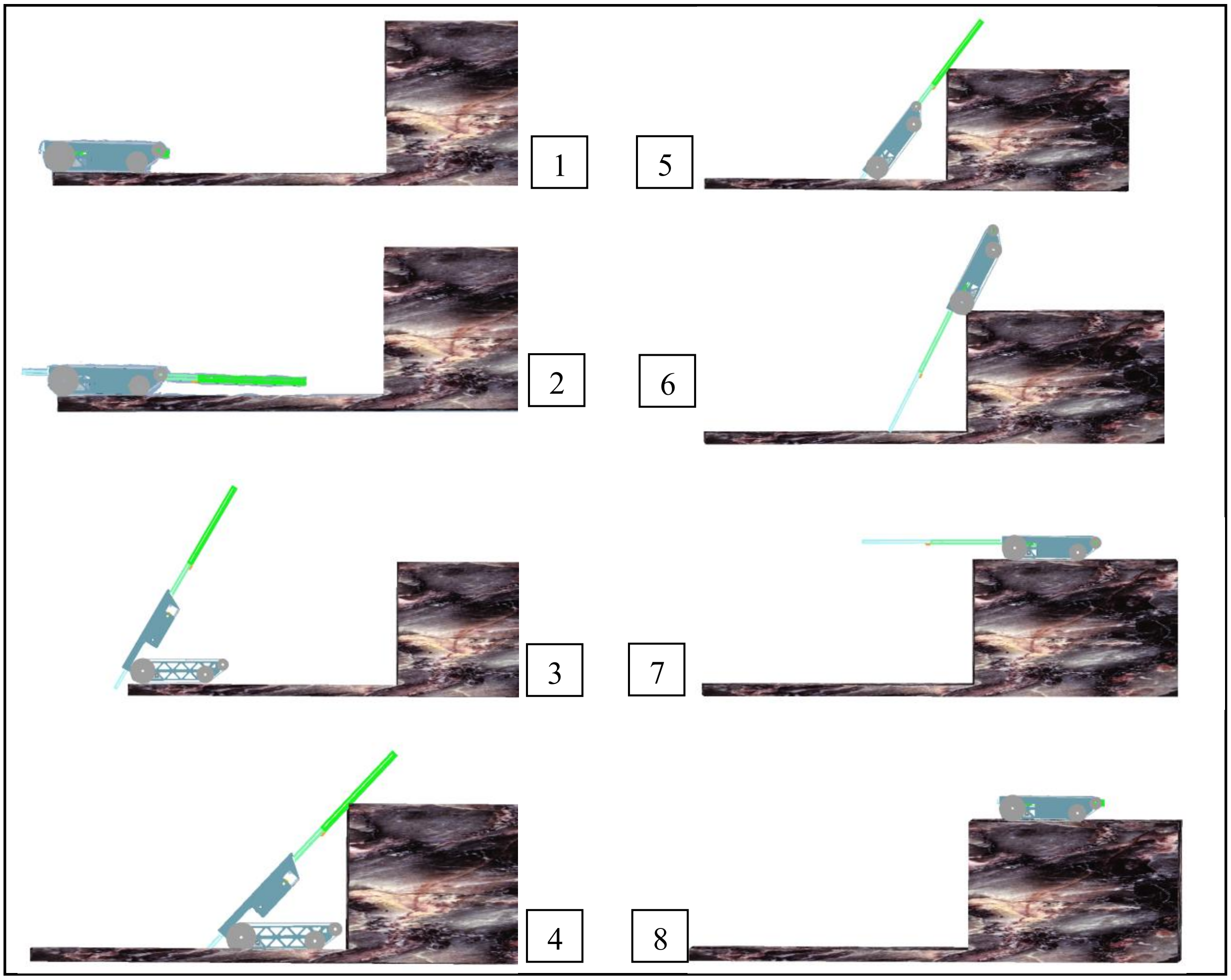


Figure 18 – Ledge negotiating sequence

To negotiate ledges, the device approaches the ledge, and extends the telescoping ladder, next, the “body”, which houses the ladder, positions the ladder against the edge of the ledge. Next, the treads are retracted parallel with the ladder, and rollers which contact the ladder are driven in order for the device to climb. Similarly, to cross a crevice, the ladder is extended, with a short length remaining extended from the rear of the device. By simply driving into the crevice, the ladder contacts both edges and the device may power the rollers to trolley across the crevice, and allow the treads to contact the opposing side, and continue on its mission.

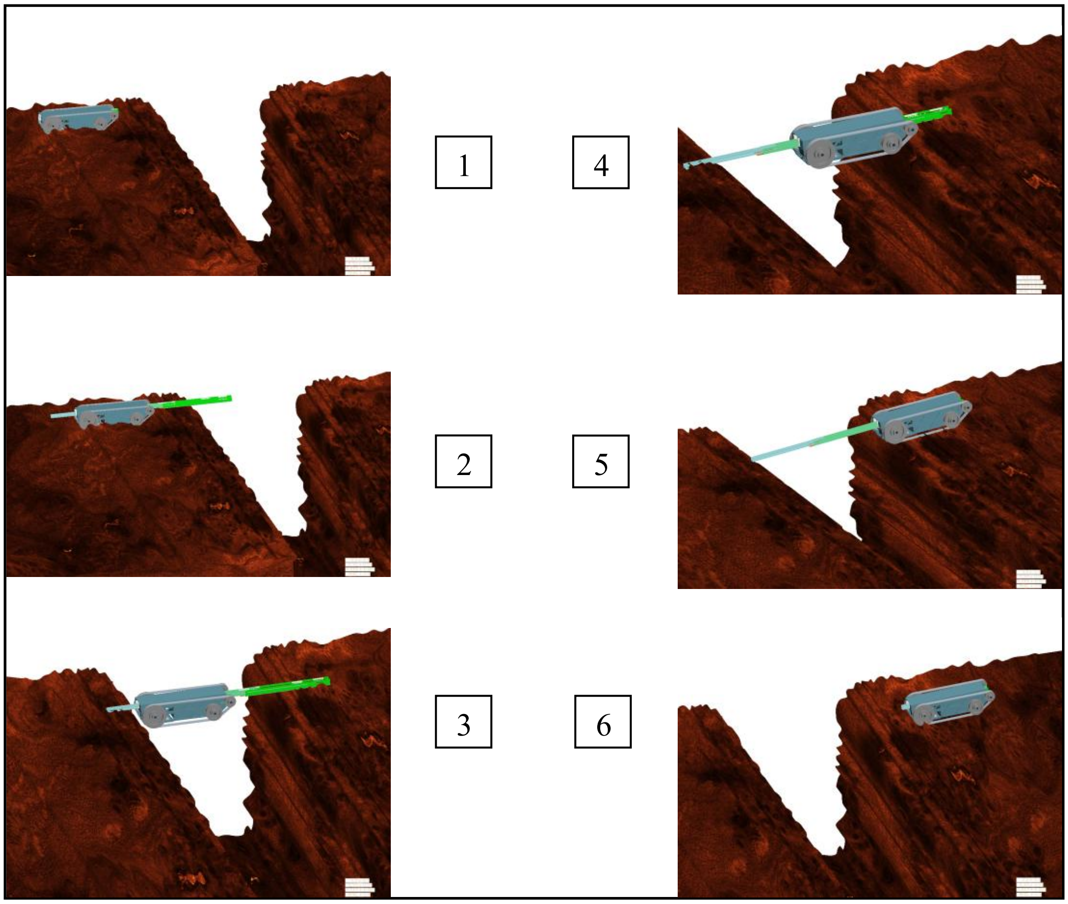


Figure 19 – Crevice traversing sequence

MECHANICAL DESIGN

Design Features and Operation

The device consists of two main subassemblies, the drivetrain and the "body" which houses the ladder system. The drivetrain assembly gives the device mobility and capability to traverse rough terrain and small obstacles. The body houses the telescoping ladder, which will allow the device to overcome relatively large obstacles and crevices. The concept embodiment and subassemblies are shown below in Figure 20.

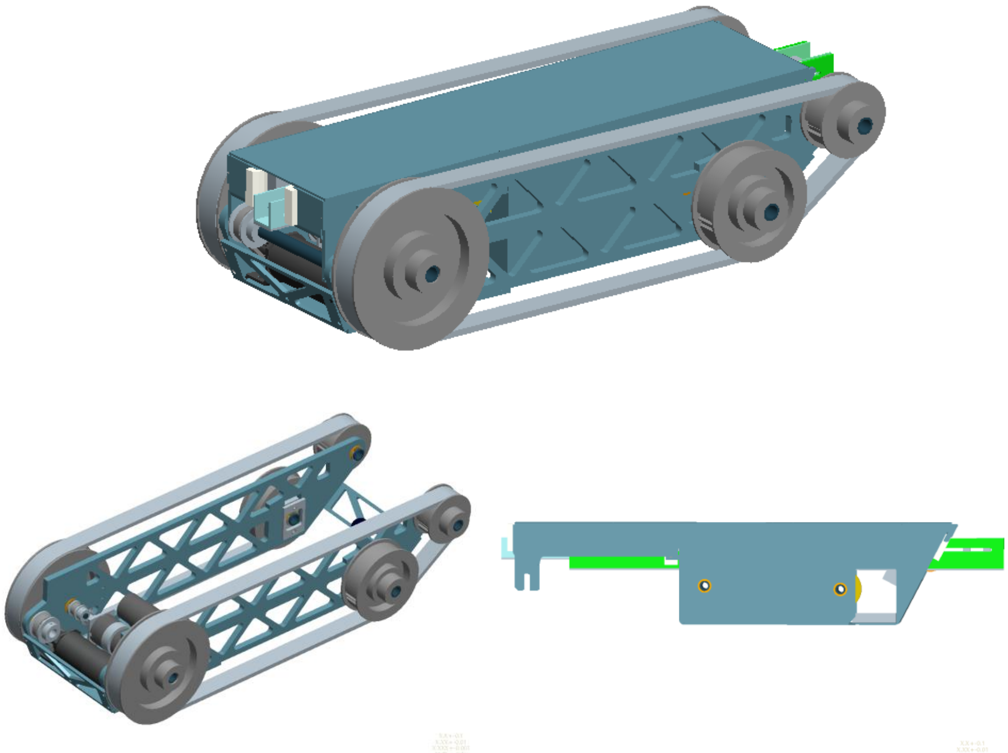


Figure 20 – Concept embodiment (top) and subassemblies (bottom: drivetrain left, body right)

The drive train comprises of two treads, each controlled by an individual motor to allow steering and avoid complications of a clutching system if the two were to be driven by a shared power source. Roller chains connect the DC motors to the drive pulley, and idlers maintain tension and give the tread its geometry. A slope is designed into the leading side of the device to aide overcoming obstacles, climbing out of crevices and over the edge of vertical obstacles. The tread system is also designed to allow operation of the device right side up and upside down by ensuring all components are located inside the upper and lower dimensions of the device. The drivetrain details are shown in Figure 21.

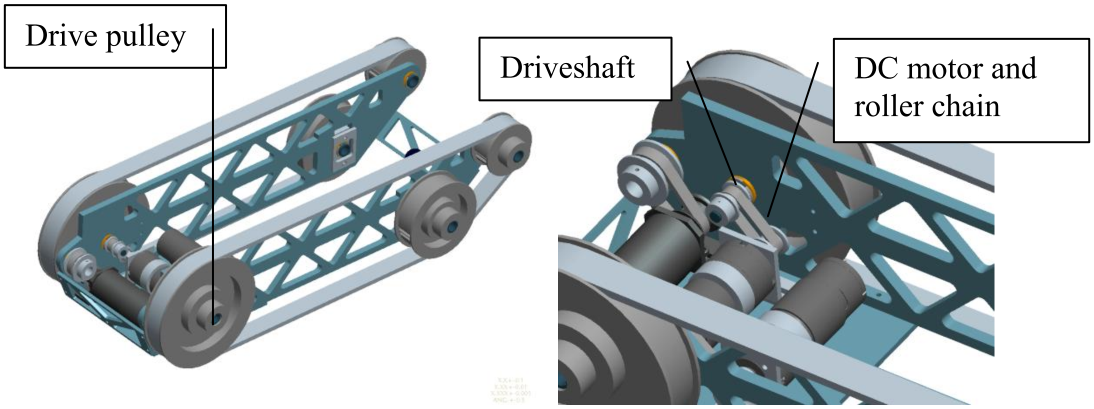


Figure 21 – Drivetrain, right highlights dc motors and roller chain connection to drive shaft and drive pulley

The body's main function is to house and orient the telescoping ladder to allow the surmounting of vertical obstacles and crossing crevices. To allow the placement of the ladder upon vertical obstacles such as ledges or stairs, the device can rotate the ladder upward with a dc motor, by pivoting about a shaft on the rear of the device. The longitudinal position of the ladder is controlled by two independent rollers, which may be manipulated to both shift the position and extend and collapse the ladder segments. Body images and descriptions are shown in Figure 22.

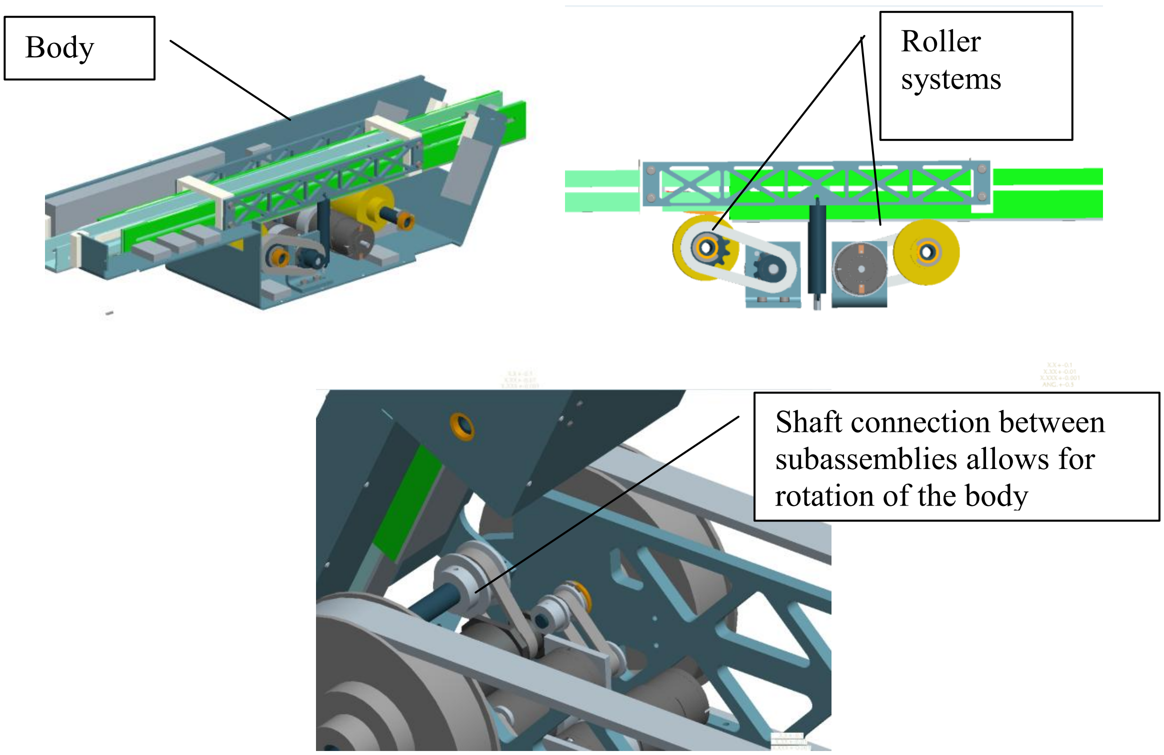


Figure 22 – Body subassembly and roller system (top), orientation feature (bottom)

Rational to selecting particular components, configurations, and solutions to specific design challenges are discussed below in the following sections.

Design for Manufacturing

Material selection, manufacturing process selection, and utilization of off-the-shelf components and preformed stock material for the prototype plays a critical role in the mechanical design, especially at the prototyping level, due to the implications these choices have on the overall cost and schedule of the device. It should be expected that prototypes will need to be assembled and disassembled multiple times for testing, modifications, and repairs, thus, it is important that the design be easily assembled, including order of assembly operations and access to fasteners and other connections. If reasonable manufacturing processes are available in-house, utilizing them may drastically reduce cost, as does choosing materials that may be worked with in-house. The benefits of in-house work are amplified further when undesirable but likely events occur that require the redesign and remanufacture of components such as mechanical failure or incompatible assemblies. If the rework can be completed in-house, research personnel can start redesign and manufacturing immediately, bypassing negotiations of cost and schedule with outside sources.

For material properties, the weight to strength ratio is of particular importance for both the size and mass of the device. The length and width of the device will likely be determined by the size of the DC motors anticipated to drive and lift the device, so the lighter the device is, the smaller the required motors will be, allowing for a smaller device capable of fitting through tighter access points. Stiffness is of secondary importance since moderate deflections are not anticipated to noticeably affect performance. The material should be machined easily to utilize in-house machining capabilities, as well as minimizing tooling costs, time, and difficulty.

Ashby highlights the general relationships of a variety of materials with respect to weight to strength ratio and cost; these are illustrated in Figure 23 and Figure 24 [122].

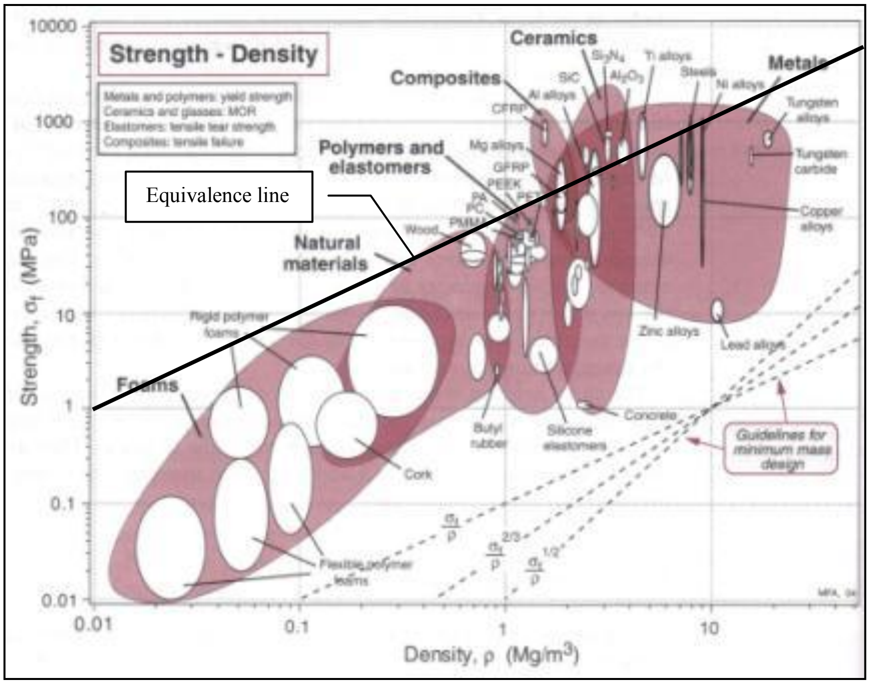


Figure 23 - Relative performance of strength versus density [122]

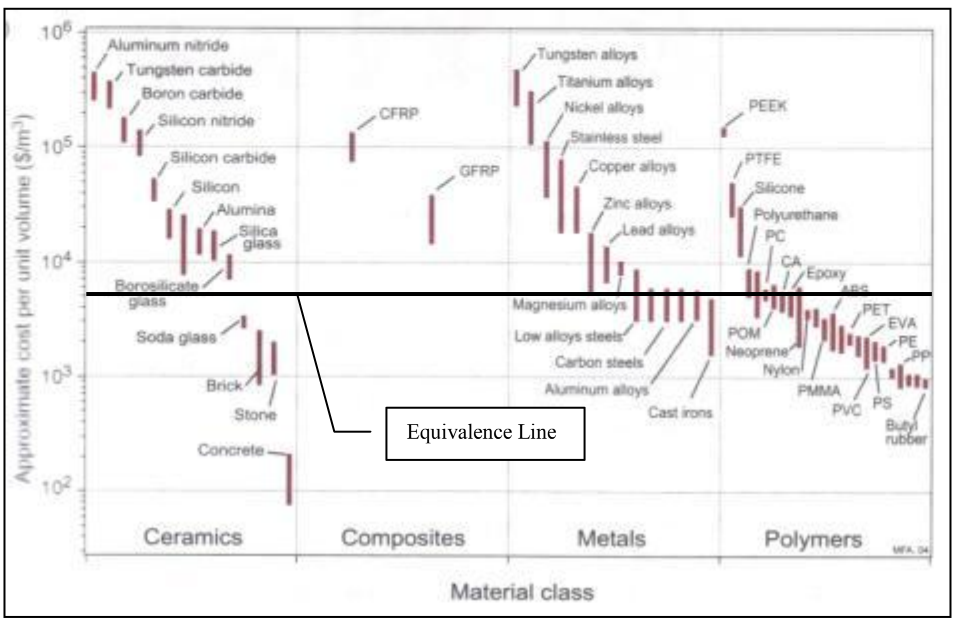


Figure 24 - Material cost per volume versus material class [122]

Equivalence lines are shown on the charts to ease comparison of the various materials. In Figure 23, the equivalence line shows an equal weight of strength and density; if non-equal weights are desired, the slope of the equivalence line would change accordingly. If aluminum and steel alloys are treated as benchmark materials, it is observable that several materials perform better than the benchmark materials including carbon and glass reinforced plastic (CFRP, GFRP), titanium alloys, some high performing polycarbonates, and even some varieties of wood. On Figure 24 it is shown that polycarbonate, steel, and aluminum alloys are all very similar on a volumetric cost basis, while CFRP/GFRP and titanium alloys are orders of magnitude more costly. With these facts in mind, it is thought that choosing a high strength aluminum alloy such as 6061 will fulfill the structural needs of the prototype best, including machinability, low cost, and low weight. Material selection is also addressed for specific needs, such as shafts, stiffeners, and sliders or guides. Due to cost, higher modulus of elasticity, and wear resistance, steel alloys are chosen for shafts and stiffeners. Teflon® serves as low friction guides due to its low coefficient of friction and suitable machinability. It is important to note that utilizing materials such as CFRP and titanium alloys are worth exploring for a full production model as they may allow for an even higher performing device due to the large influence overall mass has on energy consumption and the size of the device which are crucial design criteria.

Utilization of off-the-shelf components and standardized material dimensions allows for minimal required machining of components and contributes towards design for manufacture. For example, steel shafts are desirable to use at several locations in the design but have the potential to negatively impact overall mass significantly. One method to mitigate the impact on mass is to utilize hollow shafts, which may require boring hard steel; however, if shaft dimensions are chosen thoughtfully, standard outer diameters and wall thicknesses should be specified to reduce or eliminate any machining aside from cutting the shafts to length, allowing for easier and efficient manufacture. Clearly there is also advantage to utilizing off-the-shelf components, such as chain sprockets (among others), even if it is possible to manufacture the component in house, since particular companies have previously minimized the expense of manufacturing those components through investing in specific tooling for the components and through large volume manufacture and sale of the components.

Throughout the design, there exist locations that are difficult to assess with the human hand. In these locations, designs that eliminate the need to reach into the device are crucial for easing assembly and repair. In the embodiment of the selected design, the need to maintain access to connections and connectors, as well as minimizing the need to reach into the device is held as an important design criteria. The solutions to easing such access are presented below in the design solutions section.

Design Challenges

Embodying the chosen, preferred concept requires addressing several design concerns including tight physical packaging, a strong motivation to utilize transformation, sizing and choosing appropriate DC motors and a design that allows for easy assembly and disassembly.

Ladder Design

Firstly, producing a product capable of entering small entry points leads to a high priority being placed on compact packaging. There is a strong likelihood that utilizing transformation will, in part, allow for a well packaged device, in particular if used for the ladder that is proposed to allow the device to negotiate obstacles. If the ladder could be designed to expand and collapse, the length of the device might be significantly reduced. However, expanding and collapsing presents the design challenges of needing to remotely expand and collapse the ladder as well as requiring a system to remotely lock and unlock the ladder in and from its extended position. Compliance may be needed in the system if dimensions vary among each sequential expanding segment, and the ladder mount must restrict 2 degrees of freedom, but allow longitudinal freedom, as well as restricting (or controlling) all three rotational degrees of freedom and lastly, a method to control and move the ladder's position must be established.

Ladder Orientation

Designing a system to orient the ladder system entails carefully accounting for required torque and its effects on motor selection and gearing. Addressing the transmission of torque for the ladder orientation is likewise important as relatively high stresses are expected. The ladder orientation system would benefit from a one-way drive effect, such that the DC motor might adjust the orientation, but that outside forces (such as gravity) would not be able to drive the motor; such that orientation while negotiating obstacles may be more easily controlled.

DC Motor Selection

DC motors must be selected to have sufficient power for the device but have minimum dimensions and energy consumption. This is a critical design consideration as the motors are expected to contribute nearly 50 percent of the overall device mass, where larger mass increases the difficulty of climbing as well as increasing the size of the device. Utilizing the appropriate size motor will also increase motor efficiency, allowing for maximum deployment time between recharging or refueling

Reliable Tensioning Mechanisms

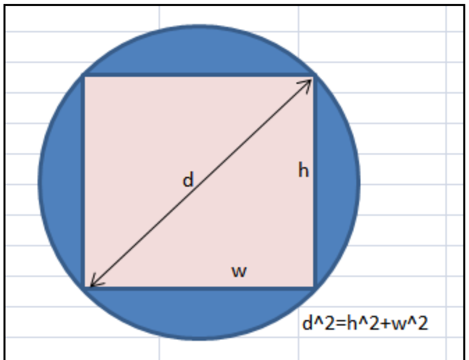
A reliable method to adjust tension among the drive chains and treads is required. Belts are utilized as treads for locomotion, and must be tensioned appropriately to prevent skipping teeth or being over-tensioned and causing the bushings to bind. Having a mechanism to adjust the tension will also ease installing and removing the drivebelts. Similarly, there should be a method to adjust the tension in the chains that transmit torque from the drive motors to the drive shafts, and from the orientation motor to the body axis.

Design Tools

To address the various mechanical design challenges, various tools and design aids were employed including electronic spreadsheets for basic stress, torque, and geometric calculations, a bond graph to understand DC motor dynamics, 3D modeling software (CAD) for detailed embodiment, and finite element analysis software (FEA) to calculate stress in components with complex geometry.

Packaging and Form Factor

A simple spreadsheet is established to determine width and height combinations that would allow the device to be inserted through the desired bore diameter. It is desirable to use a wider width than height, in order to have a more stable device (less prone to rolling over) due to a lower center of gravity. Once a set of dimensions are chosen, they set an upper bound on many packaging requirements. The length of the device is less critical, but it is desired to create as compact a device as possible in an attempt to maximize portability while minimizing mass and both energy consumption and storage requirements. Figure 25 shows the spreadsheet and graphic used as a design aide to set these dimensions. The spreadsheet shows the allowable diameter and associated width options with the corresponding height option. For a good starting point, a width of 6 inches and height of 5 inches is chosen to provide width for stability, and height for payload volume and space for dc motors and the telescoping ladder.



Diameter, d (in)	Width, w (in)	Height, h (in)
8	4	6.92820323
	4.5	6.614378278
	5	6.244997998
	5.5	5.809475019
	6	5.291502622
	6.5	4.663689527
	7	3.872983346
	7.5	2.783882181
	8	0

Figure 25 – Ratio and dimensioning design aid

Stress Calculations

As various components were detailed to a sufficient level, basic stress calculations were able to be performed in order to verify structural integrity and working conditions, as well as finalize dimensions. Calculations were performed in an electronic spreadsheet in order to ease computation as well as expedite recalculations due to design changes or explore effects of proposed changes. Calculations include bending stress, shear stress, and normal stress. Various components were analyzed to ensure proper function and to avoid failure; these include the stop spring in the ladder, torque transmission key, body axis, and others discussed in the following sections. A sample of the spreadsheet calculations are shown in Table 6. For parts with more complex geometry, where manual calculation of stress would be labor intensive and potentially inaccurate, FEA is performed using the built in software package within the CAD computer software.

Table 6 – Stress calculations sample

Part	Find	Calculation												
			Length, in	Width, in	Height, in	I, in^4	c, in	Modulus, psi	Displacement, in	x - Displacement Location	a - load location, in	Force, lbf P=(6EI)(w(x))/(x^2*(3a-x))	Moment, in-lb	Bending Stress, psi
Stop Spring	Force / Bending Stress	Canilever Bending Stress	3.2500	0.2500	0.0300	5.6250E-07	0.0150	2.9700E+07	0.4000	2.3750	3.0000	1.0729	3.2188	85835.5302
			3.0000	0.2500	0.0150	7.0313E-08	0.0075	2.9700E+07	0.4200	1.9000	2.7500	0.2296	0.6313	67339.5206
				Width, in	Height, in	Area, in^2	mg, lbf	Tension Stress, psi						
		Tension Stress		0.2500	0.0300	7.5000E-03	20.0000	26666.6667						
				0.2500	0.0150	3.7500E-03	20.0000	53333.3333						
Stop	Min. "Latch" Thickness	Shear Stress	Width	Force, lbf	Allowable Stress, psi	Area A = F/ss	Min. Thickness, in							
			0.2500	20.0000	10000.0000	2.0000E-03	0.0080							
Body Axis	Torsional Stress	Shear Stress	L, in	p, lb/in^3	T, lb-in	Do, in	Di, in	co, in	ci, in	J, in^4	Shear Stress = Tp / J	mass, lb		
			4.5000	0.2840	30.0000	0.3750	0.2450	0.1875	0.1225	1.5877E-03	3542.8146	0.0809		
Body Key	Shear Stress	Shear Stress	Height	Width	Area	Force	Shear Stress	Allowable	FOS					
			0.1875	0.1875	0.0352	2.0000E+02	5688.8889	1.5000E+04	2.6367					

Length Calculations

Due to various design changes, it is beneficial to utilize an electronic spreadsheet to manage lengths of the belts and chains. Using the 3D CAD software to measure lengths, they may be entered into the spreadsheet where pitch lengths may be measured, and the closest length ordered for the physical part. This method is also used in order to calculate the number of chain links required for the three chain drives utilized in the design.

Sizing of DC Motors

Executing careful motor selection ensures the DC motors are correctly sized. Appropriate sizing allows for minimum sizing of the device, ample available power, and minimum energy storage requirements. Using an electronic spreadsheet to find minimum torque requirements and gear ratios, while accounting for several variables, helps establish required motor specifications. To assist visualize and understand the motor dynamics and requirements, a bond graph of the system is developed and programmed into a mathematics oriented software program.

To increase understanding of the design bounds, including minimum and maximum speeds, and a range of gear ratios that ought to be considered, calculations in an electronic spreadsheet are performed. Analysis is also done in order to determine the minimum torque required of the motors. For the drive motors, first the required reduction ratio is analyzed over a range of desired top speeds, in miles per hour (MPH). The curve shown in Figure 26 is calculated based on a max motor rpm of 7000 and use the drive pulley diameter of about 4 inches.

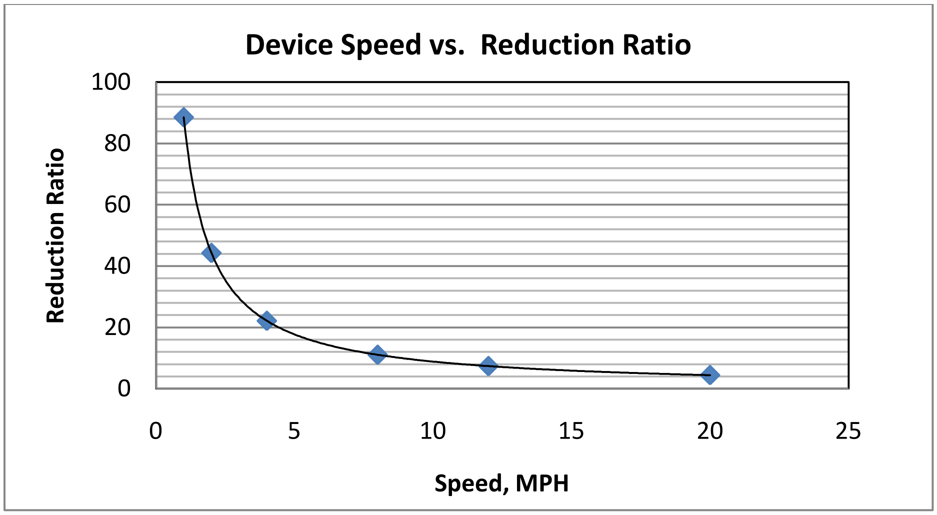


Figure 26 – Graph of required reduction ratio versus desired top speed

It should be noted that the relationship between reduction ratio and speed is non-linear, and selecting too high of a reduction ratio has a very small pay off, for example, if the top speed changes by about 10 MPH between a reduction ratio of 10 and 20, but by negligible amount between ratios of 60-90. This is sufficient reason to avoid such high ratios for drive motors as added gearing adds mass and larger dimensions to the design.

Similar analysis is performed to gain insight in the required reduction ratio of the roller motors, which will drive the robot up the ladder in order to surmount obstacles. The calculations for this analysis considered a motor rpm of 3500, or ½ the top speed, where the motor operates with peak power [123]. Figure 27 shows that if a climbing velocity of near 5 inches per second is desired, reduction ratios of 30 to 60 should be considered; based on utilizing a roller diameter of 1.5 inches.

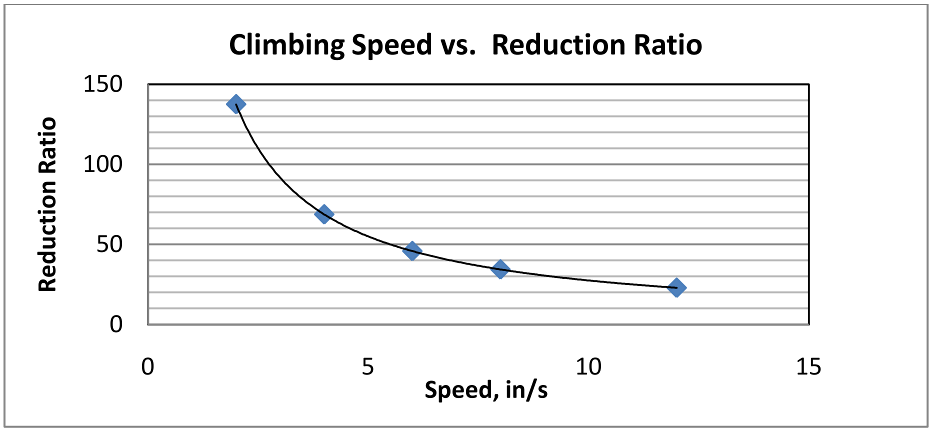


Figure 27 – Chart showing relationship between reduction ratio and climbing speed

In addition to the reduction ratios, the minimum required torque must also be known in order to select the correct motor. The torque value allows for the calculation of the current expected to run through the motor, which indicates the expected life of the motor windings. The minimum torque is crucial for the roller motors and body motors, and while it is less important for the drive motors, it should not be ignored. For the roller motors, the minimum torque is calculated by assuming one roller must provide sufficient torque to drive the device up the ladder when positioned vertical, and is calculated using Equation 5.1.

$$Torque_{roller\_motor} = (m*g*R_r) / Re \qquad \text{Equation 5.1}$$

where m is the mass, g the acceleration due to gravity, R_r the roller radius, and R_e the motor reduction ratio, including the gearhead and the reduction between the motor sprocket and the sprocket on the roller shaft. Similarly, the torque is calculated for the body orientation motor; in this case the weight and center of gravity of the ladder and body mechanism must be calculated with respect to the body shaft position. Using these values, the required torque is calculated based on force multiplied by distance. Summaries of torque calculations are shown in Table 7. Drive motor minimum required torque is based on a general design principal that the drive motors should have sufficient torque to drive the device up a near-vertical slope; this loosely guarantees the drive motors will provide enough torque for general locomotion. In the sample calculations, T_x represents torque, and W_x represents a rotation velocity for various components.

Table 7 – Sample torque calculations for motors

Min Roller Motor Torque Calculations												
Tm = mgRr / Re												
mg (lbf)	Rr (in)	Re	Tr, in-lb	Tm (lb in)	Tm (oz in)	Tm (g cm)	T (mN m)					
10	0.75	35	7.5	0.214286	3.428571	246.8829	24.21					
Body Motor Torque / Power												
T = mgL												
h=L												
P = mgh / t												
Wb = Angular velocity - body												
Wm = Angular velocity motor												
m, slug	g, in / s^2	h, in	t, s	P, in-lb / s	P, W	T, lbf in	Wb, rad/s	Wm, rad/s	Re	T, oz in	T, mNm	T, g cm
0.01501	386.4	10	5	11.6	1.310568	58	0.314159	733.0383	2333.333	928	6552.84	66822.96
				spring		36.36694				581.871	4108.736	41899.07
				motor		21.63306				346.129		

Bond Graph

As previously mentioned, a bond graph is developed as a tool to understand the motor dynamics, particularly on startup for the roller motors. If the motors are undersized, there is a potential for them to operate at their stall current for a sufficiently long period of time that they may melt their windings, so it is of interest to model the motors to ensure they will operate within safe limitations. The development of the model is included in Appendix F: Bond Graph Development and Code. Appendix F also includes the code for engineering software to computationally solve the differential equations developed from the bond graph in order to visualize current, power, and speed of the motors on a time scale during start up. The code was utilized to explore motor dynamics at both 12 volts and 24 volts as 12 volt batteries are common, but 24 volt may reduce the motor amperage improving winding life; the highlighted portion of the appended code indicates values that must change with a change in desired battery voltage. The following figures highlight the motor dynamics upon startup, and are useful in determining required power ratings of selected motors, as well as amperage requirements. The results help determine if the selected motors will operate within safe limits, and operate suitably before purchases are made. In the model, a controller regulates the voltage supplied to the motors as a function of the percentage of actual speed compared to desired speed, so when starting from a stop, the motors are supplied full voltage, and then is modulated as the robot nears the desired speed; code is also implemented to ensure the voltage is restricted between 0 volts and the desired maximum or nominal battery voltage.

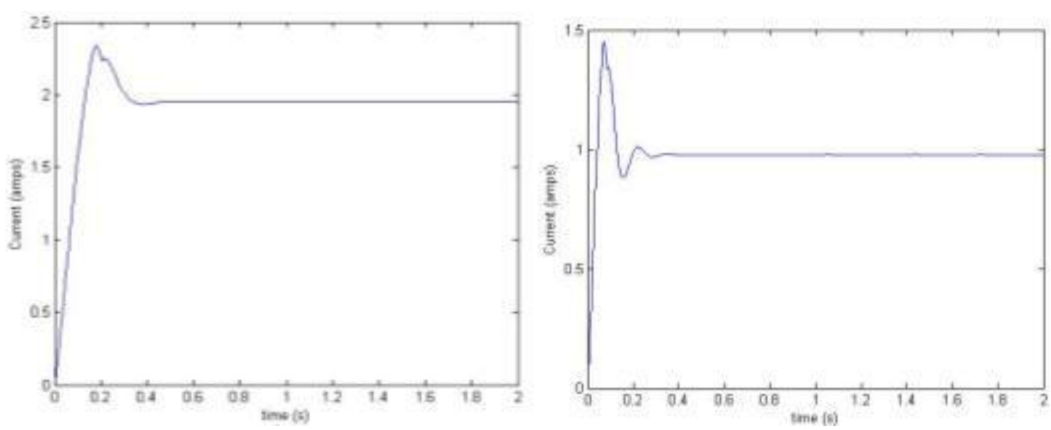


Figure 28 – Current versus time; 12 volt on left, 24 volt on right

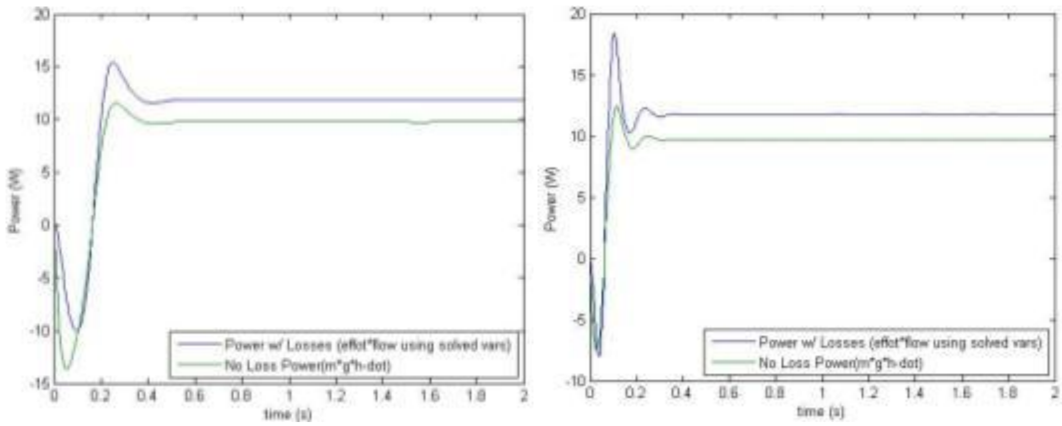


Figure 29 – Power versus time; 12 volt on left, 24 volt on right

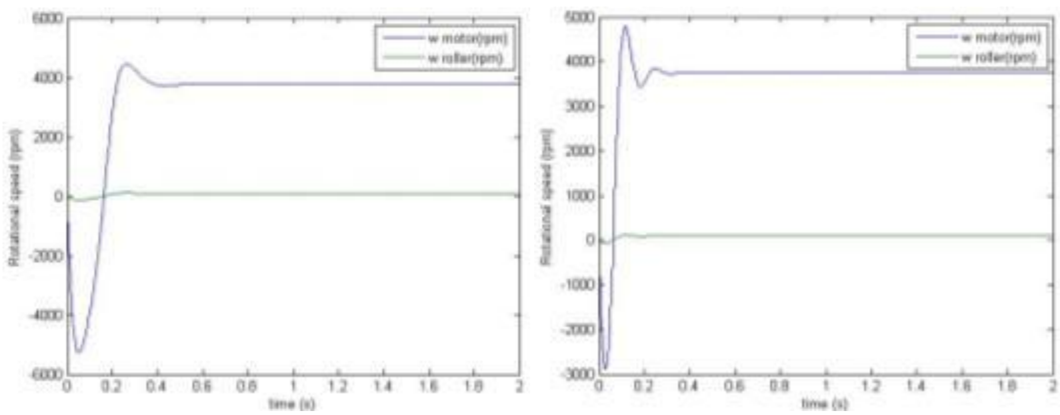


Figure 30 – Rotation speed versus time; 12 volt on left, 24 volt on right

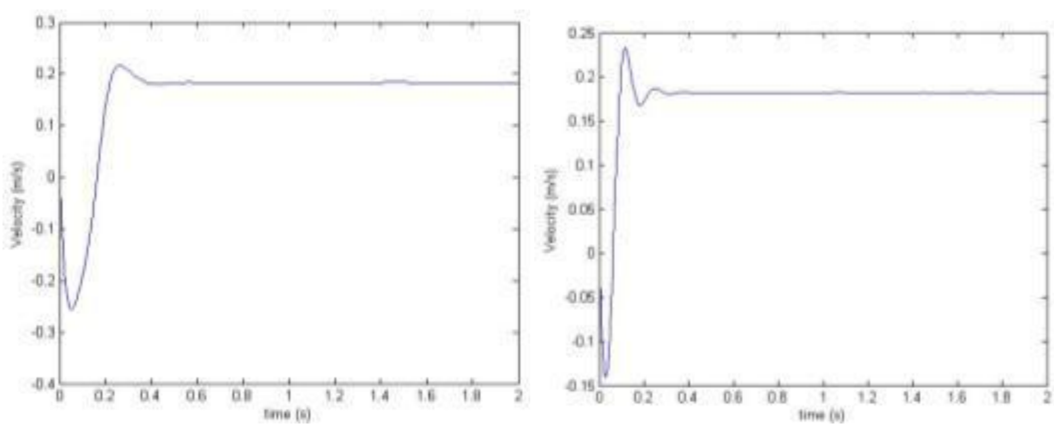


Figure 31 – Climbing velocity versus time; 12 volt on left, 24 volt on right

The results shown in Figures 24-27 are based on a motor of interest, and based on the published specifications [124]; the particular motor chosen has a gear ratio of 35:1, the largest ratio available in a form factor that is agreeable with design constraints.

Noteworthy results from the bond graph chiefly are centered on the results of current flow. In both voltage cases, the transient start up time (~0.5s) is sufficiently short as to not trigger alarms about melting windings due to extended time running at stall current. However, the steady state current values at 12 volts are potentially harmful for the motor, or may significantly reduce its life; thus it is decided that the motors should be run at 24 volts. The 24 volt response mimics a critically damped curve, where the 12 volt is closer to an overdamped system. This result indicated the 12 volt configuration would likely be operating at its upper limits, or potentially have insufficient torque, where as the 24 volt configuration appears to have ample torque for the system. Additionally, calculated power outputs indicate that the 19 Watt rating on the selected motors should be sufficient to drive the roller motors as about a 12 Watt load is expected.

Design Solutions

Ladder transformation

A ladder was designed, and embodied with the help of 3D modeling software. The ladder solves the stated design problems by utilizing telescoping segments which may be separated and locked into place with the use of rollers, which are to be included in the design of the device. Though enclosed tubing would provide greater structural integrity, extruded c-channel was utilized for two main reasons. Firstly, utilizing channel allows for great ease of assembly for the components such as the stop, spring, and guides that will be inserted into the segments and secondly, it is desirable for the particular design that the top of each segment be flush with one another to ease mounting and guiding the ladder during negotiation of obstacles. Figure 32 shows the three telescoping segments of the ladder in their collapsed and expanded states. The desired length of the ladder was calculated based on the need to negotiate a two foot vertical obstacle as well as estimating an angle at which the ladder would be utilized.

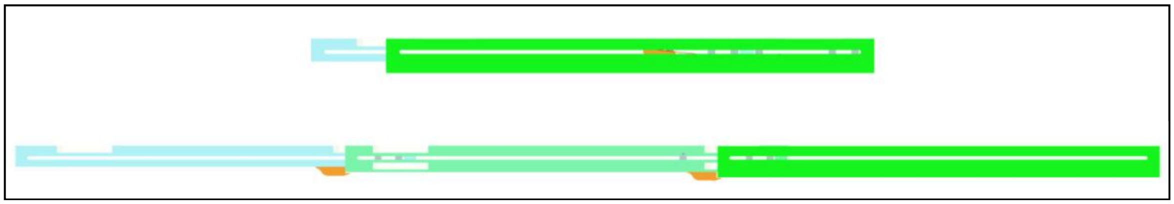


Figure 32 – The ladder in its collapsed (top) and expanded (bottom) states

In order to connect the segments, yet allow for telescoping motion and force transmission, slits are cut out along the channel sides in order to both house the guides, and provide the space for the guides to run along, analogous to a cam and follower with no curvature. The guides are shown in Figure 33. Additionally, it is shown in Figure 33 how dimensions are specified such that the tops of each segment are flush with one another. Teflon strips are used to maintain each segment in a centered position, shown in Figure 33.

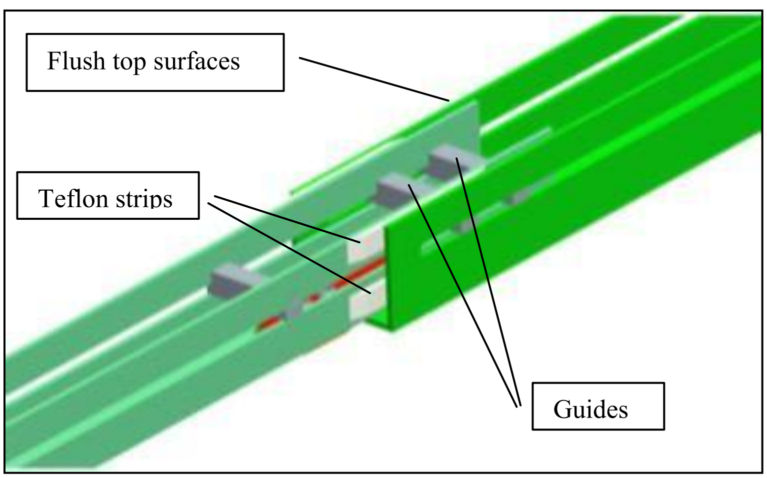


Figure 33 – Ladder view highlighting the guides, Teflon centering strips, and flush top surfaces of the channel

When the ladder is expanded, and oriented such that the device may climb an obstacle, a locking mechanism is implemented such that the segments remain expanded, and not collapse. To do this, the locking mechanism was designed such that the control roller could simply roll over the lock, but also depress the lock in order to collapse the ladder for exploration. Details of how the locking mechanism and roller interaction operation are highlighted in Figure 34 and Figure 35. The ladder or individual segments are manipulated via rubber rollers that contact the ladder and are driven by dc motors. In order for the rollers to have a sufficient contact force for both climbing and extending the ladder, a mounting scheme allows for longitudinal motion, but allows the mount to pivot to account for height differences in each segment, and holds the ladder tight against the rollers via extension springs, as shown in Figure 34. The extension springs are sized according to tension and packaging requirements, assuming a coefficient of friction between the roller and ladder. To increase the coefficient of friction, both a soft rubber adhesive backing and coarse sandpaper are to be applied during prototype testing; and a 1/16 inch gap is designed into the ladder system to allow for clearance for the backing.

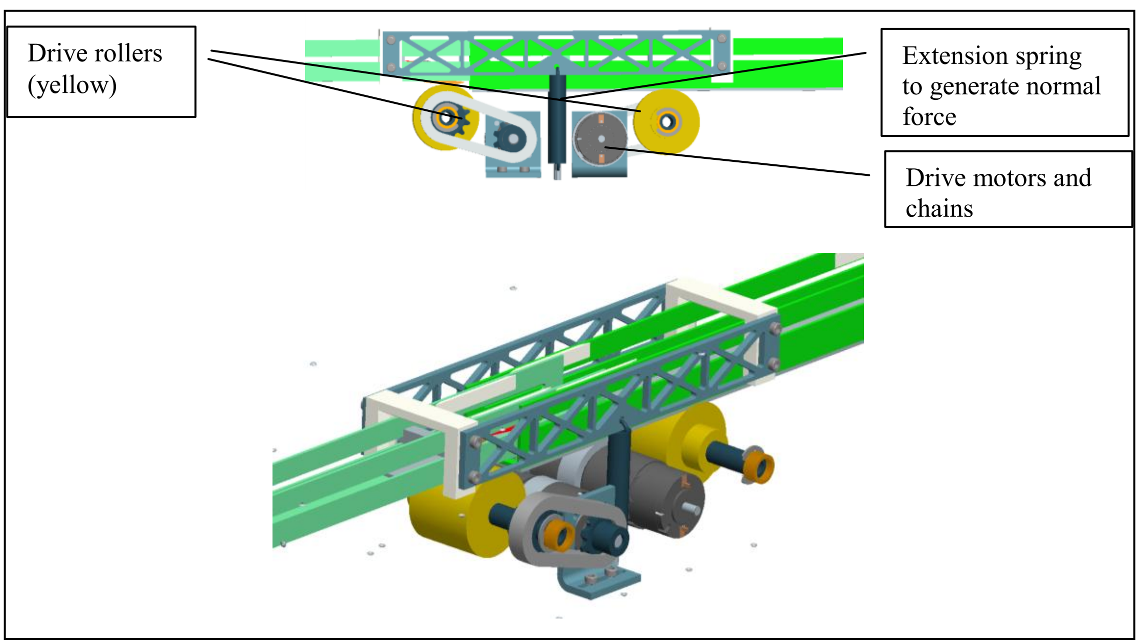


Figure 34 – Details of the rollers and 3D view of mounting system

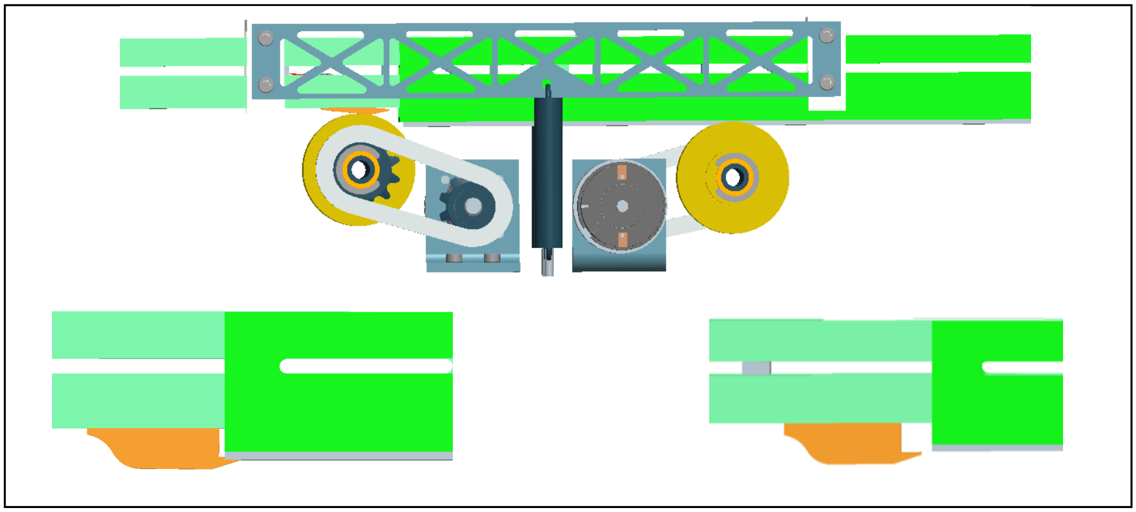


Figure 35 – **Top**: Rollers can be driven in the same direction to move the ladder, and in opposite directions to drive segments together or apart. **Bottom**: When the lock is in position, the lip prevents the roller from depressing it; when the lock is positioned away from the next segment, the roller will depress it and allow the segment to be collapsed into the next segment.

It was necessary to also include a travel limited stop to prevent one segment from closing too far, which may damage the locking mechanism of the next segment, this travel stop is shown in Figure 36.

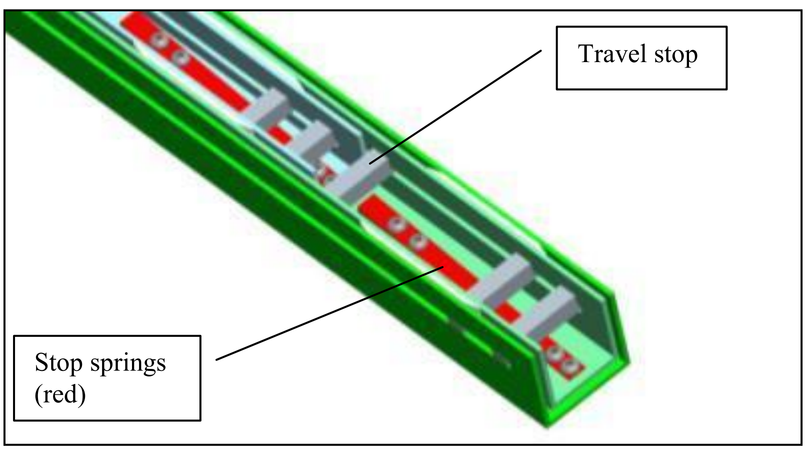


Figure 36 – Travel stop

To enhance the climbing operation, course sandpaper is fixed to the bottom of the ladder to form a high coefficient of friction with the rubber control rollers. The completed design of the ladder results in a collapsed design that measures 18.5 inches and an extended length of 42.5 inches, resulting in an expansion of 2.3 times. With the expanded and collapsed dimensions, the ladder can be nearly concealed within the dimensions of the device, and sufficiently long to be used to negotiate two foot ledges and crevices.

Ladder Orientation

Including a method to rotate the ladder to rest upon the edge of an obstacle is deemed to be advantageous to the design. Designing for this function requires the careful planning and calculation of weights of components, their position, and the required torque in order for the subsystem to operate. Calculations of the torques are discussed above in the design tools section. A motor was selected that would both fit in the tight packaging constraints of the device, and provide sufficient torque. This was the most difficult motor to obtain due to the extremely high torque required for the size. A motor with an attached 516:1 planetary gear head was located which met the design requirements. In addition, the extremely high gear ratio also acts as a one way drive mechanism in which the motor may orient the ladder, but outside factors such as gravity will not be able to affect the orientation, which greatly eases control of the device. To orient the ladder, torque is generated in the motor via batter current, and torque is then transmitted through the motor output shaft to a chain drive linking a sprocket on the motor, and a sprocket on the body axis. The body axis contains a slot in which as key is housed at each end, and the axis transmits torque into the keyways which, in turn, transmit torque into the body frame which allows for the orientation of the body. Figure 37 highlights the design of the torque transmission.

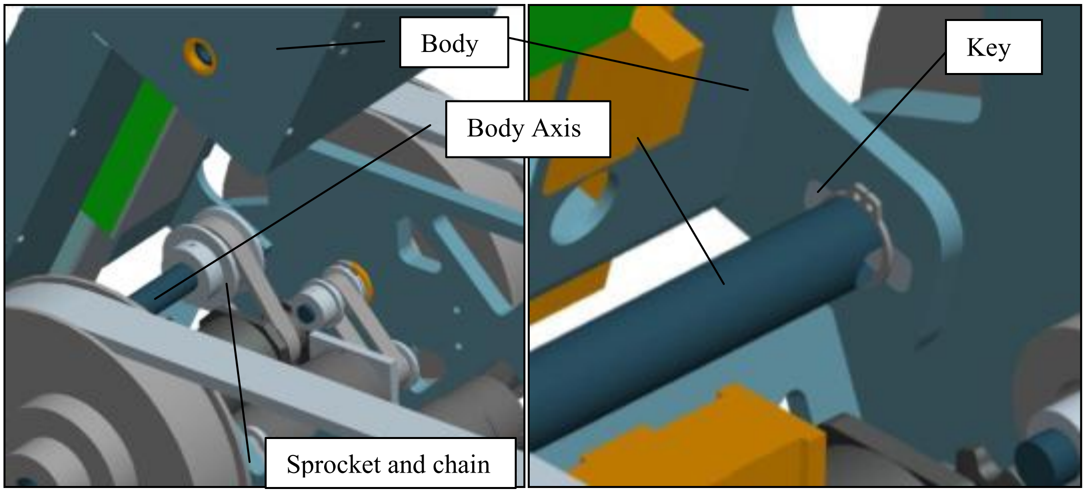


Figure 37 – Chain and sprocket used to transmit torque to body axis (left) Custom keyway used to transfer toque from body axis to the body side (right)

Tensioning Mechanisms

When utilizing drive chains or drive belts, it is critical to allow for the proper tension to be obtained, whether it be with careful placement of pulleys and idlers and their associated mounting locations, or more commonly, with a method to adjust the tension. For the selected concept, both drive treads require tension adjustment, as well as the drive chains for the roller motors, the drive motors, and the motor used to orient the ladder's rotational position.

To allow for tension adjustment between the motor and the associated driven shaft or component, the motor mounts are slotted to allow for adjustable distance. In addition, the slots have a wider dimension on the top portion, such that a nut will not rotate; this prevents the need to insert hands or tools to hold the nut during assembly. The motor mount and mentioned features are shown in Figure 38. Due to tight packaging, one drive motor must also utilize idler pulleys to prevent the drive chain from contacting the other drive motor, as well as to mange tension. The idler pulleys are shown in Figure 38.

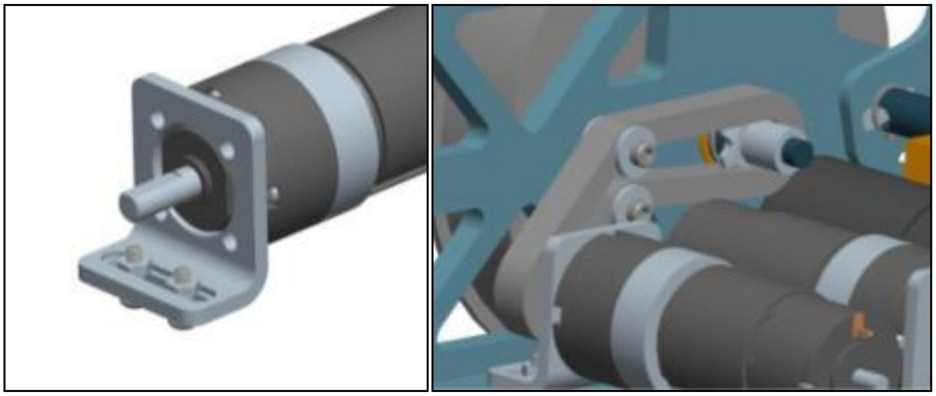


Figure 38 – Motor mount (left) and idler pulleys (right)

To allow for a variable tension in the drivebelts, two of the three shafts are held fixed in the chassis, but the third shaft is allowed to move vertically. The tensioning mechanism fits in a rectangular cutout in the chassis, with the outer plate riding in the cutout, as well as having a lip to contact the outer face of the chassis. An inner plate contacts the inner chassis face, such that when the plates are fastened together with two clamping bolts, friction between the tensioning plates and the chassis faces prevent the plates (and shaft) from moving; however, if the fasters are loosened, the shaft is allowed to move up and down within the bounds of the rectangular cutout dimensioning. This both allows for adjustment of the drive tread's tension, but also allows for easier assembly and disassembly by loosening the tension prior to installation or removal of a drive tread. Details of the drive tread tensioning mechanism are shown in Figure 39.

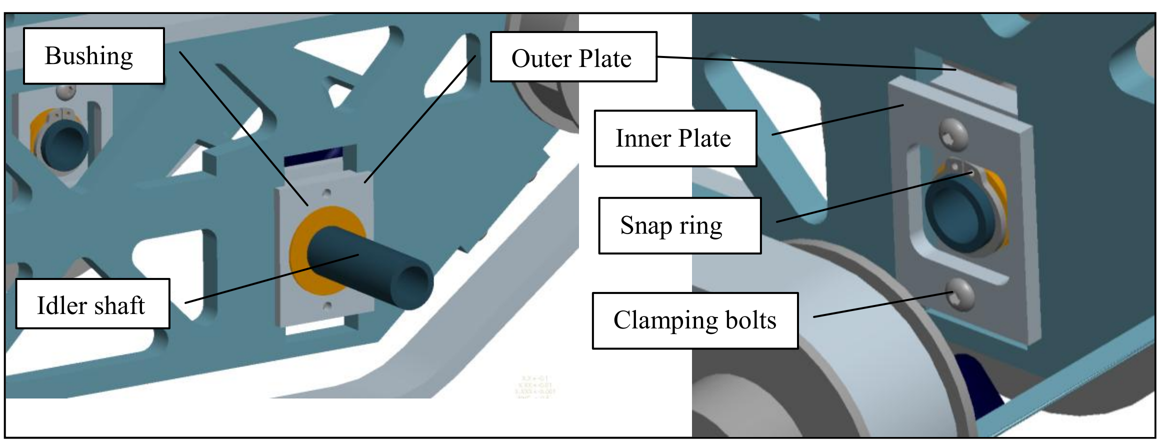


Figure 39 – Details of the tread tensioning mechanism

Other Design Considerations

Since total device weight is a crucial design parameter, wherever it was possible, an attempt to reduce weight was made. One weight saving method was to create "trussing" along the components to retain high stiffness and strength, but significantly reduce weight. Two parts utilizing the trussing are shown in Figure 40.

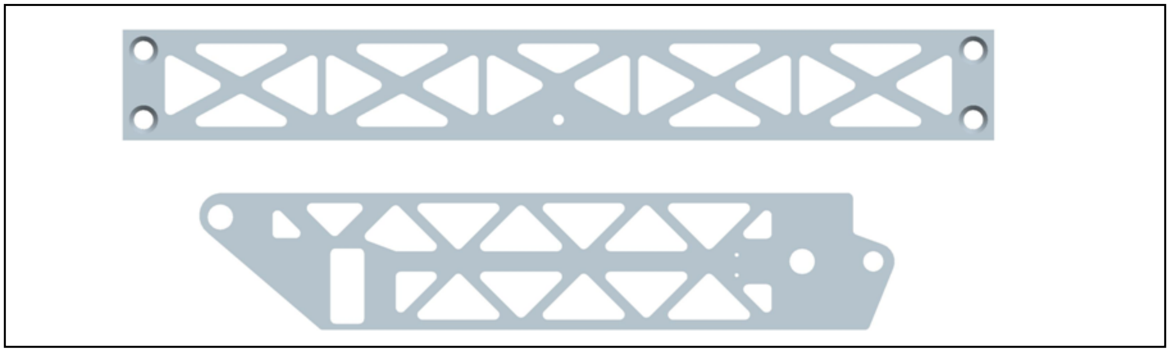


Figure 40 – Highlights weight reducing geometry

Some of the connections are designed to utilize a press fit. Where a press fit was required, namely the 8 holes in which bushing are to be pressed, it was critical to hold tight tolerances during machining as well as call out appropriate tolerances on the component's engineering drawing. For the bushing holes, an unsymmetrical clearance of -0.000 in., +0.002 in., was utilized, this allows for a tight press fit suitable for use but not so tight to cause difficultly in assembly. For other materials or geometry it could be necessary to require different tolerances.

To retain the various shafts in their correct position, snap rings are utilized, which requires grooving each shaft with an appropriate sized groove. Bushings are utilized on the shaft to provide a bearing surface and they are selected over roller bearings to reduce cost at the prototyping level. Appropriate sized and sealed needle roller bearings would be suitable for a final model for their reduced friction, small diameter, and moment carrying capability.

Another critical aspect for design for manufacturing is that the parts that require machining have certain geometry to allow for easy clamping. Iterations on several parts were made such that there were sufficiently long straight edges that the parts may be easily clamped in standard milling machine vices.

SUMMARY

Concepts are collected from the designer and experimental concept generation methods. These concepts are filtered and a promising design is selected based on standard concept selection processes and insights gained from the design method. The embodiment of the chosen design is documented as well as the mechanical design and operation features allowing the device to perform as desired. A detailed analysis of required DC motors is performed in order to insure proper motor sizing, and is aided by the development of a bond graph of the system, used chiefly to ensure safe operating currents. With the help of 3D CAD, the concept embodiment is readied for production.

Chapter 6: Prototype Testing and Assessment

INTRODUCTION

This chapter covers the assembly, testing, and repairs of the prototyped highly mobile robot. Also documented are the measurable results and a discussion of the results against design goals and against the collection of data stored in the repository to highlight the impact on the field.

ASSEMBLED DEVICE

Assembly of the device was performed in three stages consisting of the electrical system, drivetrain, and ladder system, or "body." The purpose of separating assembly stages is to ease troubleshooting should incompatibilities or other failures occur, and when each subsystem operates as intended, they are combined to complete the device.

All electronics were mounted onto a test assembly in order to test functionality and correct wiring configuration, as well as to verify the condition of each component before installation onto the device. Additionally, communication between the radio, receiver and speed controllers are configured and set up while all components are accessible on the test fixture in order to ease the complexity of final installation. Figure 41 shows this electrical test fixture.

Figure 41 – Building electronic test fixture (left), completed fixture (right)

The next subsystem assembled is the drivetrain. Due to out of tolerance bushing bores, there was too much friction present for the drive motors to turn the drivetrain. One partial solution was to “break in” the bushings and shafts by affixing the assembly to a lathe at low rpm to “set’ the connections (Figure 42). The addition of a grease lubricant also reduced friction, as the PTFE impregnated bronze bushing proved to bind under load. In addition to the introduction of grease and breaking in the surfaces, the drive motors were switch to a higher reduction ratio, as discussed in the following redesign section, to provide more torque to the system.

Figure 42 – Reaming poor tolerance bushings (left) and seating bearings and shafts (right)

The final subsystem assembly is the ladder system, or “body”. The body houses the roller drive motors to orient the ladder, as well as the radio electronics and other electronic equipment such as the camera. Upon assembly of the ladder and body, the system’s mechanical functionality is verified to insure mechanical operation and assembly clearances (Figure 43, Figure 44).

Figure 43 – Ladder assembly, from left: lock assembly, ladder extended and resting on an obstacle, ladder in collapsed configuration

Figure 44 – Body and ladder subsystem assembly

Upon completion of each subsystem, the device in its entirety may be assembled and formally evaluated. The completed device is shown below in Figure 45.

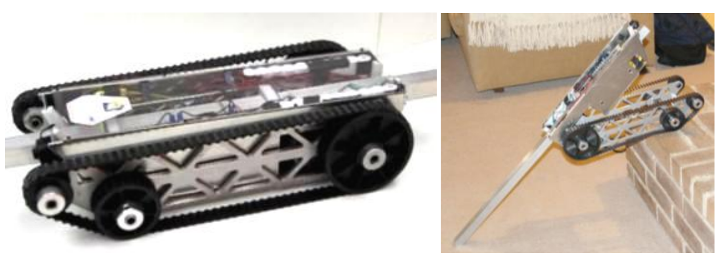


Figure 45 – Completed alpha prototype

REQUIRED REDESIGN: UNFORESEEN PROBLEMS AND FAILURES

Between final assembly and formal testing, several design oversights and flaws were made apparent and required addressing before testing could be continued.

As mentioned above, the first set of ordered bushings had loose tolerances leading to binding shafts. New bushings with tighter tolerances were ordered, reamed prior to installation, and shafts lubricated with lithium grease. These changes allowed for reduced friction in the drivetrain, but still produced enough resistance to overload the motors through the 14:1 gearbox. It was decided that utilizing a 35:1 ratio, identical to the roller drive motors, would provide sufficient torque while still allowing for acceptable top speeds at around 4 feet per second (1.1 m/s).

The coefficient of friction of 35A durometer rubber against itself was overestimated at a value of 1. The original design utilized the mentioned durometer rubber for both the roller and rubber backing on the ladder. Due to the overestimation of the coefficient of friction, the ladder tended to slip when the device was trying to climb at near vertical angles. Two changes were implemented to mitigate slipping. Firstly, the rubber backing was changed to 30 grit sandpaper, which was affixed to the back of the ladder with two-part epoxy. Also, the original extension springs (see Chapter 5) were swapped for springs of similar geometry, but would produce twice the tension when installed on the device.

The ladder also would tend to slip where it contacted the ground. In order to resist ground contact slipping, screws were epoxied to the bottom of the ladder, as well as sharpened as to dig into the ground surface Figure 46.

Figure 46 – Screws affixed to the ladder for increased ground contact friction and adhesion

Virtually all the set screws failed to maintain their tension, and would back away from the shafts after minimal usage even with the utilization of thread locking compound. To mitigate the problems associated with set screws, holes were drilled into all shafts under ½ inch in diameter, and set screws installed in such a way that they are loaded in either single or double shear, depending on the part) in order to reduce the tendency to loosen. In the case of the body motor, a shear pin is utilized instead of a set screw in shear to limit damage should the body orientation motor fail to shut off in the appropriate position, the pin is designed to shear at approximately 1.3 times the require torque and requires about 20 minutes of labor to replace. The body orientation motor requires 100+ lb-in torque to orient the ladder system, but that amount of torque was also found to shear set screws, snap motor shafts, shear planetary gear teeth, and plastically deform the motor mount, as shown in Figure 47. A clutch system that simply slips in the event of over-torque or hyper extension, or position switches that limit motion would be an ideal modification for future versions of the device.

Figure 47 – Failed motor mount due to body orientation motor failing to shut off in the appropriate position

Another change that improved climbing performance was to remove the front chassis brace, connecting the two chassis sides. The screws mounting the brace would contact the edge of an obstacle, preventing proper negotiation. While removing the brace makes the device more susceptible to damage upon falling off a vertical ledge, or other high loading conditions, the chassis could be retrofitted with stiffeners to regain the lost strength; and the device overcomes the corners with much more ease without the brace.

TEST PROCEDURE

Method and Metrics

The test procedure to establish performance of the device is a combination of procedures to record easily measureable values, such as dimensions and mass and more difficult evaluations, such as determining how rough of terrain the device is able to traverse. The metrics previously discussed in Chapter 3 in the development of the repository are used to measure the main performance goals of the device, including obstacle height, mass, speed, minimum cross sectional diagonal, locomotive and vertical power consumption, payload mass, and operational time.

Due to the highly unpredictable and unreliable nature of prototype devices, as opposed to commercial products, initial testing is performed in a controlled office environment in order to minimize time wasted commuting to a test site, only to have a failure require a trip back to a suitable repair area. After the device is proven in the office environment, it may be brought to a more rugged outdoor setting comparable to the intended usage environment. In the office environment, the device may attempt to overcome file cabinets, desks, or chairs, in order to determine the height in which it can negotiate, as well as creating crevices between desks to test if the device can successfully cross a crevice. Payload mass is determined by fixing a spring scale to the device to read at which value of scale tension causes the rollers to slip, rather than drive the device up the ladder, this serves as the maximum payload mass as it is the mass at which the device can no longer perform as required. The metrics mentioned above will be measured and recorded, and other goals of interest will be investigated, such as the tallest object the device can surmount without high centering.

After initial testing is completed, the device is able to be tested in an environment more closely resembling real world conditions. A metropolitan park featuring packed dirt trails, rocky trails, limestone ledges, and settings suitable for testing the devices ability to negotiate ledges, crevices, and rough terrain in a "real" test environment.

RESULTS

The device's physical performance results were evaluated as well as compared against devices discussed in the highly mobile robotic background section in Chapter 2. The physical results and plots highlighting relative performance are discussed below. Measured results are shown below in Table 8, and are based on preliminary testing in a controlled environment. Outdoor environment testing is expected soon and is discussed in the future work section in Chapter 7. One design goal was for the device to be capable of entering a drilled hole, or small opening 8 inches in diameter. The device currently has a minimum cross section of 9.25in, but can be easily modified to meet the 8 inch criteria by redesigning the attachment of the tread idler pulleys. The off-the-shelf pulleys include a ½ inch wide aluminum hub housing the set screws to fasten the hub to the shaft. However, if these aluminum hubs were removed and the pulley fixed to the shafts with snap rings, the minimum diagonal could be reduced to 8 inches. The device was tested to have a maximum payload mass of 15 lb (6.8 kg) before the rollers that control the ladder began to slip. The maximum obstacle height is solely a function of the ladder length, and the device was tested with a ladder length of 42 inches, the length of the telescoping ladder in its extended state. A ladder length of 42 inches allowed the device to overcome a maximum vertical obstacle of 27 inches, and is able to both ascend and descend the obstacle. Also, the device was shown to be able to cross a 24 inch crevice, but had difficultly exiting the crevice due to poor tracking with the timing belt treads. The device was tested on rubber and carpeted stairs to test capability to negotiate up a staircase. The device was proven capable of surmounting stairs by using the ladder to hoist the device up 2 to three stairs and a time, allowing the device to climb a long staircase. Though the staircase must be attacked in segments, the use of the ladder adds minimum time to surmounting stairs but allows for a shorter length as it does need to maintain contact on multiple stair apexes as competing design such as the packbot [3]. Tabular quantitative results are found in Table 8 and a series of still photographs showing traversal of a vertical obstacle in Figure 48. Video footage of the device actively negotiating the obstacles can be viewed at the following URL:

http://www.youtube.com/watch?v=UmxJSIz-lSw (accessible only by URL, unlisted).

Figure 48 – Device obstacle traversal (up and down)

Table 8 - Measured performance results

Metric	**Value**
Dimensions	4.5x8.1x17.6 in 0.114x0.206x0.447 m
Minimum Cross Sectional Diagonal	9.25 in 0.235 m
Weight	12lb 13oz (5.8 kg)
Payload	15 lb (6.5 kg)
Maximum Vertical Obstacle Height	27 in (.686 m)
Maximum Crevice Width	24* (Partially successful)
Vertical Power Consumption	40 W
Horizontal Power Consumption	40 W
Speed	4 ft/sec (0.102 m/s)
Nominal Operating Time	30 min
Stair Capable	Yes

In comparing vertical and horizontal power consumption, either the reported actual measured value or reported maximum motor power output is used. The presented device utilizes two 20W motors for both traversal and negotiating obstacles, which are the recorded values. Actual consumption as estimated through the formulated bondgraph is estimated to be 12W near steady state, but may significantly underestimate the resistive frictional forces which can be difficult to measure. Nominal operation time of the devices is 30 minutes, consisting of an estimated 70 percent driving or traversal time and 30% climbing time. The operational time is limited by the two NIMH 1.1mAh battery packs currently installed in the device. Utilization of lithium ion battery packs typically have four times the energy density which may increase deployment time to 2 hours, or even longer since the lithium cells are more easily formed into custom shapes than NIMH cells which are traditionally limited to cylindrical geometry, reducing volume efficiency. The device was measured to have a top speed of 4 feet per second, nearly identical to the calculated top speed based on motor RPM and gear ratios. Also, the device clears obstacles measuring up to 2 inches using momentum and traction, but not the ladder system. However, obstacles measuring only 0.5 inch, such as a small branch or extension cord could, on occasion, high center the device preventing motion. Soft rubber treads were affixed on top of the original timing belt treads, which decreased the tendency to high center, but were not reliable. Further tread modifications are discussed in the future work section in Chapter 7.

The performance of the device relative to other devices in the repository is shown below. One of the prime goals of the device was to have a small cross sectional area but maximum obstacle capabilities. Some pneumatic and spring launched devices have impressive height capabilities, but often suffer from small payload capabilities. Figure 49 shows that the presented device was able to allow a tracked vehicle to dramatically increase its obstacle performance, performing equivalently to tracked segmented designs with more than two to three times the cross section. The presented device is circled by a dotted line while the other two similar markers are previous prototypes utilizing a cylindrical two wheeled design at USAFA. The closely performing segmented design near the presented design is the Omnitread design [77]. Two improvements are shown here. One improvement includes an obstacle height improvement of 9 inches. Also, the Omnitread design utilizes multiple segments, resulting in a relatively long package, similar to snake type devices. The proposed design is able to collapse its telescoping ladder which allows for a more compact device which may help traversal in tight quarters, which are expected to be encountered in the proposed applications.

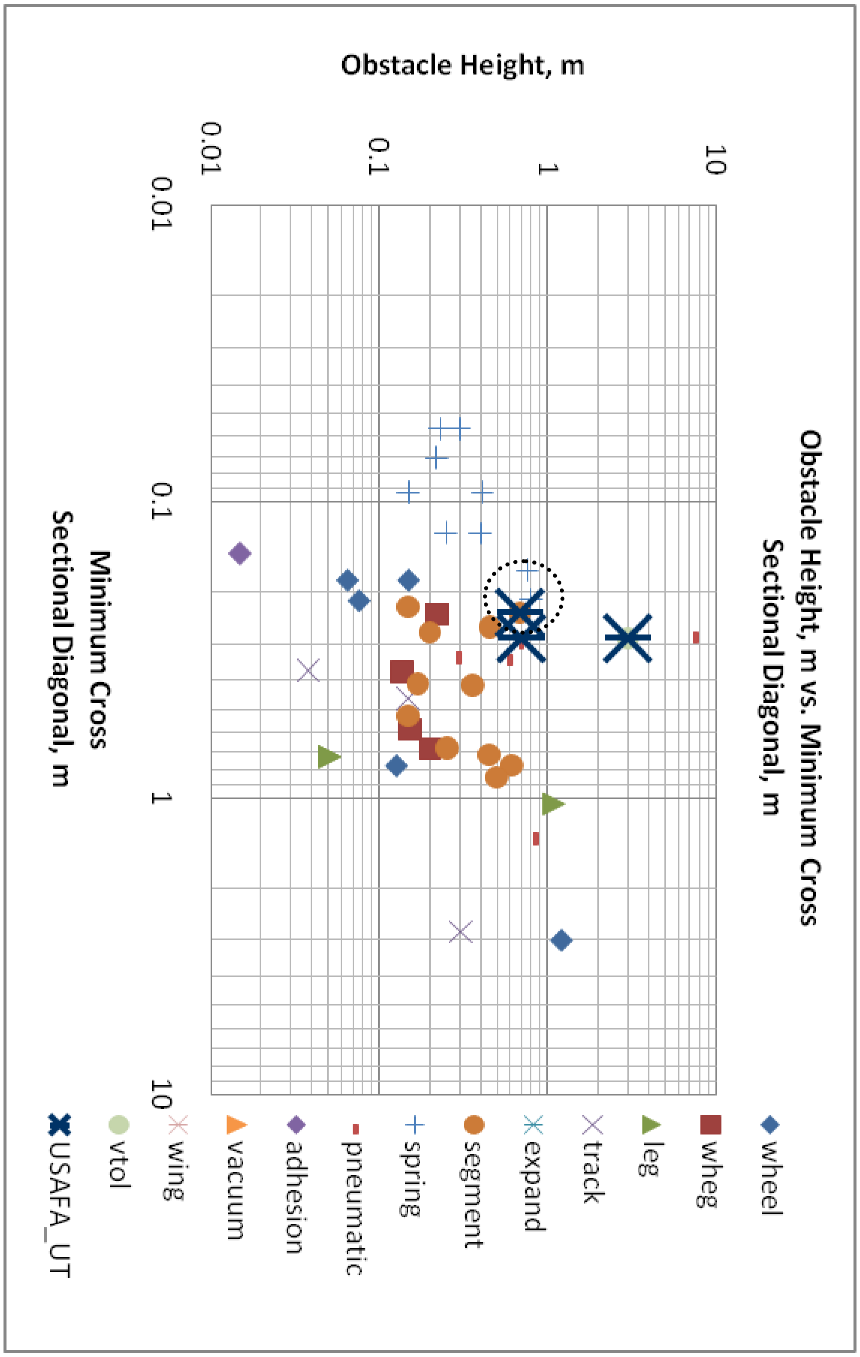


Figure 49 – Plot of obstacle height versus cross sectional size

Noteworthy on Figure 50, comparing obstacle height versus mass, is that the proposed device fills an apparent void in the design space, shared only with one USAFA solution, mentioned above, which adds a pneumatic cylinder to a two wheeled design resembling the toughbot [90]. Aside from very large devices, only sprung, pneumatic, and thrust based designs were capable of obstacles of near to 1 m in height. One downfall to those designs is their applicable mass ranges, meaning, they are not suitable for large, more massive, devices. The proposed device is able to perform as well as these devices, yet expand the mass range significantly compared to springs, and by double relative to top performing pneumatic design, meaning the proposed solution could be preferable when payloads are required. Figure 51 highlights that the design is able to reduce power consumption for overcoming obstacles as compared to non-sprung devices, yet maintain a large obstacle capability. Figure 52 and Figure 53 show the proposed design followed the existing trends in payload capacity on a mass basis as well as locomotion power requirements, which are two of the more developed trends of all the data indicating innovation in these areas might be very difficult.

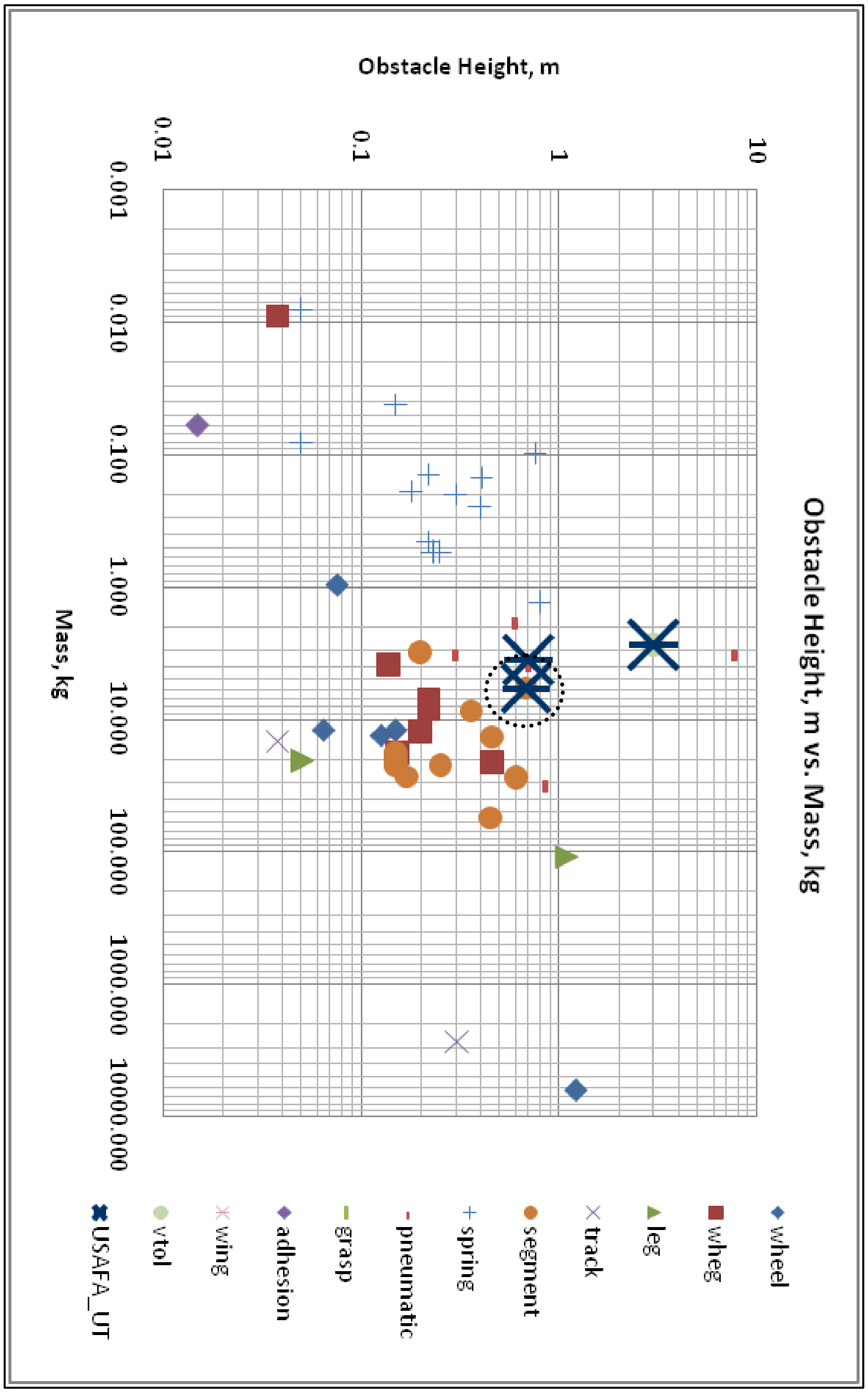


Figure 50 – Obstacle height versus mass

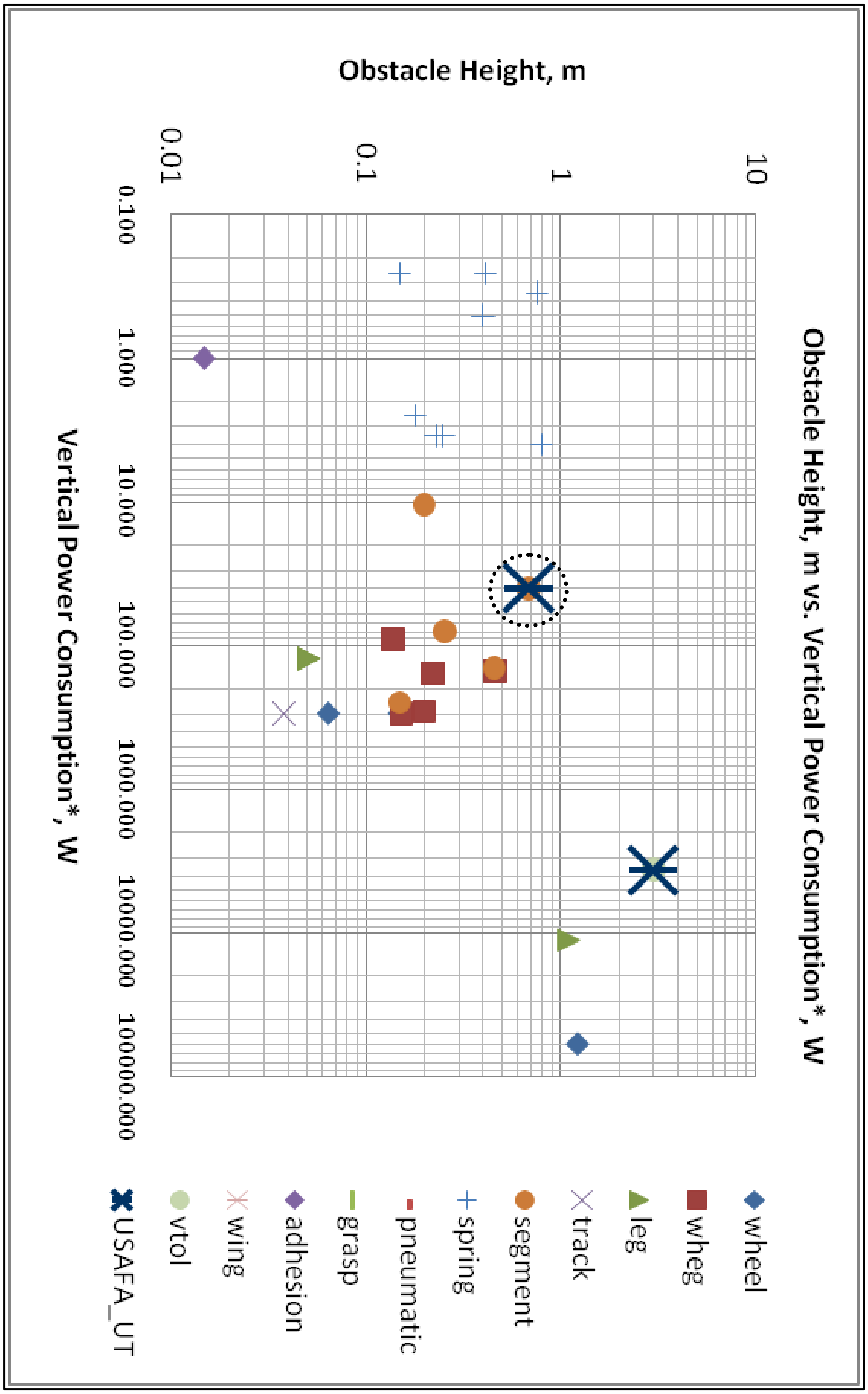


Figure 51 – Obstacle height versus vertical power consumption

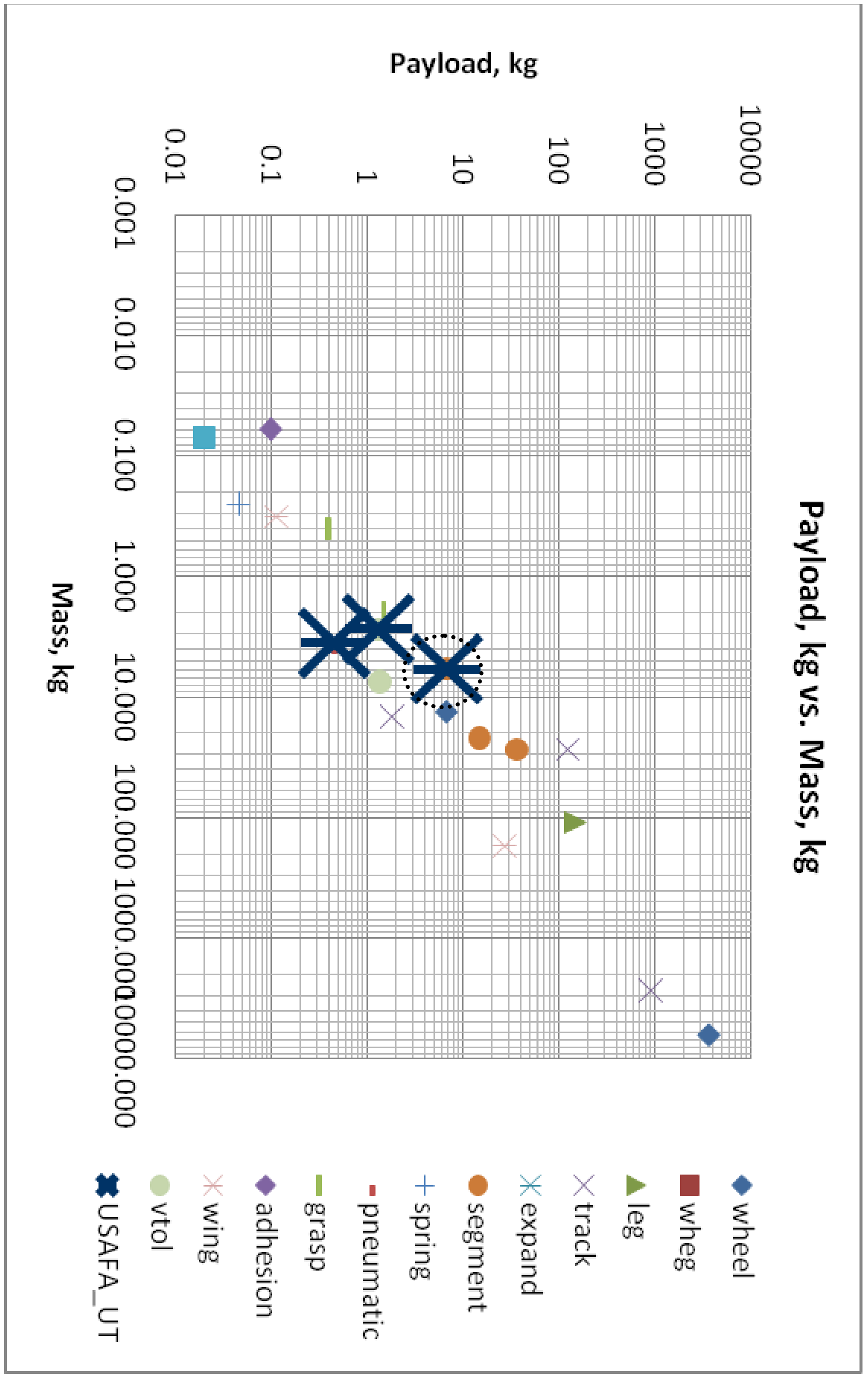


Figure 52 – Payload versus mass

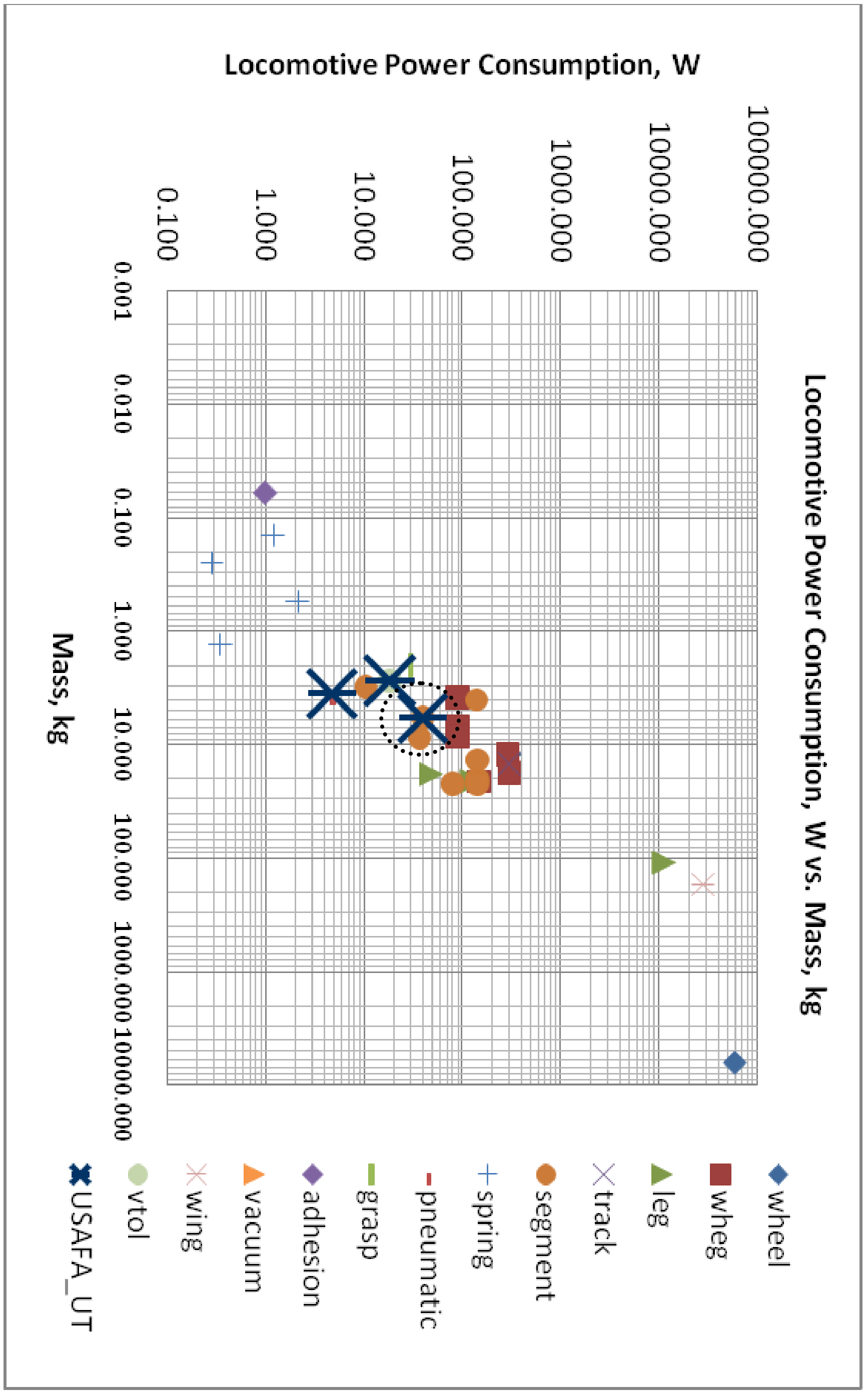


Figure 53 – Locomotive power versus mass

Summary

A prototype is manufactured and tested to evaluate if the design methodology and insights may lead to innovation, in this case, a device to expand the existing design space to allow highly mobile robots to perform well with respect to various metrics, including obstacle negotiation, compact size, and low energy consumption. The embodied concept, which utilizes a telescoping ladder to overcome obstacles, proves to overcome relatively tall obstacles, outperforming existing devices while requiring less energy than existing designs. The device expands the existing design space with respect to its size to obstacle size ratio and payload capacity with respect to device mass. The prototype proves the methodology can lead to innovative ideas, and is tested to meet the critical design criteria. Shortcomings and future work for the device are discussed.

CONCLUSION

Chapter 7: Conclusion and Results

This work on a whole has lead to exciting insights and advancements in the research areas addressed. The proposed research methodology has, thus far, proved to be useful in increasing innovation and exploration of the design space at the conceptual stage. The methodology also leads to a deliverable electronic spreadsheet with code that allows for the easy capture, analysis, and presentation of data. Using the methodology to development and manufacture of a highly mobile robot proves the usefulness of the methodology to find solutions in unexplored design space, outperforming existing devices in several respects. Discussions of these results and final thoughts are addressed below.

DESIGN METHODOLOGY AND TOOL

The design tool was developed to aid the design process and design decisions, but more importantly, to encourage and generate creativity, invention, and innovation. The empirical study of the current state of highly mobile robotics allowed for the creation of a repository, housing relevant data for the devices. Plots created from the data were useful in analyzing the data and obtaining insights into the current state of technology. The review of the technological field provides a basis for seeking innovative solutions such as hybrid designs, or combining existing knowledge with data from the plots could help designers find innovative solutions and expand the existing design space. A study using participants from The University of Texas at Austin and the United States Air Force Academy validates these hypotheses. Most notably, the study found that participants were able to match the number of ideas generated in initial concept generation sessions after exposure to the design methodology. The relevance of this finding is supported by the emphasis given on quantities of ideas with respect to product development success

[116] as well as implications associated with the presentation of analogies. Linsey finds that through presenting student designers with analogous solutions, the designers find solutions they are otherwise unlikely to realize [19], [118], [29], [117]. One conclusion about the results on quantity is that through presenting analogous solutions, the collection of robotic data as a whole, designers are able to generate more solutions to the design problem. Novelty and quality, however, were not shown to be significantly impacted after exposure to the design tool. This may be accurate, or depend heavily on how the particular metrics are measured as they are a more subjective attribute to quantify than quantity.

Future Work

Two major considerations to address to solidify the developed methodology and associated experiments are the use of inter-rater reliability and the participant sample size. Inter-rater reliability serves to make the results independent of the grader reviewing the concept generation results, removing bias. Also, the relatively small sample size of the study at UT Austin of 12 participants limits the significance of the finding. To further validate the findings, both the increasing the sample size and utilizing a control group to determine the effect of a lingering design problem in the minds of participants should be investigated, to determine if the subconscious consideration of the design problem during the time between study sessions contributes significantly to the number of ideas produced. Other considerations to address include using multiple concept generation methods so that the results are independent of the method and investigating the effects of interpersonal dynamics of the participant groups.

Design of a Highly Mobile Robot

Using the proposed design methodology, multiple concepts are generated while searching for solutions to the design problem. A concept which utilizes a telescoping “ladder” is selected to embody which is expected to outperform existing devices with respect to critical design requirements, which may both validate the design methodology as well as expand the current design space of highly mobile robots. Modeling the device in a 3D CAD program aids the mechanical design process. Other design tools in addition to the modeling software allows for addressing several design challenges. Bond graph theory aids in the selection of appropriate DC motors in conjunction with a working bond graph model built in Matlab. Electronic spreadsheets and computational FEA allow for the calculation on various highly loaded components to ensure proper operation.

The design is manufactured and assembled for testing and multiple unforeseen problems with the device are addressed to improve performance of the device. Once operable, the device performs well and shows notable improvements to the current state of technology. The device fills a design space that was previously void, performing as well as sprung devices in terms of maximum obstacle height, while drastically increasing device mass capabilities. Additionally, the presented design outperforms a similarly impressive device utilizing multiple tracked segments in a snake-like configuration, in form factor. The presented design is able to overcome obstacles 9 inches taller, yet due to the telescoping ladder, can be configured to a much shorter overall length. Similarly, the presented design expands the current design space by increasing the allowable mass for similar designs and reducing energy consumption. Previously, similar sized devices were significantly lighter, a virtual requirement in order for the designs to overcome tall obstacles. By climbing the ladder instead of jumping, the device shows it’s possible to carry larger devices and payloads without losing the ability to overcome large obstacles. Also, as shown in Figure 10 of Chapter 6, the device uses less energy when negotiating vertical obstacles than the observable average, while still being capable of negotiating taller obstacles.

Future work

While the prototype demonstrates satisfying results, there are several areas of improvement required for the device to progress toward a deployable or commercial state. One critical area of improvement is the operation of the telescoping ladder. The ladder was successfully shown to be expanded remotely, and used by the device to overcome 27 inch obstacles. However, due to mechanical interference the ladder is difficult to collapse and store in the device for further exploration. Work to increase the compatibility of the ladder and ladder support system could greatly increase the marketability of the device. A known limitation of the prototype was due to monetary constraints and considerations and limits ground clearance as well as traction. The limitations are due to the utilization of timing pulleys and belts for a tread system as custom tread systems cost thousands of dollars, or an order of magnitude more than the prototype configuration. A custom rubberized tread with flexible treads might be utilized to increase traction, serving to help overcome the corners of ledges as well as increase ground clearance to prevent high centering of the device. The device can, at times, fall to the side while climbing the ladder to overcome obstacles. The easiest solution to tipping could be to add a “foot” to the ladder which widens the contact at the base of the ladder allowing for more stability. Switching NIMH battery cells to lithium polymer cells might also serve to dramatically increase deployment time, increasing usefulness of the device.

FINAL THOUGHTS

The work presented here shows great potential for future exploration and development. The systematic approach of collecting empirical data to analyze, extract knowledge, inspire new ideas, and guide design direction shows potential for increasing the number of ideas and likelihood of success. The associated electronic repository and code may be easily adapted and applied to new problem domains to continue evaluation of the methodology. Similarly, the robotic device performed exceptionally well for an alpha level prototype due, in part, to the meticulous design and aid of solid modeling software as well as careful machining. The device shows promising results to an untraditional solution, and may be easily pushed forward to be competitive with commercially available and state-of-the-art technologies.

The opportunity to work on such an interesting and open ended design problem, in both methodology and physical realms, is truly an opportunity of a lifetime, and will continue to be a value experience for future work experiences. The author is grateful for all the help offered from UT Austin faculty and staff, students, friends, and family.

Appendix A: Repository VBA Code

VBA code to sort technology according to locomotive technology

Sub create_loco_sheet()

```
' Creates a header, creates space for various obstacle negotiaing robots, creates filter criteria _
' hides extra rows (for future use), and colors the used space for visual aide.

Application.ScreenUpdating = False
ThisWorkbook.Worksheets("locomotion_tech").Select

'populate header
Range("a1").Value = "=shname(a1)"
Range("a2").Value = "Loco"
'range("a3").Value = "Sorted by obstacle negotiating technology"

' fill the metrics row in the header
ThisWorkbook.Names.Add Name:="metrics", _
RefersTo:=Worksheets("DATABASE - MASTER").Range("a3:AM3")

i = Range("metrics").Columns.Count
Range("a4").Select

For j = 1 To i
   Cells(4, j) = "=metrics"
   Next j

'fill range names in header
ThisWorkbook.Names.Add Name:="range_names", _
RefersTo:=Worksheets("DATABASE - MASTER").Range("g2:Ak2")

i = Range("range_names").Columns.Count
Range("a3").Select

For j = 1 To i
   Range("g3").Cells(1, j) = "=range_names"
Next j

Columns("a:am").ColumnWidth = 30

'Add the various loco technologies

   Range("A5").Select
   ActiveCell.FormulaR1C1 = "wheel"
   Range("B5").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A6").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B6").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("a7").Value = "*" & Range("a5") & "*"

  Range("A100").Select
   ActiveCell.FormulaR1C1 = "wheg"
   Range("B100").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A101").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B101").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("a102").Value = "*" & Range("a100") & "*"

   Range("A200").Select
   ActiveCell.FormulaR1C1 = "leg"
   Range("B200").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A201").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B201").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("a202").Value = "*" & Range("a200") & "*"

   Range("A300").Select
   ActiveCell.FormulaR1C1 = "track"
   Range("B300").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A301").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B301").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("a302").Value = "*" & Range("a300") & "*"

   Range("A400").Select
   ActiveCell.FormulaR1C1 = "snake"
   Range("B400").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A401").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B401").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
```

```
   Range("a402").Value = "*" & Range("a400") &
"*"

   Range("A500").Select
   ActiveCell.FormulaR1C1 = "thrust"
   Range("B500").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A501").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B501").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("a502").Value = "*" & Range("a500") &
"*"

   'hide excess rows for ease of use

Range("20:96,115:196,215:296,315:396,415:496,515:596,615:696,715:796,815:896,915:996,1015:1196,1215:1296,1315:1396,1415:1496").Select
   Selection.EntireRow.Hidden = True

'sort the master database w/ advanced filter
Call sort_sh

'Color, bold, outline cells
Call visual_package

'name ranges to ease plot creation
Call name_ranges

Application.ScreenUpdating = True

End Sub
```

VBA code to sort technology according to obstacle negotiating technology

```
Sub create_obs_sheet()
' Creates a header, creates space for various obstacle negotiaing robots, creates filter criteria _
' hides extra rows (for future use), and colors the used space for visual aide.

Application.ScreenUpdating = False
ThisWorkbook.Worksheets("obstacle_tech").Select

'populate header
Range("a1").Value = "=shname(a1)"
Range("a2").Value = "Obs"
'range("a3").Value = "Sorted by obstacle negotiating technology"

' fill the metrics row in the header
ThisWorkbook.Names.Add Name:="metrics", _
RefersTo:=Worksheets("DATABASE - MASTER").Range("a3:AM3")

i = Range("metrics").Columns.Count
Range("a4").Select

For j = 1 To i
   Cells(4, j) = "=metrics"
   Next j

'fill range names in header
ThisWorkbook.Names.Add Name:="range_names", _
RefersTo:=Worksheets("DATABASE - MASTER").Range("g2:Ak2")

i = Range("range_names").Columns.Count
Range("a3").Select

For j = 1 To i
   Range("g3").Cells(1, j) = "=range_names"
   Next j
Columns("a:am").ColumnWidth = 30

'Add the various obstacle negotiating technologies
'wheel loco
   Range("A5").Select
   ActiveCell.FormulaR1C1 = "wheel"
   Range("B5").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A6").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B6").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"

   Range("B7").Value = "*" & Range("a5") & "*"

'wheg loco
   Range("A100").Select
   ActiveCell.FormulaR1C1 = "wheg"
   Range("B100").Select
   ActiveCell.FormulaR1C1 = "filter"
   Range("A101").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"
   Range("B101").Select
   ActiveCell.FormulaR1C1 = "=filter_crit"

   Range("B102").Value = "*" & Range("a100") &
"*"

'leg loco
```

```
    Range("A200").Select
    ActiveCell.FormulaR1C1 = "leg"
    Range("B200").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A201").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B201").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B202").Value = "*" & Range("a200") &
"*"

'track loco
    Range("A300").Select
    ActiveCell.FormulaR1C1 = "track"
    Range("B300").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A301").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B301").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B302").Value = "*" & Range("a300") &
"*"

'expand loco
    Range("A400").Select
    ActiveCell.FormulaR1C1 = "expand"
    Range("B400").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A401").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B401").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B402").Value = "*" & Range("a400") &
"*"

'segment loco
    Range("A500").Select
    ActiveCell.FormulaR1C1 = "segment"
    Range("B500").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A501").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B501").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B502").Value = "*" & Range("a500") &
"*"

'spring loco
    Range("A600").Select
    ActiveCell.FormulaR1C1 = "spring"
    Range("B600").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A601").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B601").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B602").Value = "*" & Range("a600") &
"*"

'pneumatic loco
    Range("A700").Select
    ActiveCell.FormulaR1C1 = "pneumatic"
    Range("B700").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A701").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B701").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B702").Value = "*" & Range("a700") &
"*"

 'grasp loco
    Range("A800").Select
    ActiveCell.FormulaR1C1 = "grasp"
    Range("B800").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A801").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B801").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B802").Value = "*" & Range("a800") &
"*"

 'adhesion loco
    Range("A900").Select
    ActiveCell.FormulaR1C1 = "adhesion"
    Range("B900").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A901").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B901").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B902").Value = "*" & Range("a900") &
"*"

 'van der waals loco
    Range("A1000").Select
    ActiveCell.FormulaR1C1 = "van der waals"
```

```
    Range("B1000").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A1001").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B1001").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B1002").Value = "*" & Range("a1000")
& "*"

 'vacuum loco
    Range("A1100").Select
    ActiveCell.FormulaR1C1 = "vacuum"
    Range("B1100").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A1101").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B1101").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B1102").Value = "*" & Range("a1100")
& "*"

 'bouyancy loco
    Range("A1200").Select
    ActiveCell.FormulaR1C1 = "bouyancy"
    Range("B1200").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A1201").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B1201").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B1202").Value = "*" & Range("a1200")
& "*"

 'wing loco
    Range("A1300").Select
    ActiveCell.FormulaR1C1 = "wing"
    Range("B1300").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A1301").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B1301").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B1302").Value = "*" & Range("a1300")
& "*"

 'vtol loco
    Range("A1400").Select
    ActiveCell.FormulaR1C1 = "vtol"
    Range("B1400").Select
    ActiveCell.FormulaR1C1 = "filter"
    Range("A1401").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"
    Range("B1401").Select
    ActiveCell.FormulaR1C1 = "=filter_crit"

    Range("B1402").Value = "*" & Range("a1400")
& "*"

'hide excess rows for ease of use

Range("20:96,115:196,215:296,315:396,415:496,51
5:596,615:696,715:796,815:896,915:996,1015:1196
,1215:1296,1315:1396,1415:1496").Select
    Selection.EntireRow.Hidden = True

'sort the master database w/ advanced filter
    Call sort

'Color, bold, outline cells
    Call visual_package

'name ranges to ease plot creation
Call name_ranges

Application.ScreenUpdating = True

End Sub
```

VBA code to automate plot creation

```
Sub make_plot()

'Generates a plot based on either locomotive or
obstacle tech
'prompts user to specify technology and 2 metrics to
plot

Application.ScreenUpdating = False

'Request loco or obs tech
    Dim plot_type As Integer
    plot_type = InputBox("Please specify chart type:"
& vbCrLf & _
            "Enter '1' for plot based on locomotion
technology" & vbCrLf & _
            "Enter '2' for plot based on obstacle
negotiation technology")

'Request the two metrics
    Dim x_metric As Integer
    Dim y_metric As Integer
```

```
   x_metric = InputBox("Please enter the metric
number to plot (1-30)" & vbCrLf & _
                    "on the x-axis.")
   y_metric = InputBox("Please enter the metric
number to plot (1-30)" & vbCrLf & _
                    "on the y-axis.")

'generate a list of loco and obs tech's
'   column one is for loco and c2 for obs
   Dim fltr_lo(25)
   Dim tech(25, 2)

   For j = 1 To 2
      If j = 1 Then

ThisWorkbook.Worksheets("locomotion_tech").Sel
ect
      End If
      If j = 2 Then

ThisWorkbook.Worksheets("obstacle_tech").Select
      End If

      fltr_lo(1) = 5
      ii = 100
         For i = 2 To 25
            fltr_lo(i) = ii
            ii = ii + 100
         Next i

         For i = 1 To 25

            Dim c As Range

            Cells(fltr_lo(i), 1).Select
            For Each c In Selection.Cells
            c = Replace(c, " ", "_")
            Next
            tech(i, j) = Cells(fltr_lo(i), 1)
         Next i
   Next j

'Plots Codes
ThisWorkbook.Worksheets("plots").Select

'code to generate loco plots
'use tech(i,1)

If plot_type = 1 Then

   i = 1
   j = 1
   ActiveSheet.Shapes.AddChart.Select
   ActiveChart.ChartType = xlXYScatter
   With ActiveChart
      .SeriesCollection.NewSeries
      .SeriesCollection(i).Name = tech(i, j)
      .SeriesCollection(i).XValues = Range("loco_"
& tech(i, j) & "_" & x_metric)
      .SeriesCollection(i).Values = Range("loco_" &
tech(i, j) & "_" & y_metric)
   End With

   i = 2
   j = 1
   Do While tech(i, j) <> ""
      ActiveChart.SeriesCollection.NewSeries
      ActiveChart.SeriesCollection(i).Name = tech(i,
j)
      ActiveChart.SeriesCollection(i).XValues =
Range("loco_" & tech(i, j) & "_" & x_metric)
      ActiveChart.SeriesCollection(i).Values =
Range("loco_" & tech(i, j) & "_" & y_metric)
      i = i + 1
   Loop

End If

'code to generate obs plots
'use tech(i,2)

If plot_type = 2 Then

   i = 1
   j = 2
   ActiveSheet.Shapes.AddChart.Select
   ActiveChart.ChartType = xlXYScatter
   ActiveChart.SeriesCollection.NewSeries
   ActiveChart.SeriesCollection(i).Name = tech(i, j)
   ActiveChart.SeriesCollection(i).XValues =
Range("obs_" & tech(i, j) & "_" & x_metric)
   ActiveChart.SeriesCollection(i).Values =
Range("obs_" & tech(i, j) & "_" & y_metric)

      i = 2
   j = 2
   Do While tech(i, j) <> ""
      ActiveChart.SeriesCollection.NewSeries
      ActiveChart.SeriesCollection(i).Name = tech(i,
j)
      ActiveChart.SeriesCollection(i).XValues =
Range("obs_" & tech(i, j) & "_" & x_metric)
      ActiveChart.SeriesCollection(i).Values =
Range("obs_" & tech(i, j) & "_" & y_metric)
      i = i + 1
```

```
   Loop

End If


'Label the Chart
   ActiveChart.ApplyLayout (1)

   With ActiveChart.Axes(xlCategory)
         .Crosses = xlMinimum
         .ScaleType = xlLogarithmic
         .HasMajorGridlines = True
         .HasMinorGridlines = True
   End With

   With ActiveChart.Axes(xlValue)
         .Crosses = xlMinimum
         .ScaleType = xlLogarithmic
         .HasMajorGridlines = True
         .HasMinorGridlines = True
   End With

  With ActiveChart
         .HasTitle = True
         .ChartTitle.Characters.Text =
Range("metrics").Cells(1, 6 + x_metric) & " vs. " &
Range("metrics").Cells(1, 6 + y_metric)
         '(option 2 title)  .ChartTitle.Characters.Text
= "Name the Plot"
         .Axes(xlCategory, xlPrimary).HasTitle =
True
         .Axes(xlCategory,
xlPrimary).AxisTitle.Characters.Text =
Range("metrics").Cells(1, 6 + x_metric)
         .Axes(xlValue, xlPrimary).HasTitle = True
         .Axes(xlValue,
xlPrimary).AxisTitle.Characters.Text =
Range("metrics").Cells(1, 6 + y_metric)
   End With

Application.ScreenUpdating = True

End Sub
```

<u>VBA code to name data ranges to ease automated sorting</u>

```
Sub name_ranges()

'name the orginal data range, get width
   ThisWorkbook.Names.Add Name:="perf_data", _
   RefersTo:=Worksheets("DATABASE -
MASTER").Range("g1:ak500")

   j = Range("perf_data").Columns.Count

'set filtered page as active
'ThisWorkbook.Worksheets("sorted by
locomotion").Select
' -or-
'warn user to have the filtered WS selected / user
select which one?

'set WS name for prgramming ease
   wsname = ActiveSheet.Name

'Name the metric name range
   ThisWorkbook.Names.Add Name:="x_name", _

RefersTo:=Worksheets(wsname).Range("g3:ak3")

'sets either loco or obs prefix
Prefix = Range("a2")

'make an array with the filter locations and names
Dim fltr_lo(25)
Dim fltr_nm(25)

fltr_lo(1) = 5
ii = 100
For i = 2 To 25
   fltr_lo(i) = ii
   ii = ii + 100
Next i

For i = 1 To 25

   Dim c As Range

   Cells(fltr_lo(i), 1).Select
   For Each c In Selection.Cells
      c = Replace(c, " ", "_")
   Next
   fltr_nm(i) = Cells(fltr_lo(i), 1)
Next i

'Grab range names from ea. filtered sheet
Dim metric_name(25, 50)

For a = 1 To 25
   For i = 1 To j
      metric_name(a, i) = Prefix & "_" & fltr_nm(a)
& "_" & Range("x_name").Cells(1, i)
   Next i
```

```
Next a

'assign the names created above to the appropriate ranges

j = Range("x_name").Columns.Count

For i = 1 To j
a = 6
b = 97

   ThisWorkbook.Names.Add Name:=metric_name(1, i), _
RefersTo:=Worksheets(wsname).Range(Range("x_name").Cells(a, i), Range("x_name").Cells(b, i))

'test
Range(metric_name(1, i)).Select

   Next i

a = 101
b = 197

For ii = 2 To 25

   For i = 1 To j

   ThisWorkbook.Names.Add Name:=metric_name(ii, i), _
RefersTo:=Worksheets(wsname).Range(Range("x_name").Cells(a, i), Range("x_name").Cells(b, i))

   'test
   Range(metric_name(ii, i)).Select

   Next i
   a = a + 100
   b = b + 100
Next ii

Cells(1, 1).Select
End Sub
```

VBA code calls other macros to sort data

```
Sub sort()
'
   ThisWorkbook.Names.Add Name:="orig_data", _
   RefersTo:=Worksheets("database - master").Range("a3:ak500")
'
   wsname = ActiveSheet.Name

   ThisWorkbook.Names.Add Name:="Criteria", _
   RefersTo:=Worksheets(wsname).Range("a6:b7")

   Sheets("DATABASE - MASTER").Range("orig_data").AdvancedFilter Action:= _
       xlFilterCopy, CriteriaRange:=Range("Criteria"), CopyToRange:=Range("A8:ak99" _
       ), Unique:=False


   ThisWorkbook.Names.Add Name:="Criteria", _
RefersTo:=Worksheets(wsname).Range("a101:b102")

   Sheets("DATABASE - MASTER").Range("orig_data").AdvancedFilter Action:= _
       xlFilterCopy, CriteriaRange:=Range("Criteria"), CopyToRange:=Range("A103:ak199" _
       ), Unique:=False

   ThisWorkbook.Names.Add Name:="Criteria", _
RefersTo:=Worksheets(wsname).Range("a201:b202")

   Sheets("DATABASE - MASTER").Range("orig_data").AdvancedFilter Action:= _
       xlFilterCopy, CriteriaRange:=Range("Criteria"), CopyToRange:=Range("a203:ak299" _
       ), Unique:=False

   ThisWorkbook.Names.Add Name:="Criteria", _
RefersTo:=Worksheets(wsname).Range("a301:b302")

   Sheets("DATABASE - MASTER").Range("orig_data").AdvancedFilter Action:= _
```

```
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A303:ak399" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a401:b402
")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A403:ak499" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a501:b502
")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A503:ak599" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a601:b602
")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A603:ak699" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a701:b702
")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A703:ak799" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a801:b802
")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A803:ak899" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a901:b902
")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A903:ak999" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a1001:b10
02")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A1003:ak1099" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a1201:b12
02")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
```

```
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A1203:ak1299" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a1301:b13
02")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A1303:ak1399" _
        ), Unique:=False

    ThisWorkbook.Names.Add Name:="Criteria", _

RefersTo:=Worksheets(wsname).Range("a1401:b14
02")

    Sheets("DATABASE -
MASTER").Range("orig_data").AdvancedFilter
Action:= _
        xlFilterCopy,
CriteriaRange:=Range("Criteria"),
CopyToRange:=Range("A1403:ak1499" _
        ), Unique:=False

' Hide filter crit to ease viewing

Range("8:8,103:103,203:203,303:303,403:403,503:
503,603:603,703:703,803:803,
903:903,1003:1003,1103:1103,1203:1203,1303:130
3,1403:1403").Select
    Selection.EntireRow.Hidden = True
```

End Sub

VBA code to ease usability of repository

Sub visual_package()

```
'color cells for visual effects
Rows("1:4").Select
    With Selection.Interior
      .ColorIndex = 33
    End With

Rows("5:99").Select
    With Selection.Interior
      .ColorIndex = 50
    End With

Rows("100:199").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

Rows("200:299").Select
    With Selection.Interior
      .ColorIndex = 50
    End With

Rows("300:399").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

Rows("400:499").Select
    With Selection.Interior
      .ColorIndex = 50
    End With

Rows("500:599").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

Rows("600:699").Select
    With Selection.Interior
      .ColorIndex = 50
    End With

Rows("700:799").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

Rows("800:899").Select
    With Selection.Interior
      .ColorIndex = 50
    End With

Rows("900:999").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

Rows("1000:1199").Select
    With Selection.Interior
      .ColorIndex = 50
```

```
    End With

Rows("1200:1299").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

Rows("1300:1399").Select
    With Selection.Interior
      .ColorIndex = 50
    End With

Rows("1400:1499").Select
    With Selection.Interior
      .ColorIndex = 46
    End With

'bold header for visual effects

Range("A1:b4,a5:b5,a100:b100,a200:b200,a300:b300,a400:b400,a500:b500,a600:b600,a700:b700,a800:b800,a900:b900,a1000:b1000,a1100:b1100,a1200:b1200,a1300:b1300,a1400:b1400").Select
    Selection.Font.Bold = True

    Rows("4:4").Select
    Selection.Font.Bold = True

' Outline cells for visual aide
    Range("A5:am1600").Select
    Selection.Borders(xlDiagonalDown).LineStyle = xlNone
    Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With

'freeze header for ease of use
    Rows("5:5").Select
    ActiveWindow.FreezePanes = True
```

End Sub

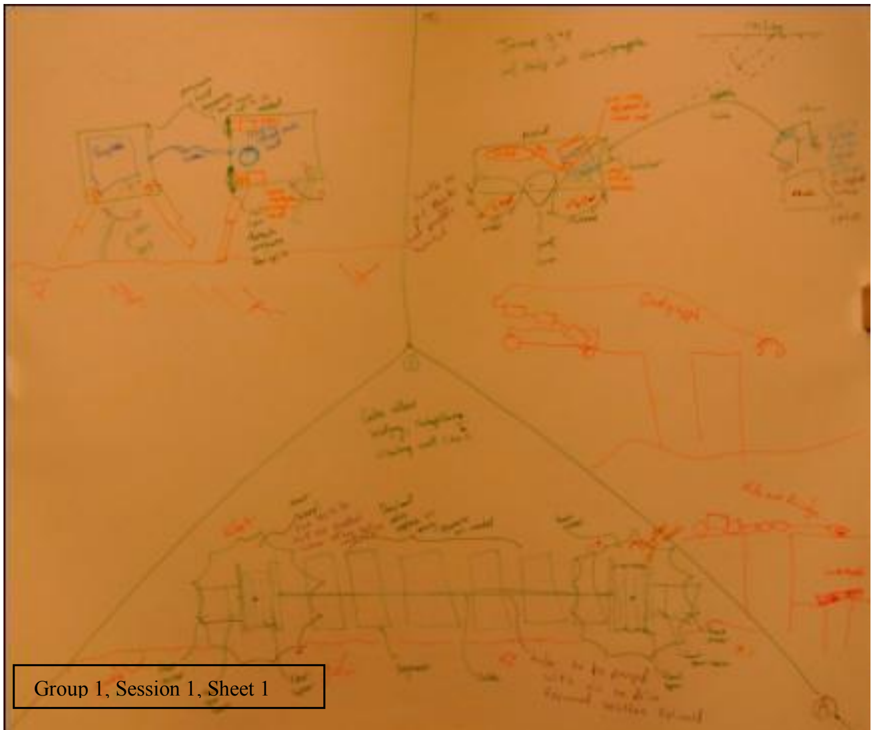
<u>VBA code to generate visual color palette to connect color number to color</u>

Sub color_pallette_scratch()

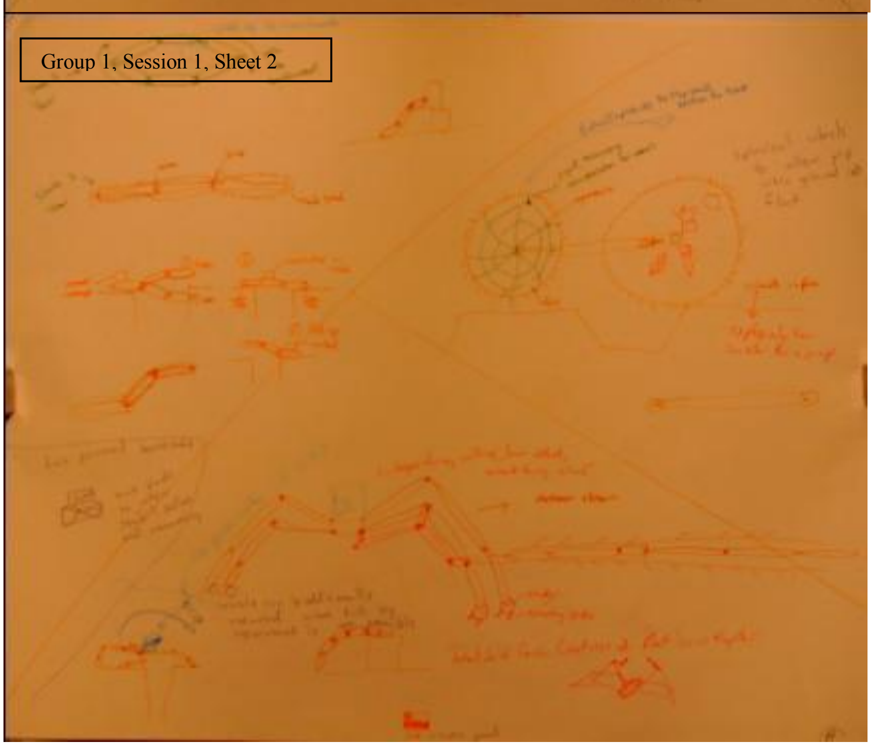
```
'Insert a pallette of colors, 1:56, into column "A" on the scratch sheet.
'Allows for a preview of colors you may want to use.
    Sheets("scratch").Select
    Columns("a:a").Select
    Selection.Insert Shift:=xlToRight, CopyOrigin:=xlFormatFromLeftOrAbove

    For i = 1 To 56
        Range("a1:a56").Select
        Cells(i, 1) = i
        Cells(i, 1).Select

        With Selection.Interior
        .ColorIndex = i
        End With

    Next i
```

End Sub

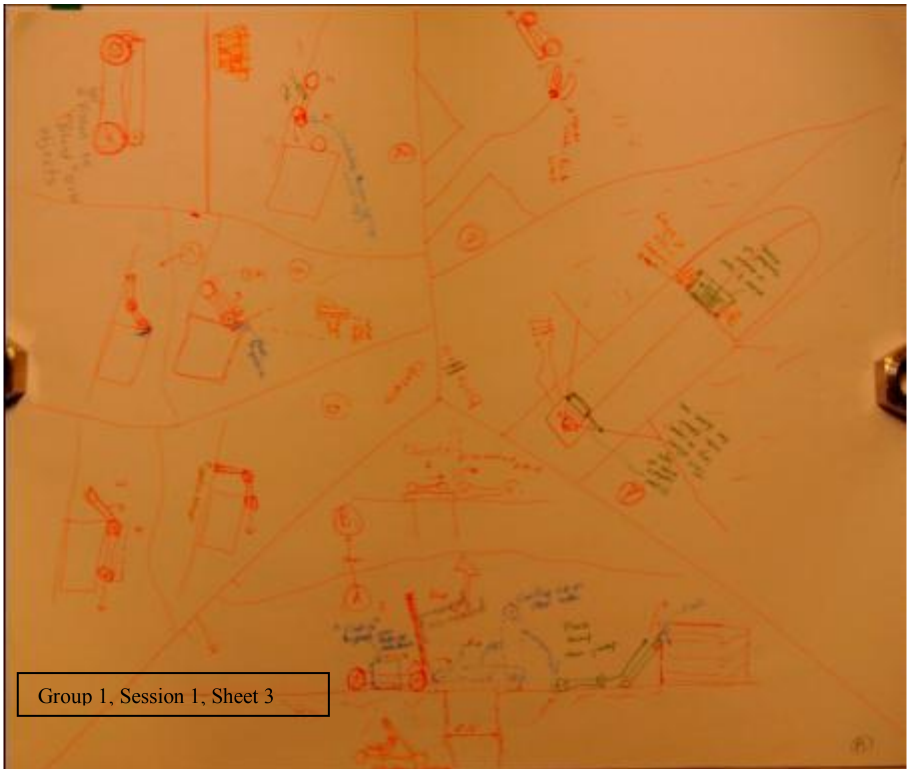
Appendix B: Experiment Validation C-Sketch Sheets



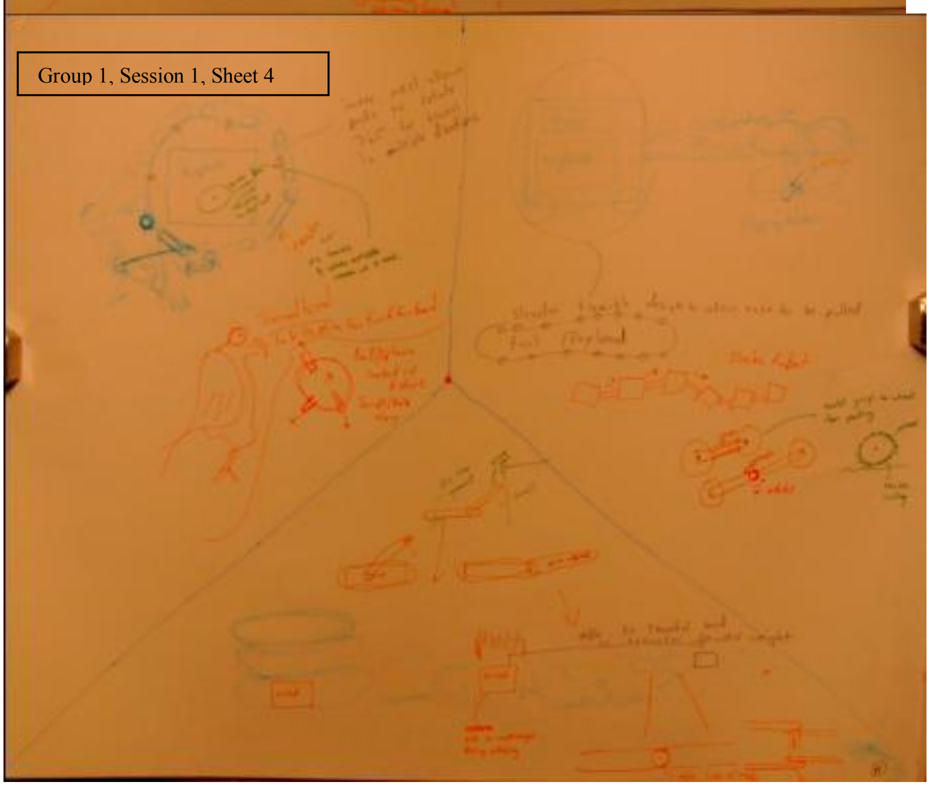
Group 1, Session 1, Sheet 1



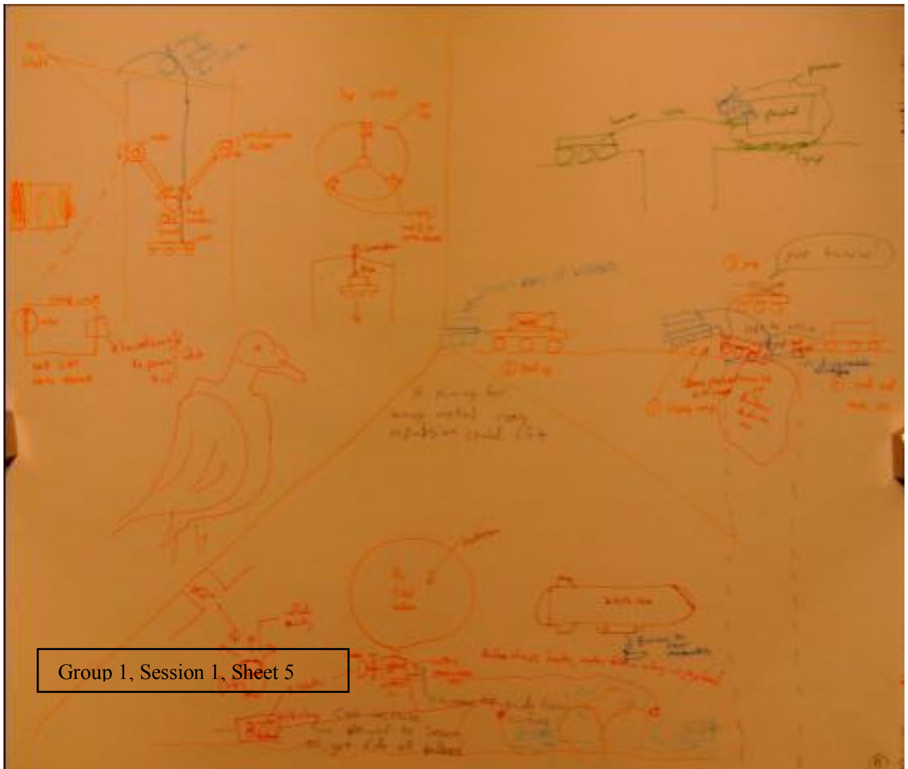
Group 1, Session 1, Sheet 2



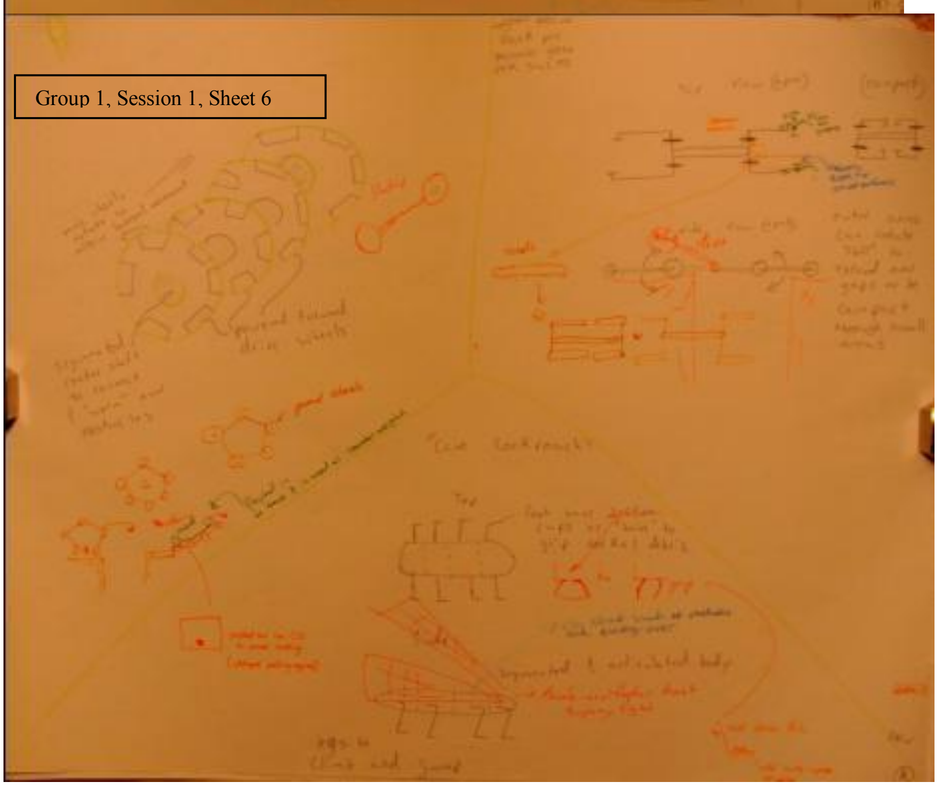
Group 1, Session 1, Sheet 3



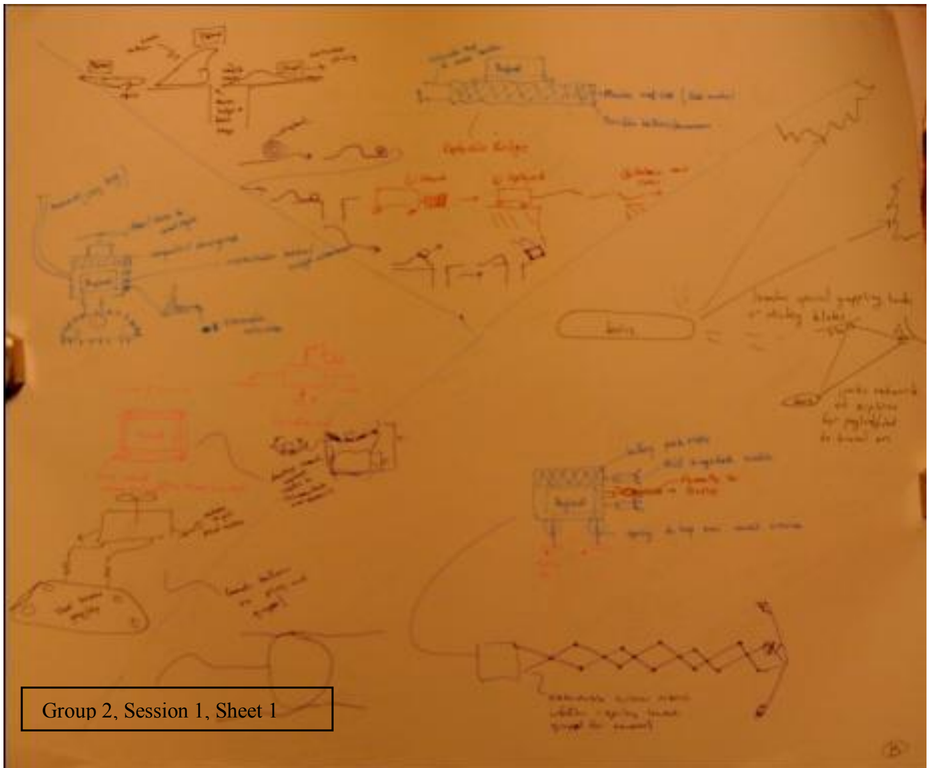
Group 1, Session 1, Sheet 4



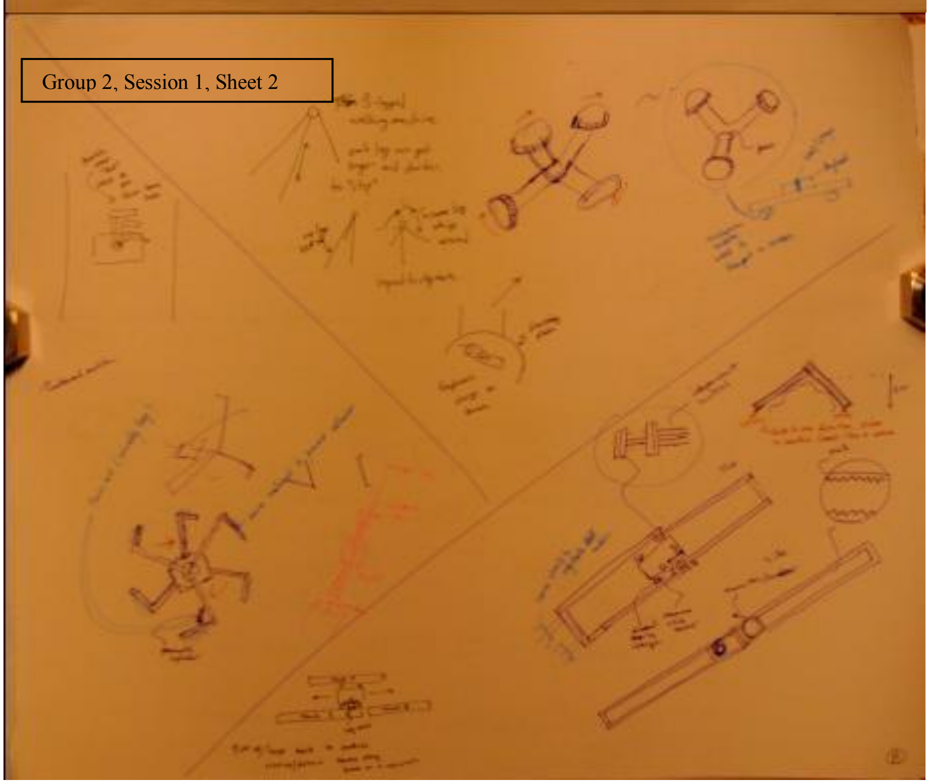
Group 1, Session 1, Sheet 5



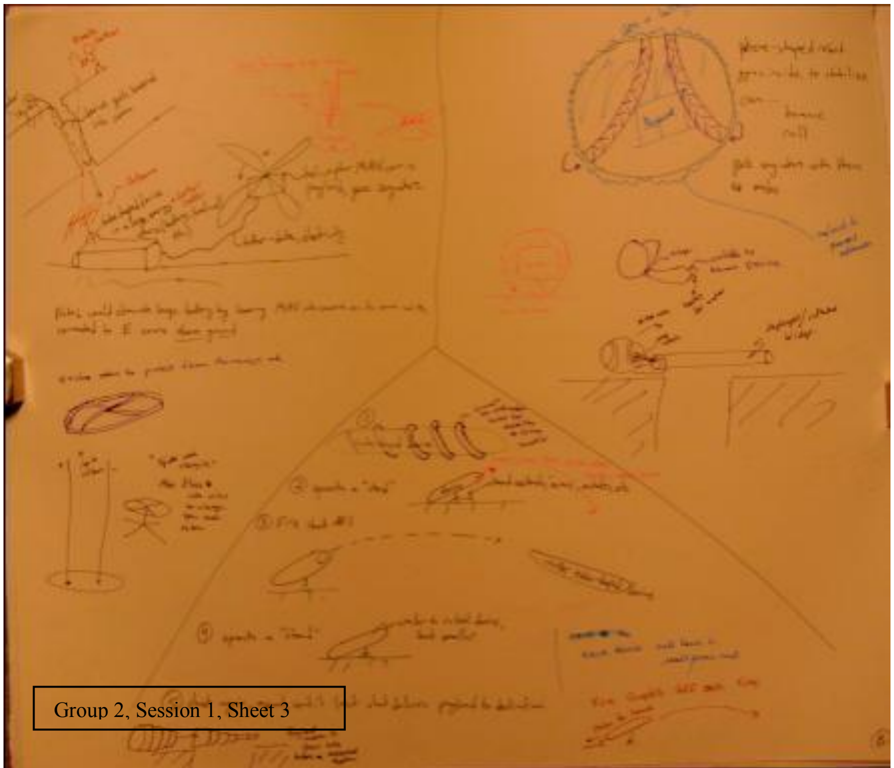
Group 1, Session 1, Sheet 6

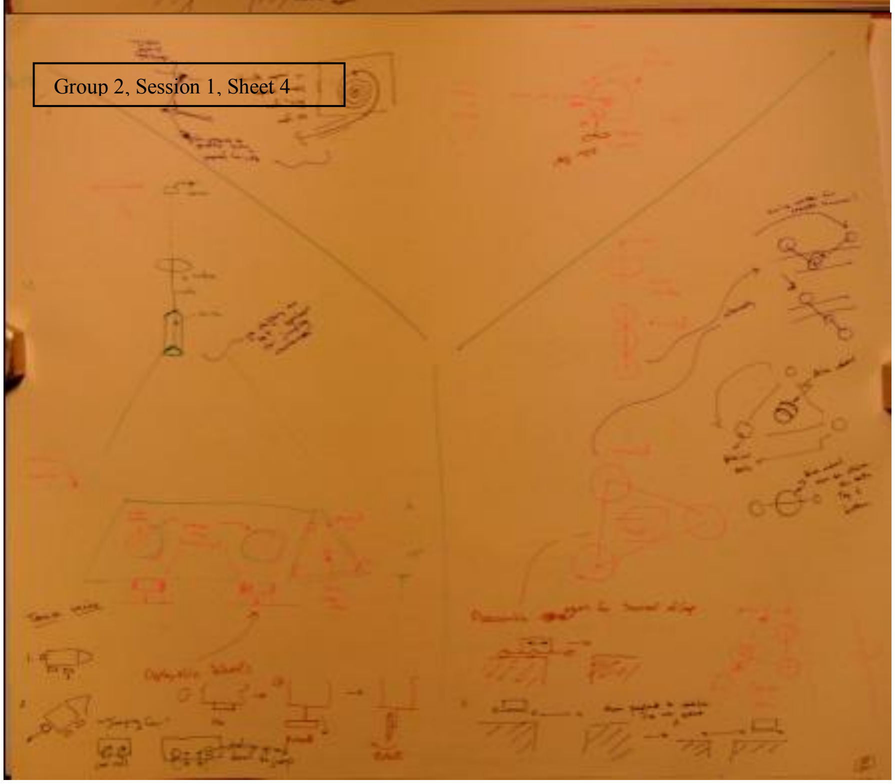


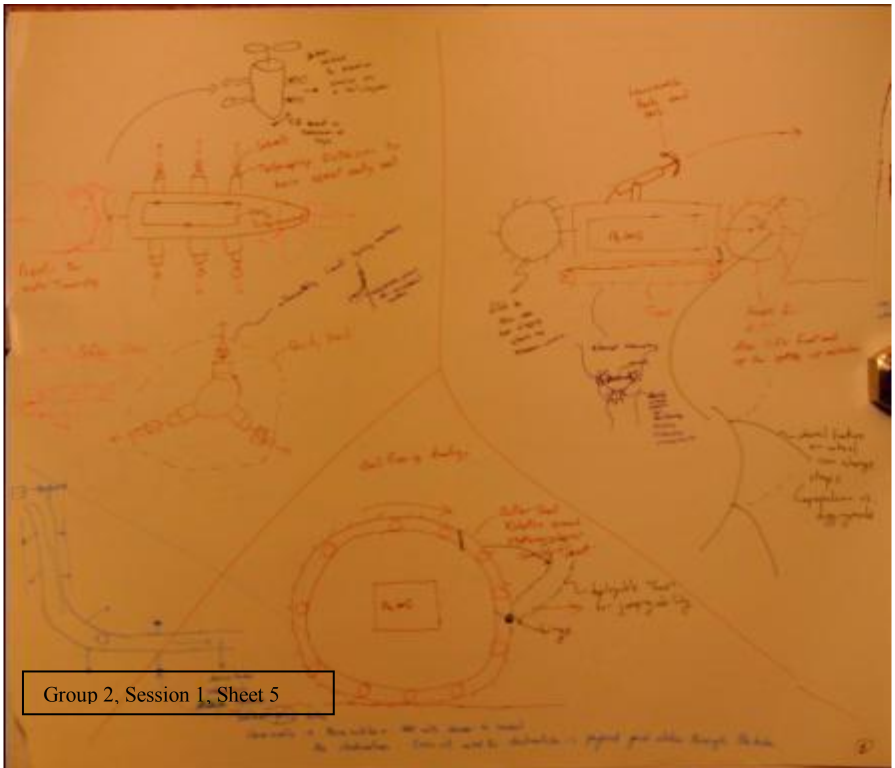
Group 2, Session 1, Sheet 1

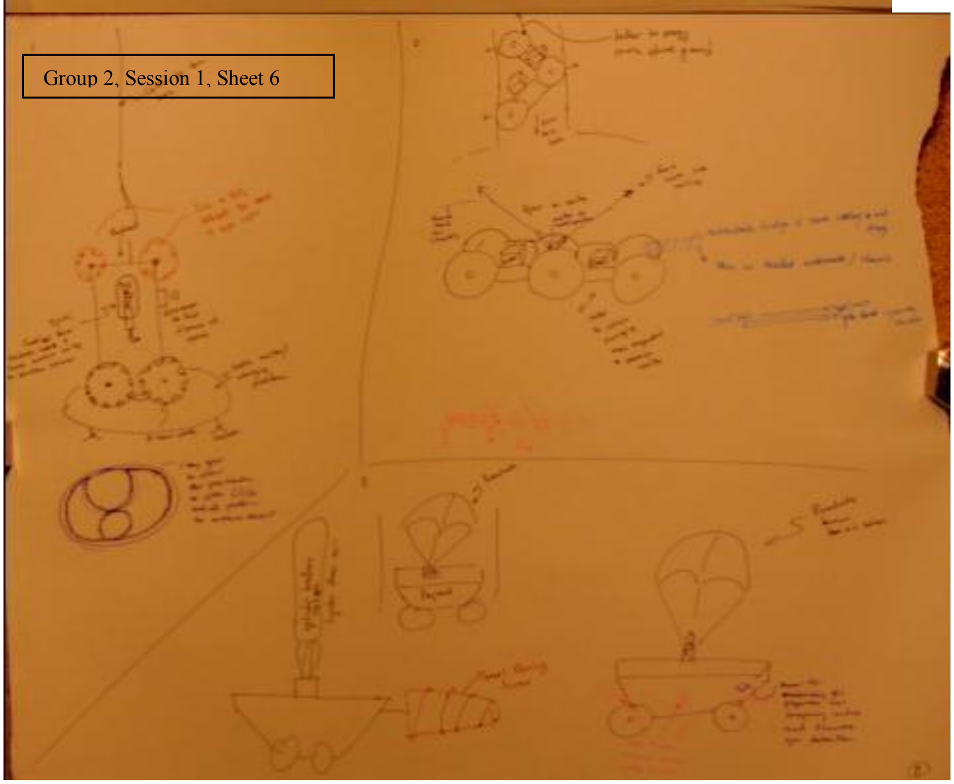


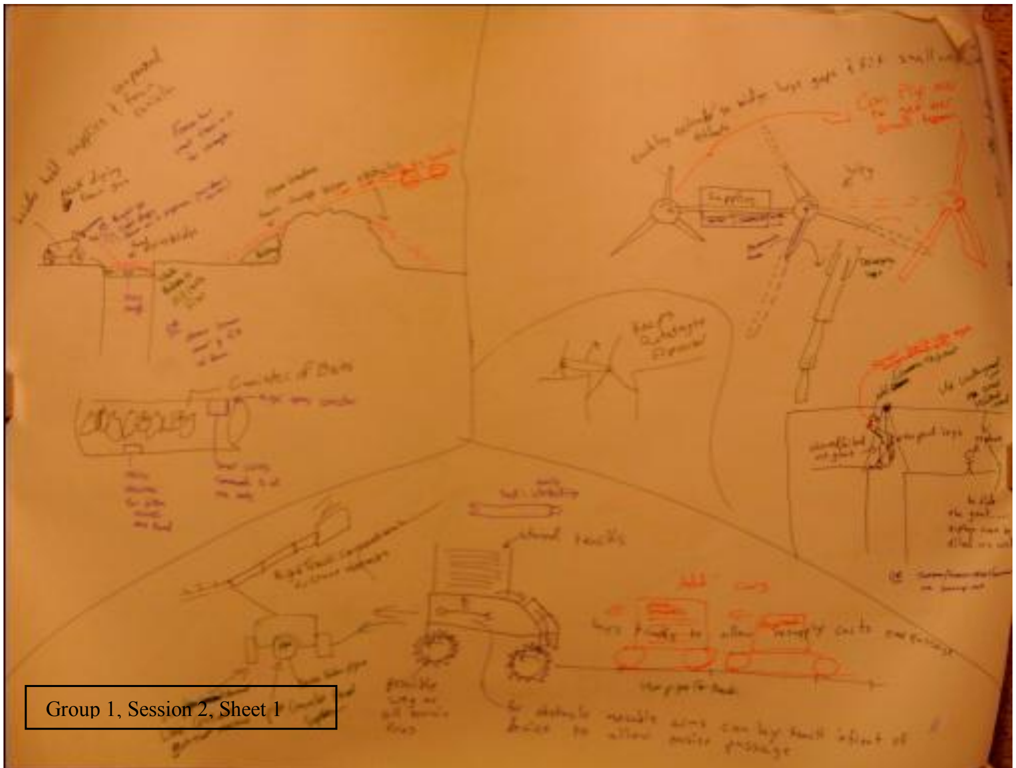
Group 2, Session 1, Sheet 2


Group 2, Session 1, Sheet 3

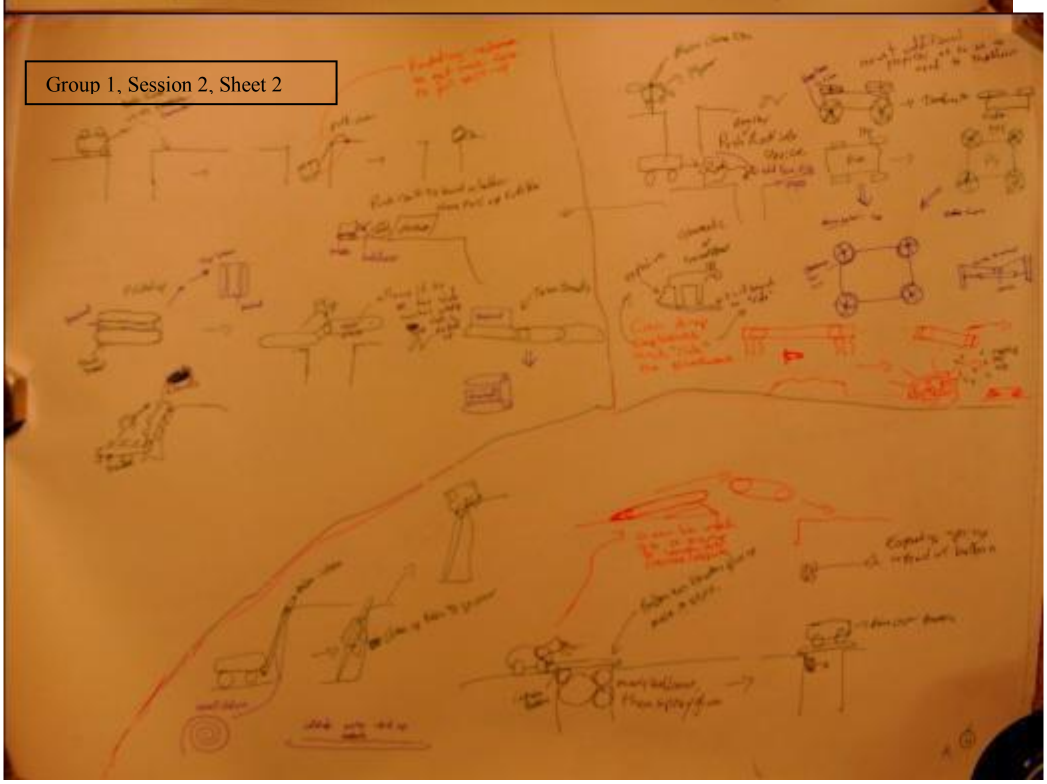

Group 2, Session 1, Sheet 4


Group 2, Session 1, Sheet 5

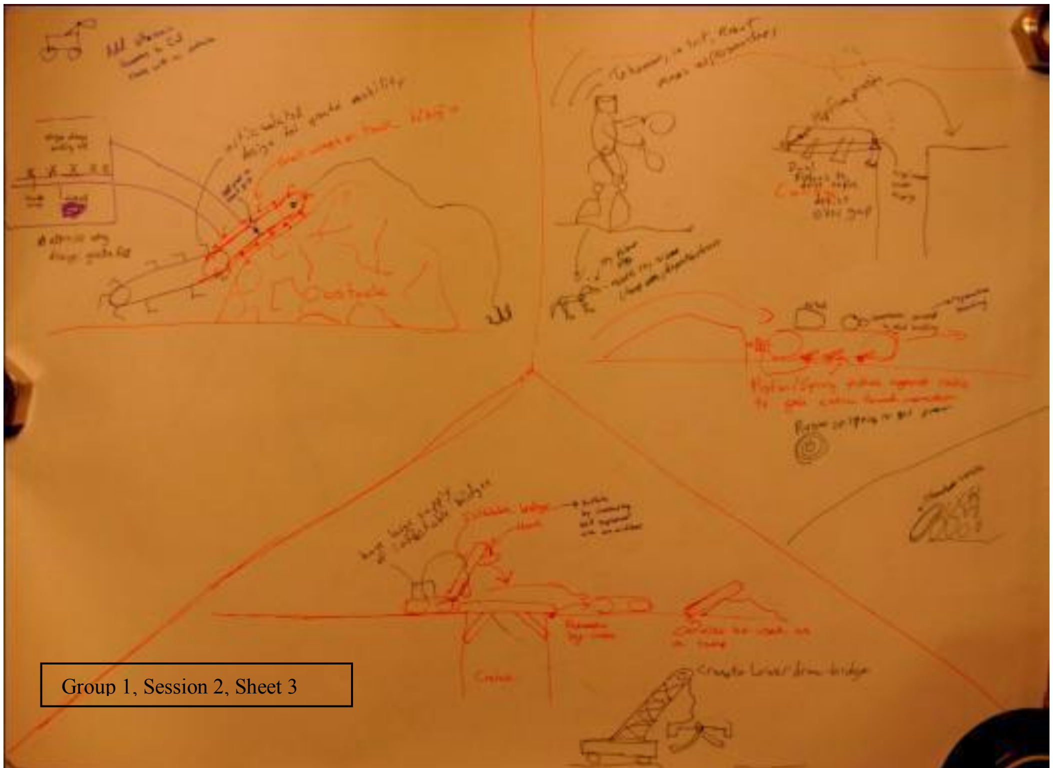

Group 2, Session 1, Sheet 6



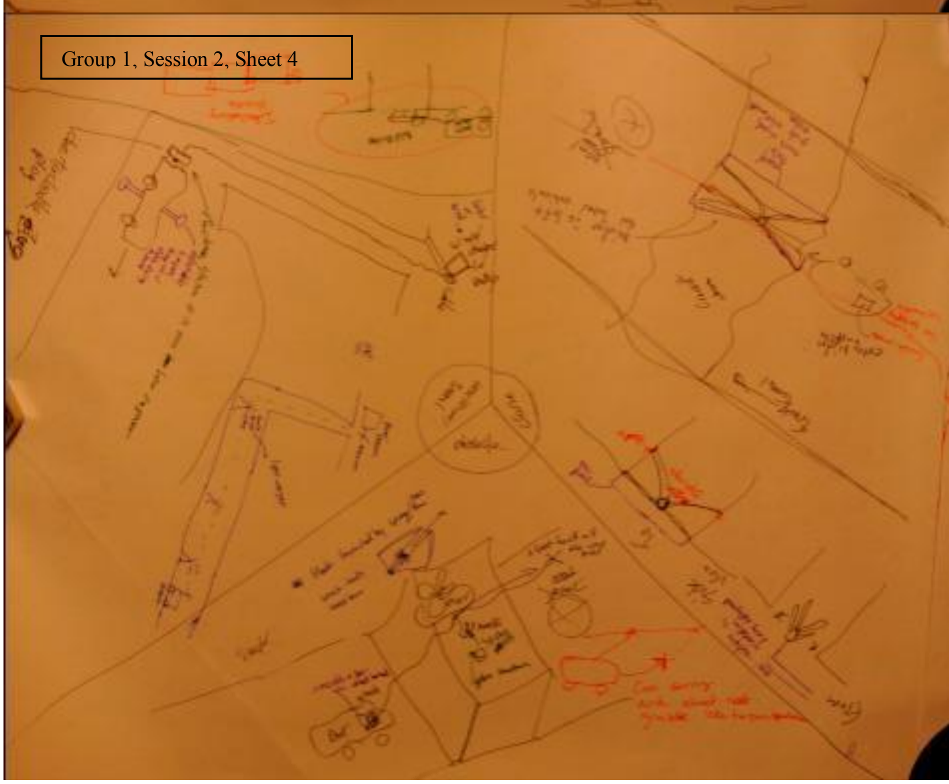
Group 1, Session 2, Sheet 1



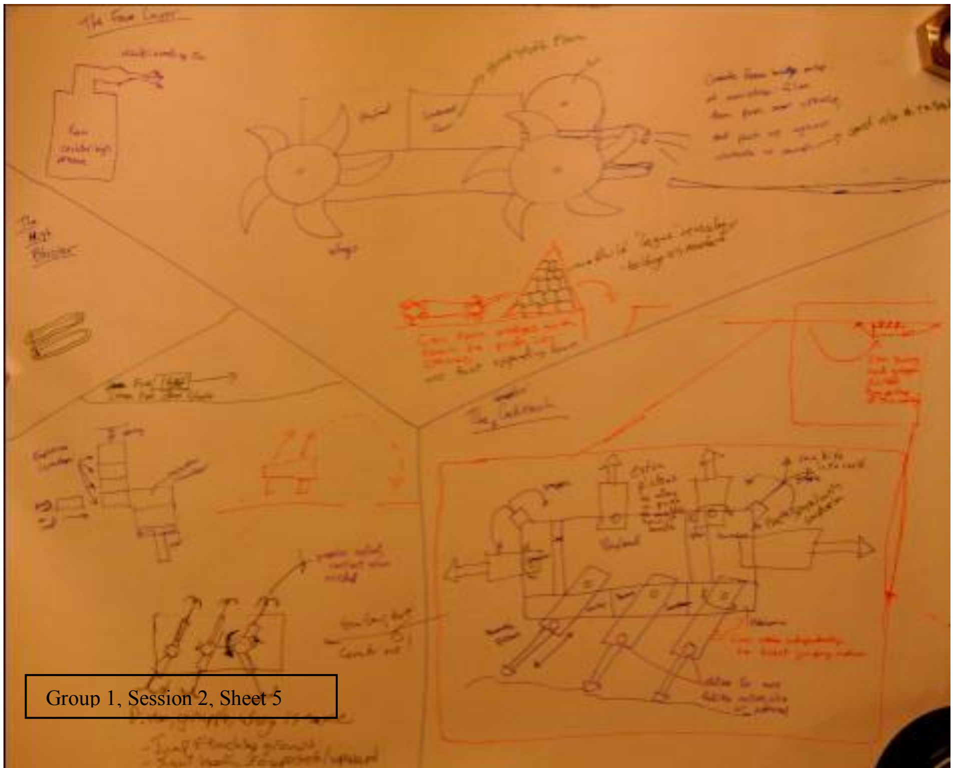
Group 1, Session 2, Sheet 2



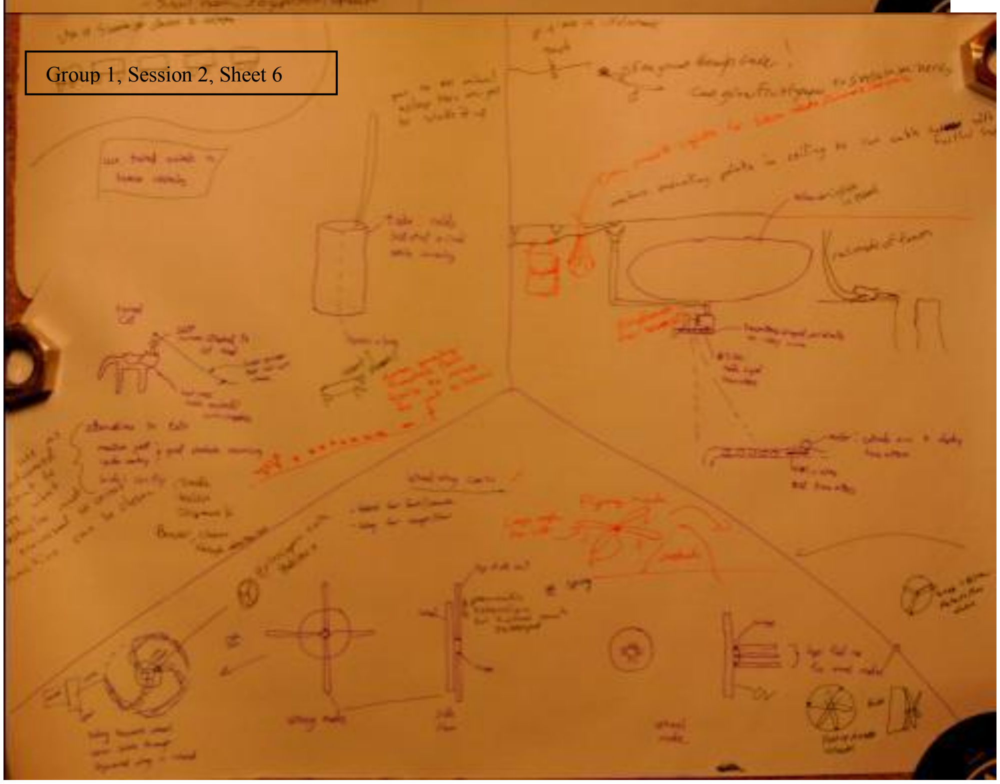
Group 1, Session 2, Sheet 3



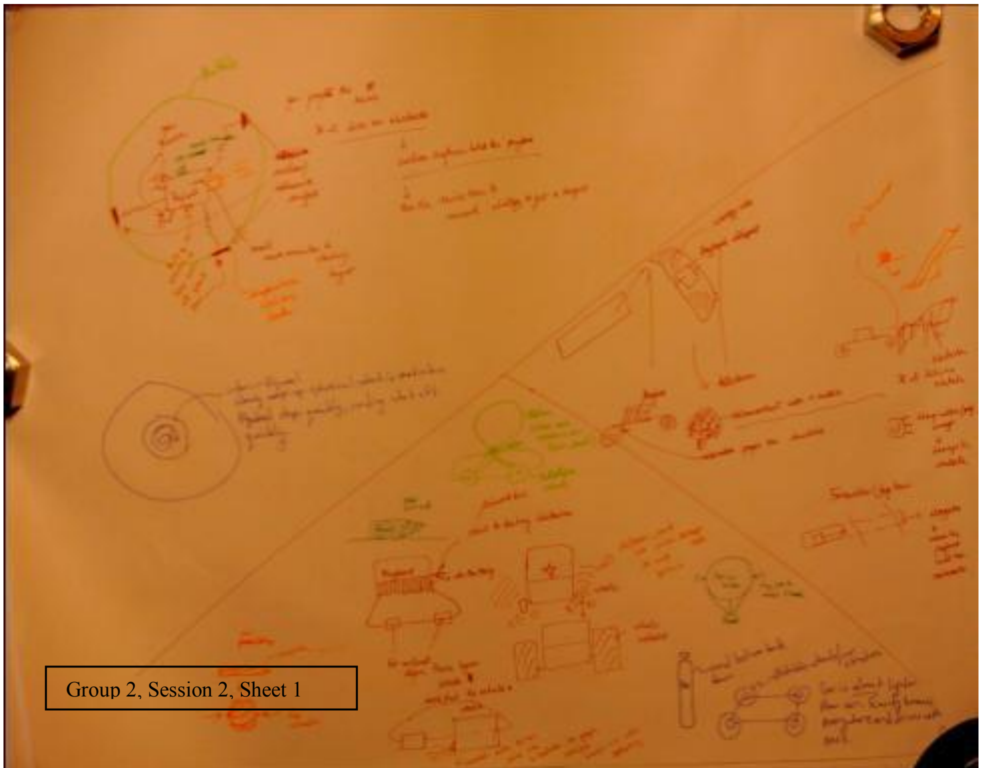
Group 1, Session 2, Sheet 4



Group 1, Session 2, Sheet 5

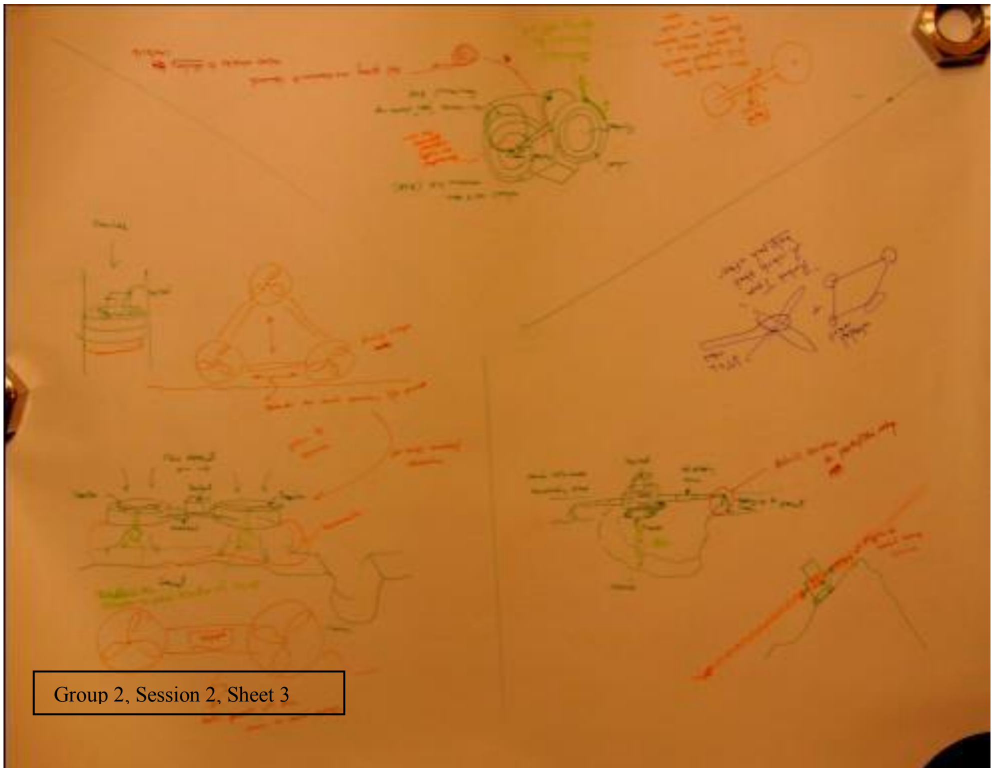


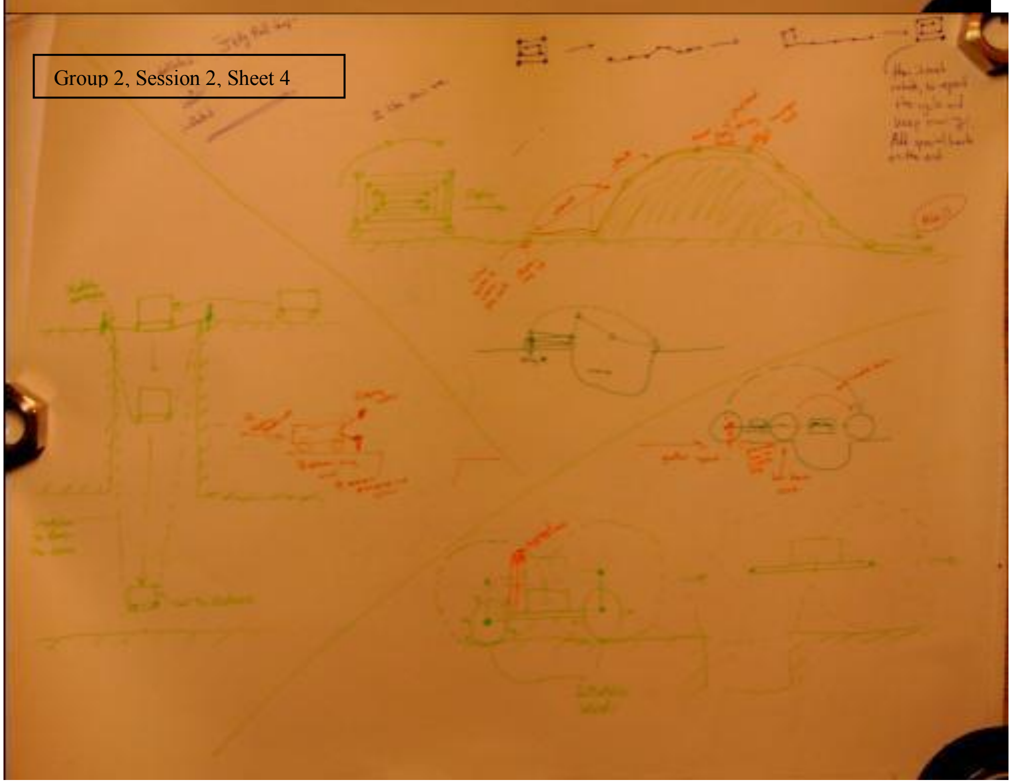
Group 1, Session 2, Sheet 6

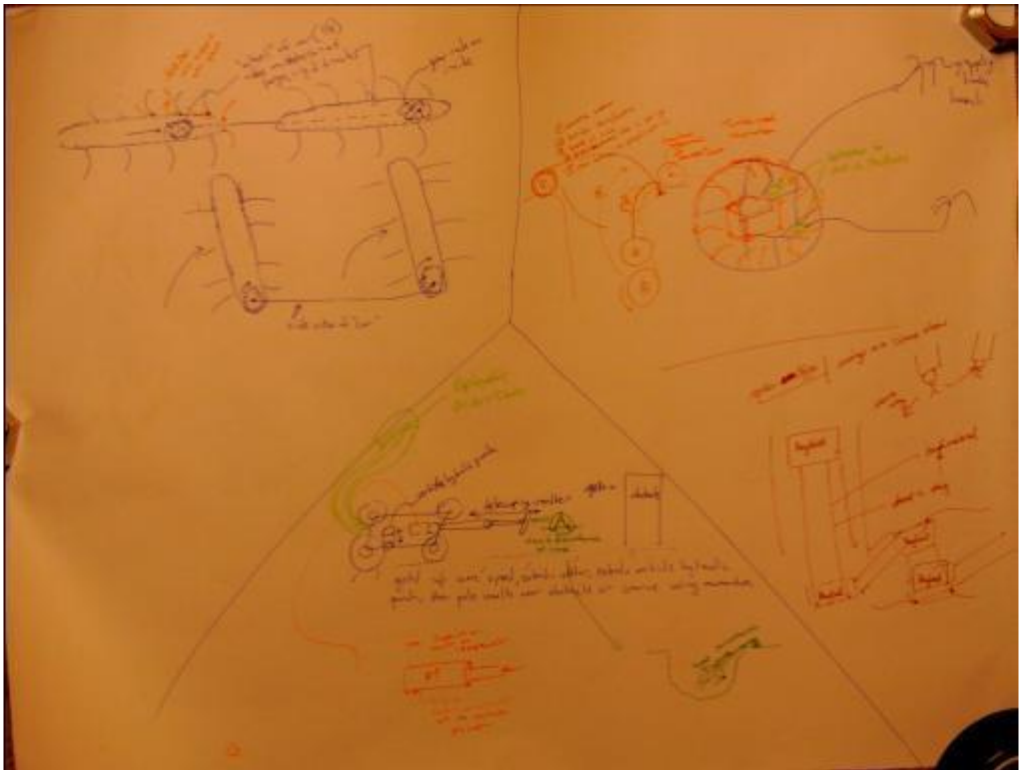


Group 2, Session 2, Sheet 1

Group 2, Session 2, Sheet 2

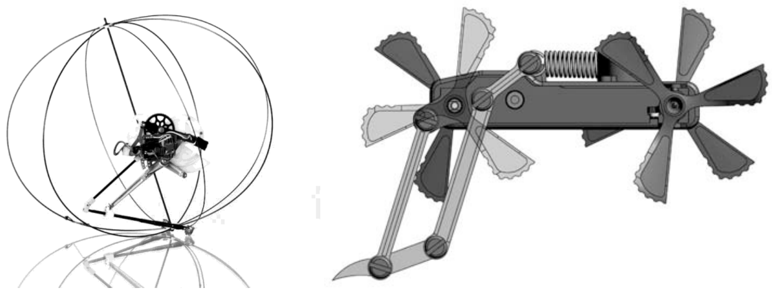

Group 2, Session 2, Sheet 3


Group 2, Session 2, Sheet 4



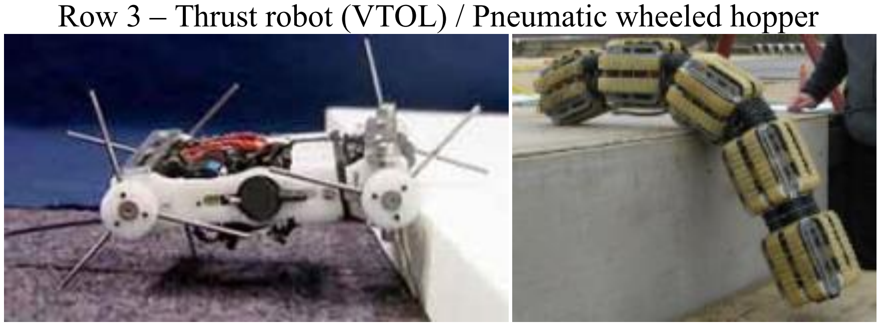
Appendix C: Photographs of Representative Technologies

Row 1 – Segmented tracked robot / Legged robot



Row 2 – Legged spring hopper / Whegged spring hopper

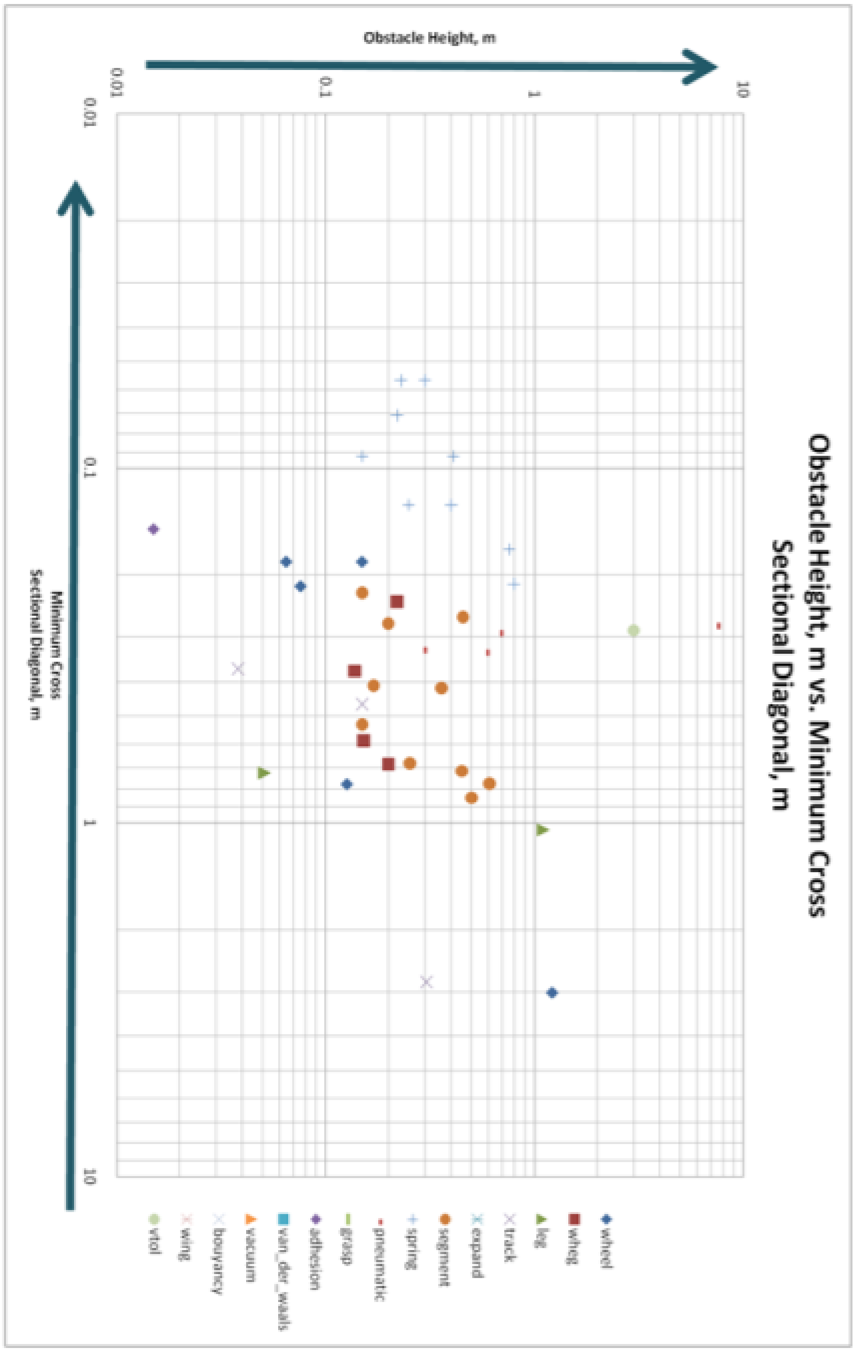
Row 3 – Thrust robot (VTOL) / Pneumatic wheeled hopper

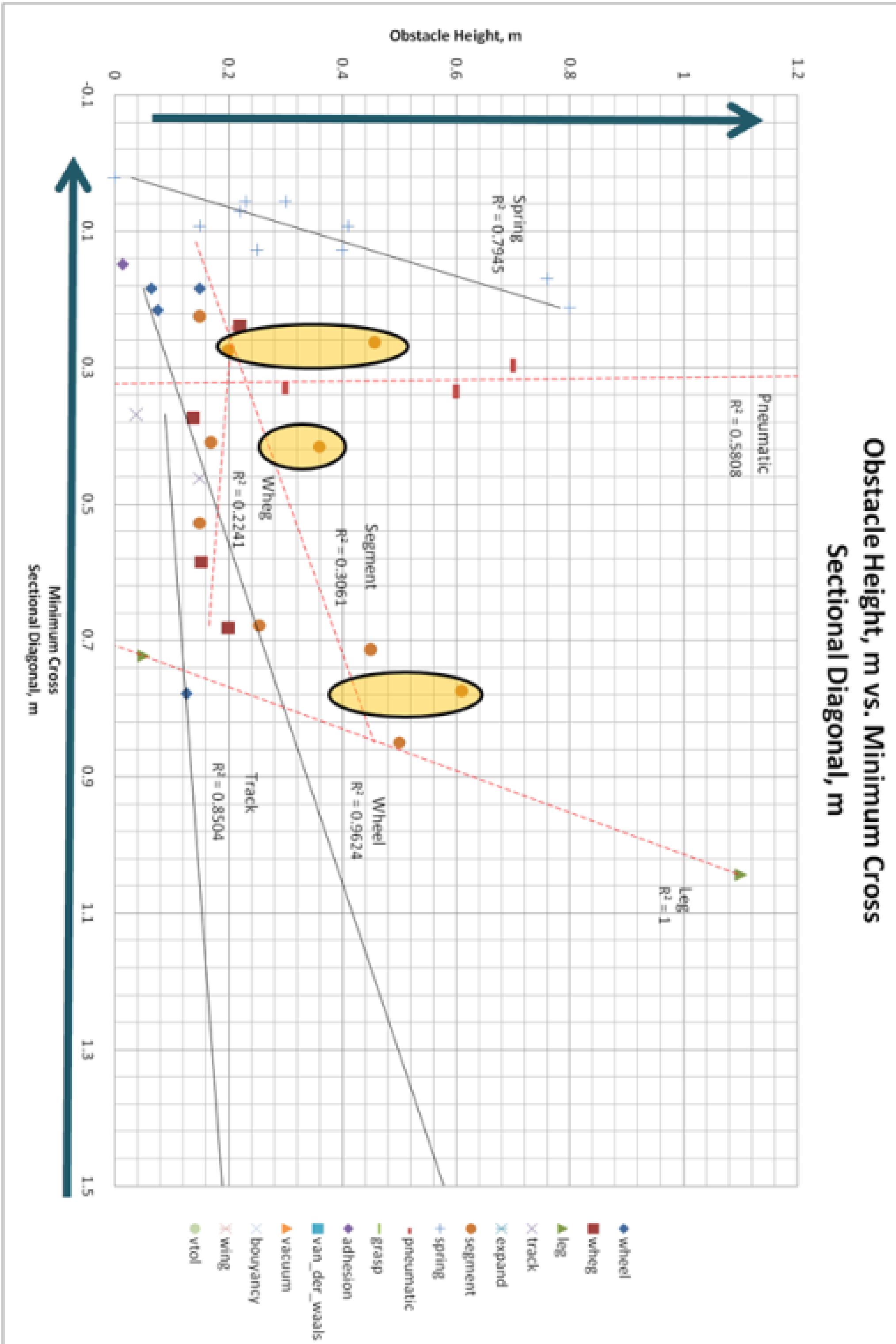


Row 4 – Miniature whegged robot / Snake-track hybrid robot

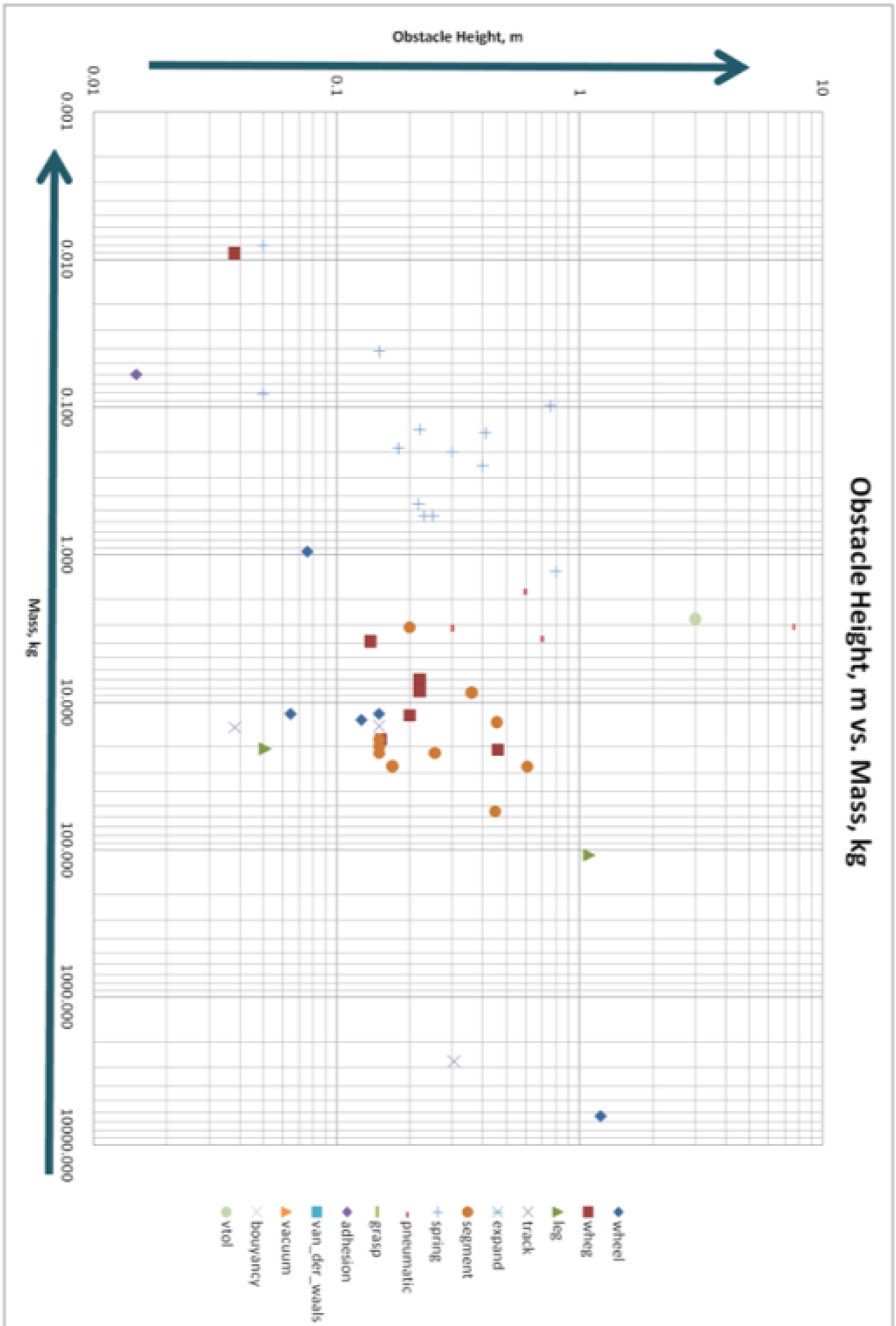
Row 5 - Segmented tracked robot / Whegged robot / 2 wheeled robot

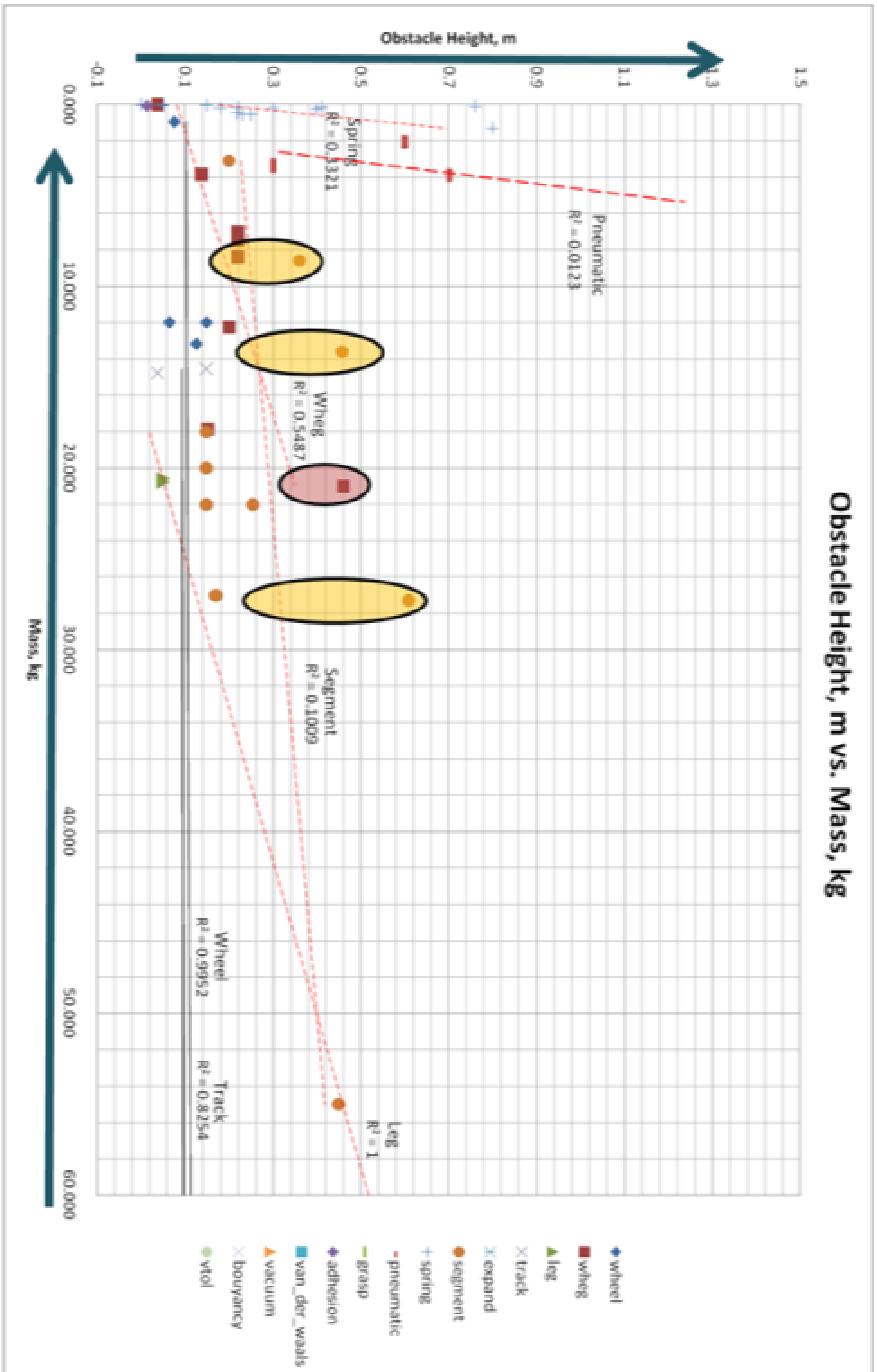
Appendix D: Resulting Plots from Repository Data



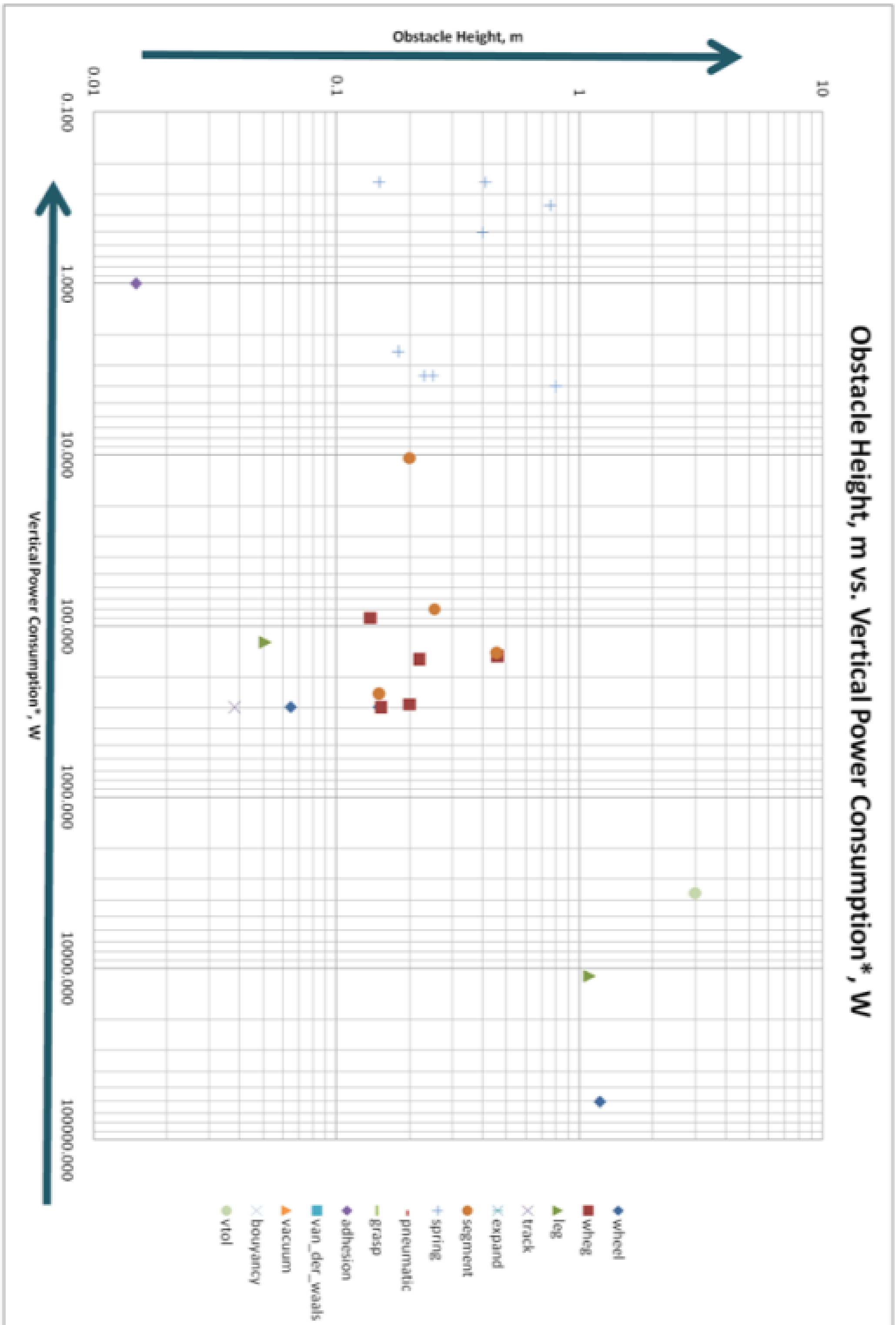


Obstacle Height, m vs. Minimum Cross Sectional Diagonal, m
Obstacle Height, m
Minimum Cross Sectional Diagonal, m
Spring
R² = 0.7945
Pneumatic
R² = 0.5808
Wheg
R² = 0.2241
Segment
R² = 0.3061
Wheel
R² = 0.9624
Track
R² = 0.8504
Leg
R² = 1
wheel
wheg
leg
track
expand
segment
spring
pneumatic
grasp
adhesion
van_der_waals
vacuum
bouyancy
wing
vtol

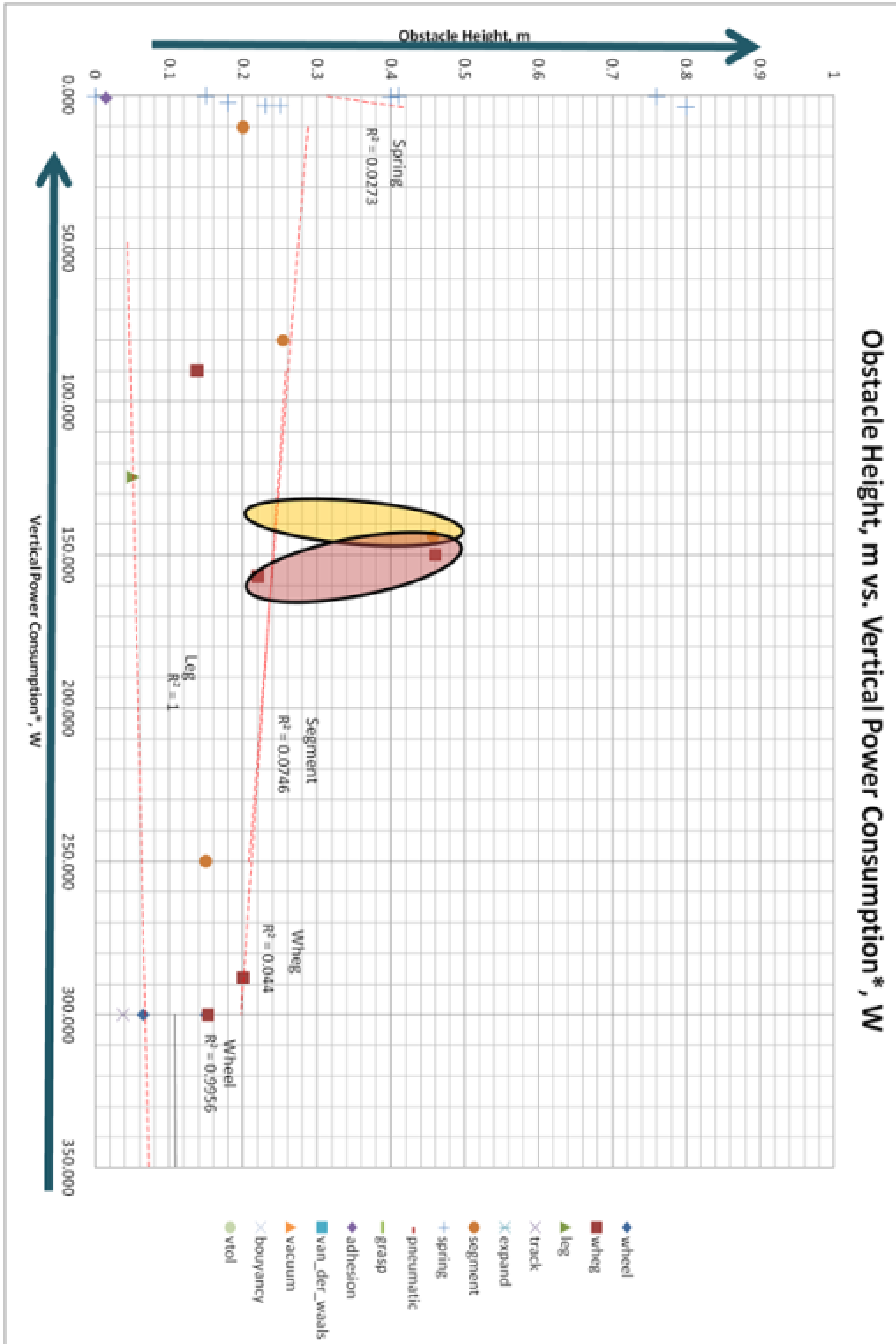

Obstacle Height, m vs. Mass, kg
Obstacle Height, m
0.01
0.1
1
10
Mass, kg
0.001
0.010
0.100
1.000
10.000
100.000
1000.000
10000.000
wheel
wheg
leg
track
expand
segment
spring
pneumatic
grasp
adhesion
van_der_waals
vacuum
bouyancy
vtol

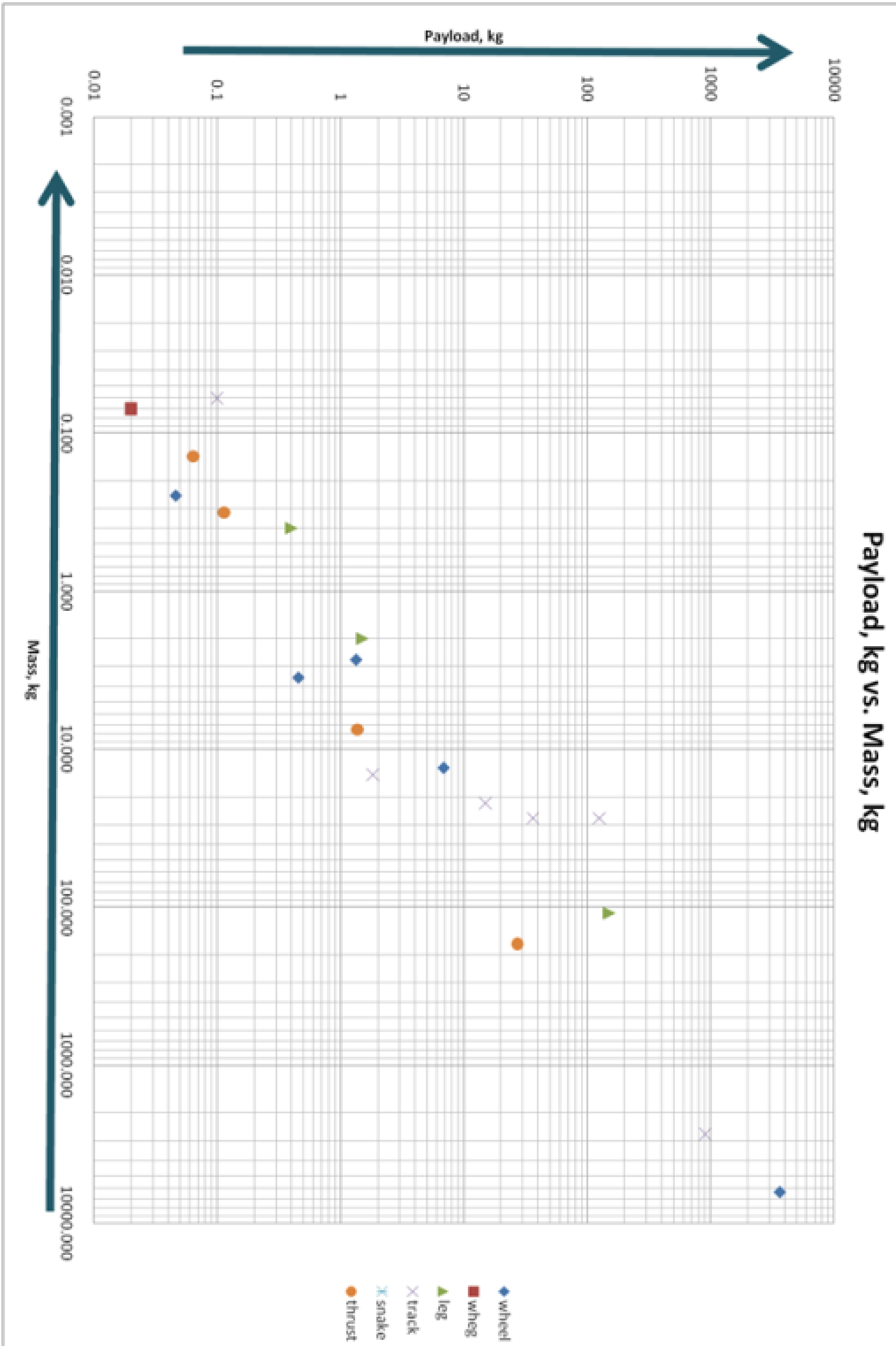


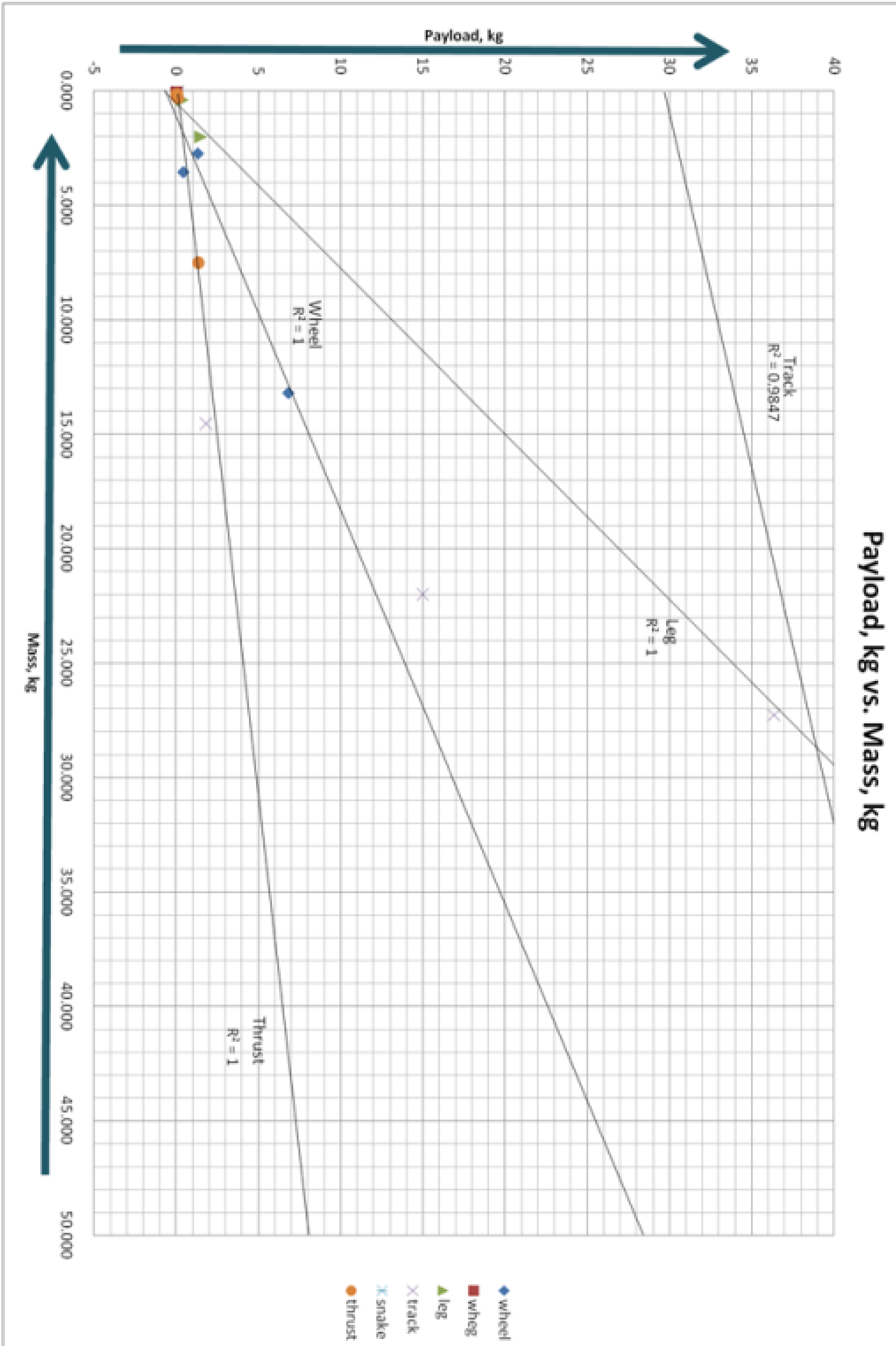
Obstacle Height, m vs. Mass, kg
Obstacle Height, m
Mass, kg
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
0.000
10.000
20.000
30.000
40.000
50.000
60.000
Spring
R² = 0.3321
Pneumatic
R² = 0.0123
Wheg
R² = 0.5487
Segment
R² = 0.1009
Wheel
R² = 0.9952
Track
R² = 0.8254
Leg
R² = 1
wheel
wheg
leg
track
expand
segment
spring
pneumatic
grasp
adhesion
van_der_waals
vacuum
bouyancy
vtol



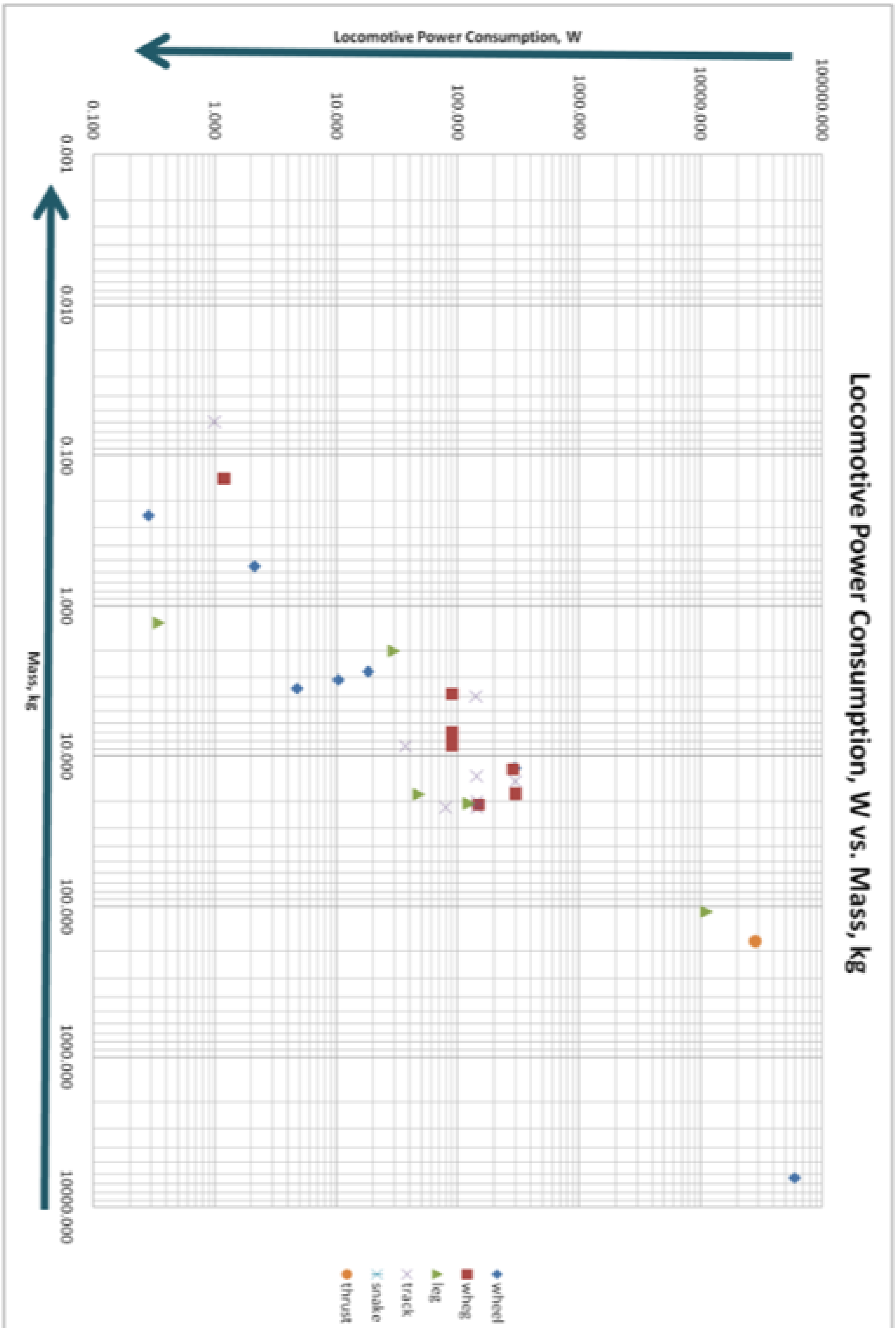
Obstacle Height, m vs. Vertical Power Consumption*, W
Obstacle Height, m
0.01
0.1
1
10
Vertical Power Consumption*, W
0.100
1.000
10.000
100.000
1000.000
10000.000
100000.000
wheel
wheg
leg
track
expand
segment
spring
pneumatic
grasp
adhesion
van_der_waals
vacuum
bouyancy
vtol

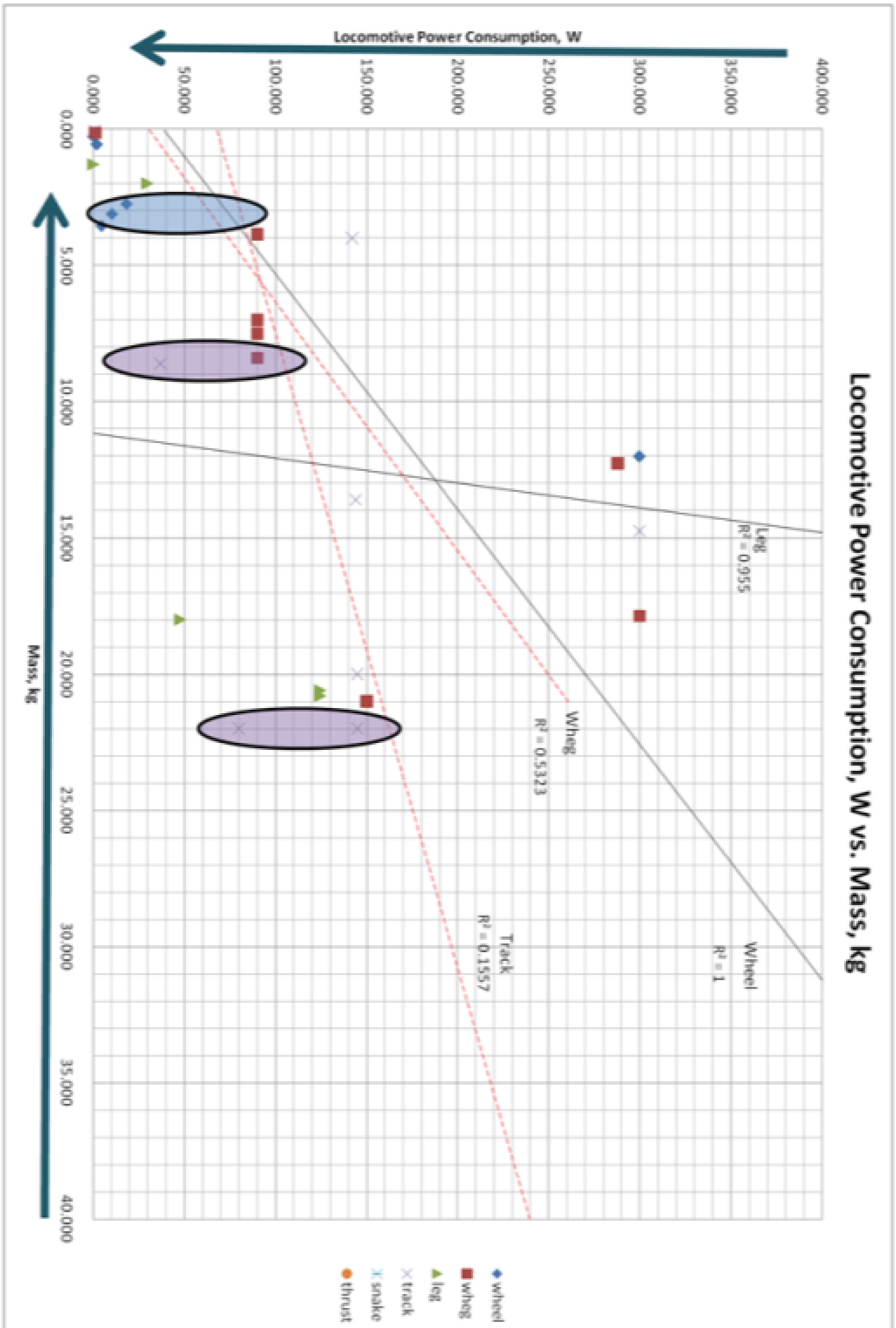

Obstacle Height, m vs. Vertical Power Consumption*, W
Obstacle Height, m
Vertical Power Consumption*, W
Spring
R² = 0.0273
Segment
R² = 0.0746
Leg
R² = 1
Wheg
R² = 0.044
Wheel
R² = 0.9956
wheel
wheg
leg
track
expand
segment
spring
pneumatic
grasp
adhesion
van_der_waals
vacuum
bouyancy
vtol


Payload, kg vs. Mass, kg
Payload, kg
0.01
0.1
1
10
100
1000
10000
Mass, kg
0.001
0.010
0.100
1.000
10.000
100.000
1000.000
10000.000
wheel
wheg
leg
track
snake
thrust



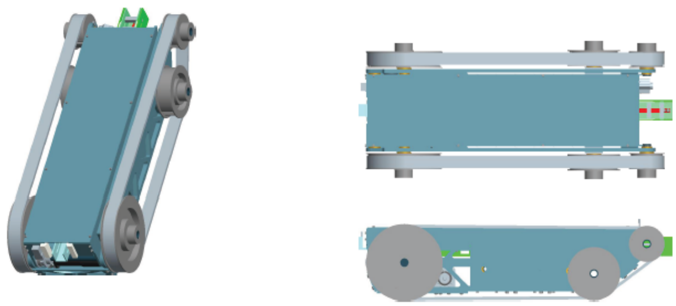
Payload, kg vs. Mass, kg
Payload, kg
Mass, kg
-5
0
5
10
15
20
25
30
35
40
0.000
5.000
10.000
15.000
20.000
25.000
30.000
35.000
40.000
45.000
50.000
Track
R² = 0.9847
Leg
R² = 1
Wheel
R² = 1
Thrust
R² = 1
wheel
wheg
leg
track
snake
thrust


Locomotive Power Consumption, W vs. Mass, kg
Locomotive Power Consumption, W
Mass, kg
0.100
1.000
10.000
100.000
1000.000
10000.000
100000.000
0.001
0.010
0.100
1.000
10.000
100.000
1000.000
10000.000
wheel
wheg
leg
track
snake
thrust


Locomotive Power Consumption, W vs. Mass, kg
Locomotive Power Consumption, W
Mass, kg
Leg
R² = 0.955
Wheg
R² = 0.5323
Track
R² = 0.1557
Wheel
R² = 1
wheel
wheg
leg
track
snake
thrust

Appendix E: General Part Profiles and Dimensions

Engineers: Patrick Pace, Sami Sultan



TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °

COUNTER TUNNEL TEAM

ROBOT_ASSEMBLY

Scale 0.200
Sheet 1 of 3

ASSEM PROFILES
MATERIAL AL6061 OR EQUIV INCH
A

Item	Part Name	Quantity
1	0-80_3-16_MACH_FL	10
2	2-64_1-4_CAP_STD	27
3	8_TAPPING_SCREW	8
4	BELT_BODY	1
5	BODY	1
6	BODY_AXIS	1
7	BODY_BOTTOM_1	1
8	BODY_BOTTOM_2	1
9	BODY_BOTTOM_2_L	1
10	BODY_CHAIN_FRONT	1
11	BODY_SIDE	2
12	BODY_TOP	1
13	BUSHING_1-2	6
14	BUSHING_3-8	2
15	BUSHING_3-8_NF	4
16	CAMERA	1
17	CAMERA_BRACKET	1
18	CHANNEL_1-25X1-25	1
19	CHANNEL_3-4X3-4	1
20	CHANNEL_1X1	1
21	CHANNEL_GUIDE_BRACKET	2
22	CHANNEL_GUIDE_END	2
23	CHANNEL_GUIDE_LONG	2
24	CHANNEL_GUIDE_MAIN	2
25	DC-PK516	1
26	DC-PK516_BRACKET	1
27	DC_PK516	1
28	DRIVE_BELT_LEFT	1
29	DRIVE_BELT_RIGHT	1
30	DRIVE_BRACE	2
31	DRIVE_IDLE_SHAFT	4
32	DRIVE_IDLER_3MM	2
33	DRIVE_PULLEY_2-0	2
34	DRIVE_PULLEY_4-3	2
35	DRIVE_PULLY_2-8_B	2
36	DRIVE_PULLY_6MM	4
37	DRIVE_SHAFT	2
38	DRIVETRAIN_BOTTOM	1
39	DRIVETRAIN_SIDE	2
40	ELEC_BATT	1
41	ELEC_BATT_CONN_F	1
42	ELEC_FUSE_HOLDER	1
43	ELEC_JUMPER_3-8	6
44	ELEC_RECEIVER	1
45	ELEC_SP_CONTROL	1
46	ELEC_SP_CONTROL_DUAL	1
47	ELEC_SWITCH	1
48	ELEC_TERMINAL_BLOCK_3-8	1
49	GUIDE_1	3

Engineers: Patrick Pace, Sami Sultan

TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °

COUNTER TUNNEL TEAM

ROBOT_ASSEMBLY

Scale 0.200
Sheet 2 of 3

ASSEM BOM1
MATERIAL AL6061 OR EQUIV INCH
A

50	GUIDE_3-4	3
51	GUIDE_CENTERING_CHANNEL	12
52	GUIDE_SUB_ASSM	1
53	KEY_3-16	2
54	M3_4_BUTTON	8
55	M3_6_BUTTON	28
56	M3_6_CAP_STD	6
57	M3_10_BUTTON	10
58	M3_20_CAP_STD	2
59	M3_NUT_STD	10
60	M32_BACK	4
61	M32_BRACKET	4
62	M32_EXT	4
63	M32_EXT_W_BRACK	2
64	M32_FILLER	4
65	M32_FRONT	4
66	PULLY_BODY_MOTOR_6MM	1
67	PULLY_BODY_SHAFT	1
68	ROBOT_ASSEMBLY	1
69	ROLLER_ASSM	2
70	ROLLER_CHAIN_REAR	1
71	ROLLER_DRIVE	2
72	ROLLER_SYSTEM_FRONT	1
73	ROLLER_SYSTEM_REAR	1
74	RUBBER_BUMPER	1
75	SHAFT_ROLLER	2
76	SNAP_RING_1-2	6
77	SNAP_RING_3-8	6
78	SPRING_ANCHOR	2
79	SPRING_EXTENSION_SIMP	2
80	SPROCKET_2-5_STL	2
81	SPROCKET_3-8	2
82	STOP	4
83	STOP_SPRING	2
84	TELESCOPING_CHANNEL	1
85	TENSION_BLOCK	2
86	TENSION_BLOCK_IN	2
87	TENSION_BLOCK_OUT	2
88	TERMINAL_BLOCK_3-8	1
89	TRAVEL_STOP	1
90	TREAD	2

Engineers: Patrick Pace, Sami Sultan

TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °

COUNTER TUNNEL TEAM

ROBOT_ASSEMBLY

Scale 0.200

Sheet 3 of 3

ASSEM BOM2

MATERIAL AL6061 OR EQUIV

INCH

A

Engineers: Patrick Pace, Sami Sultan

Item	Part Name	Quantity
1	0-80_3-16_MACH_FL	10
2	CHANNEL_1-25X1-25	1
3	CHANNEL_3-4X3-4	1
4	CHANNEL_1X1	1
5	GUIDE_1	1
6	GUIDE_3-4	1
7	GUIDE_CENTERING_CHANNEL	12
8	STOP	2
9	TRAVEL_STOP	1

SCALE 0.200

TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °

COUNTER TUNNEL TEAM

TELESCOPING_CHANNEL

Scale 0.400

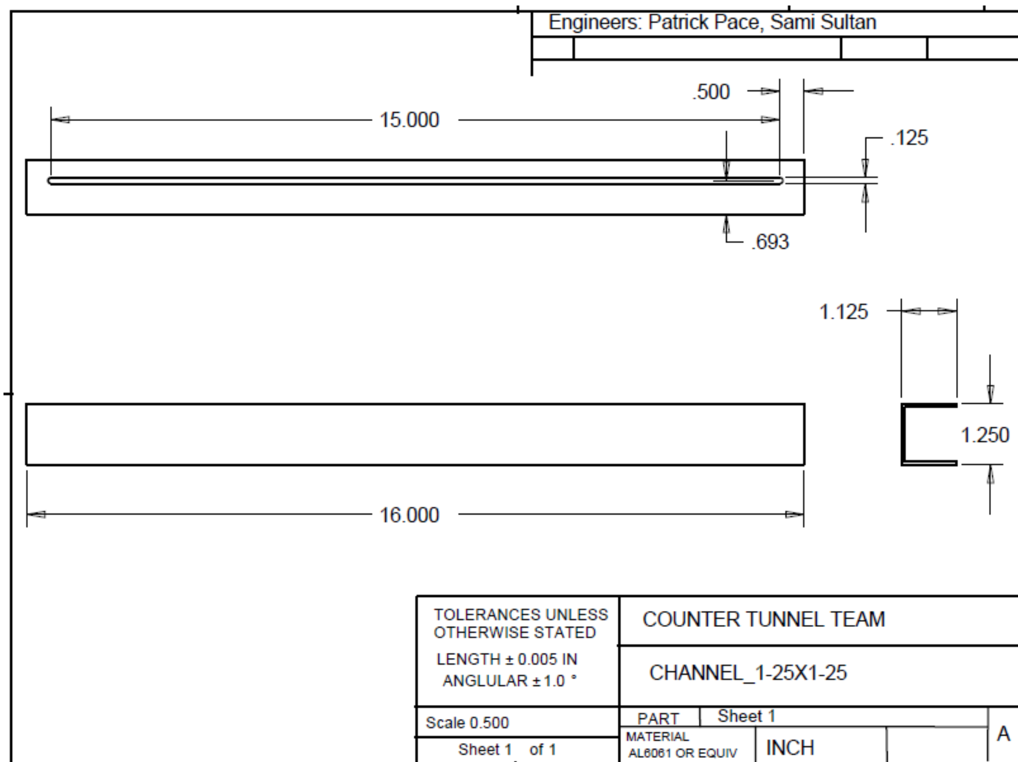
Sheet 1 of 1

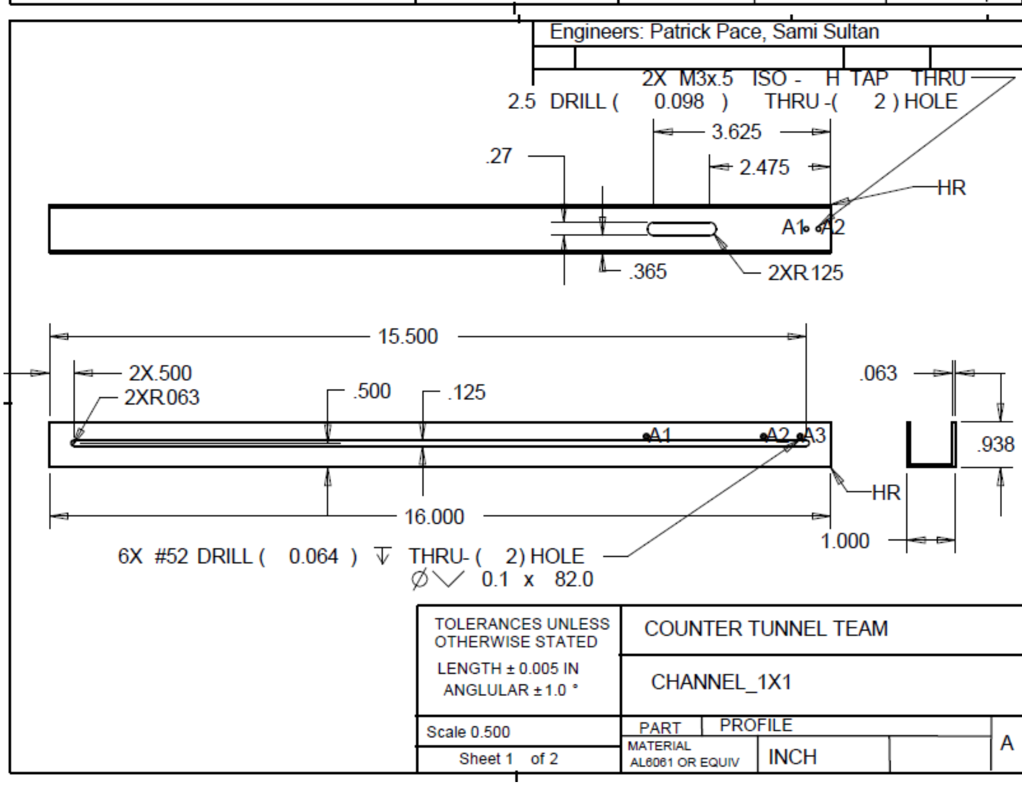
ASSEM Sheet 1

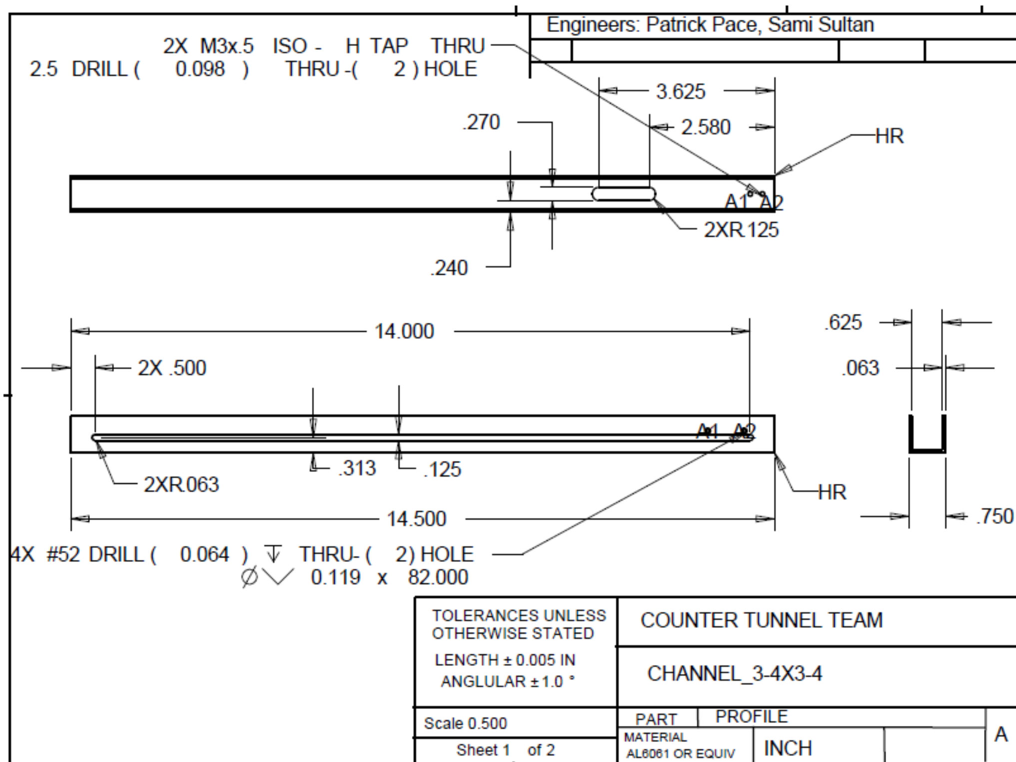
MATERIAL AL6061 OR EQUIV

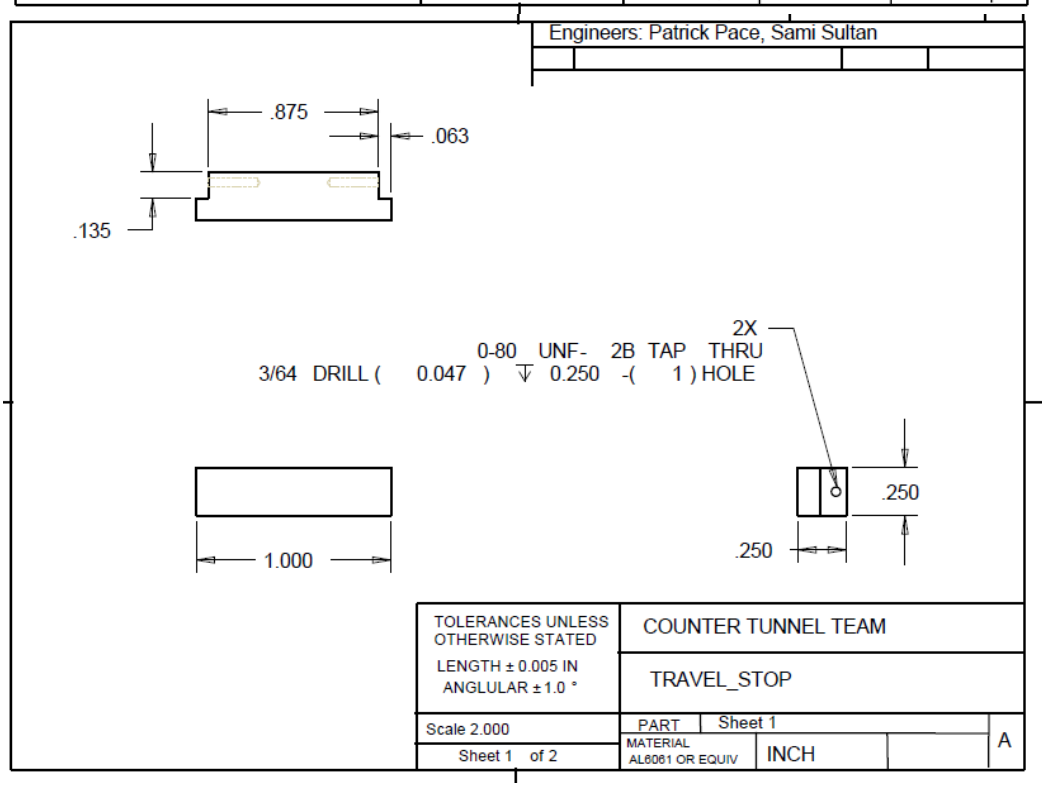
INCH

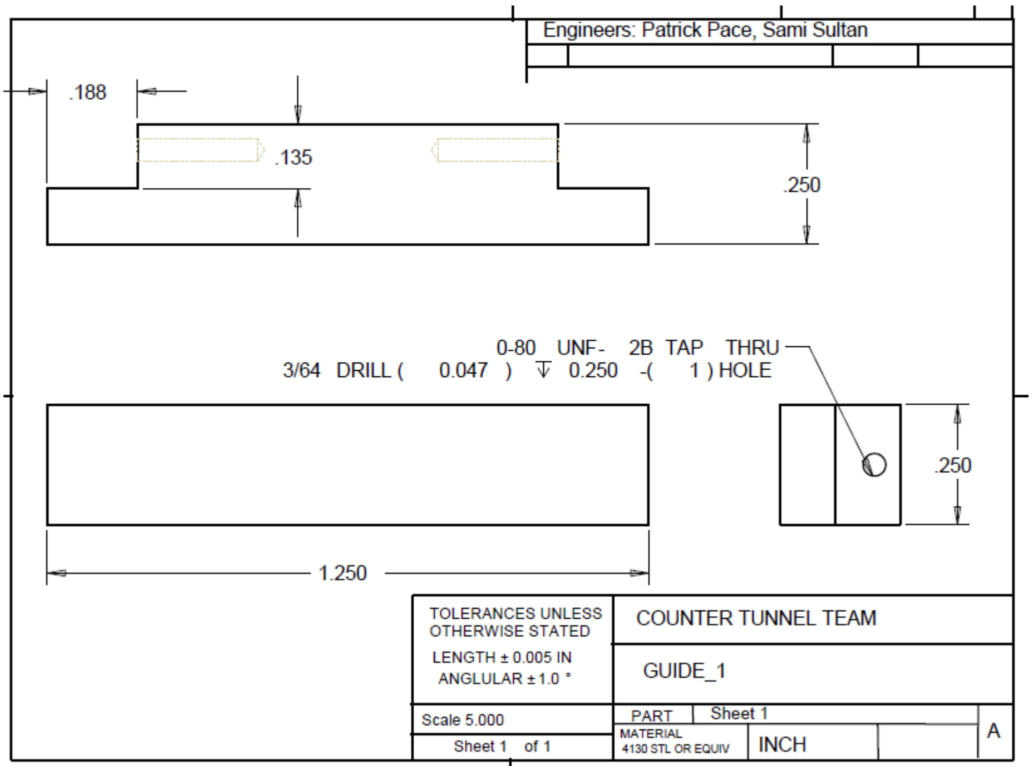
A

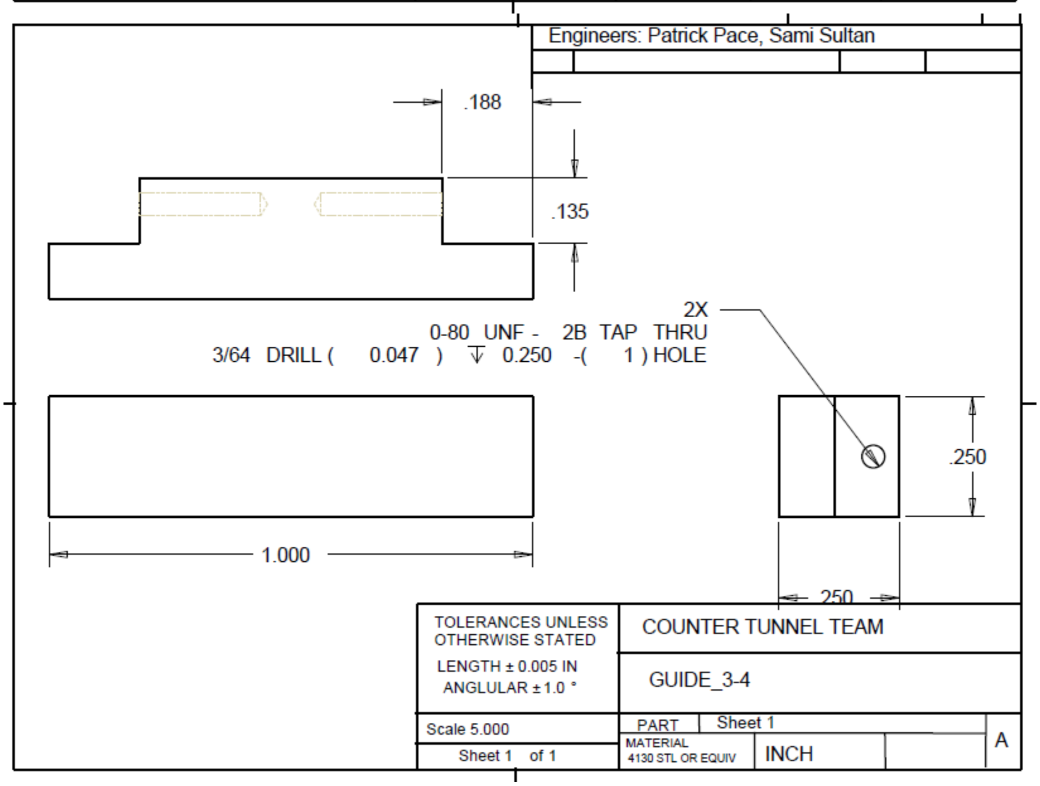

Engineers: Patrick Pace, Sami Sultan
.500
15.000
.125
.693
1.125
1.250
16.000
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
CHANNEL_1-25X1-25
Scale 0.500
PART
Sheet 1
MATERIAL AL6061 OR EQUIV
INCH
A
Sheet 1 of 1

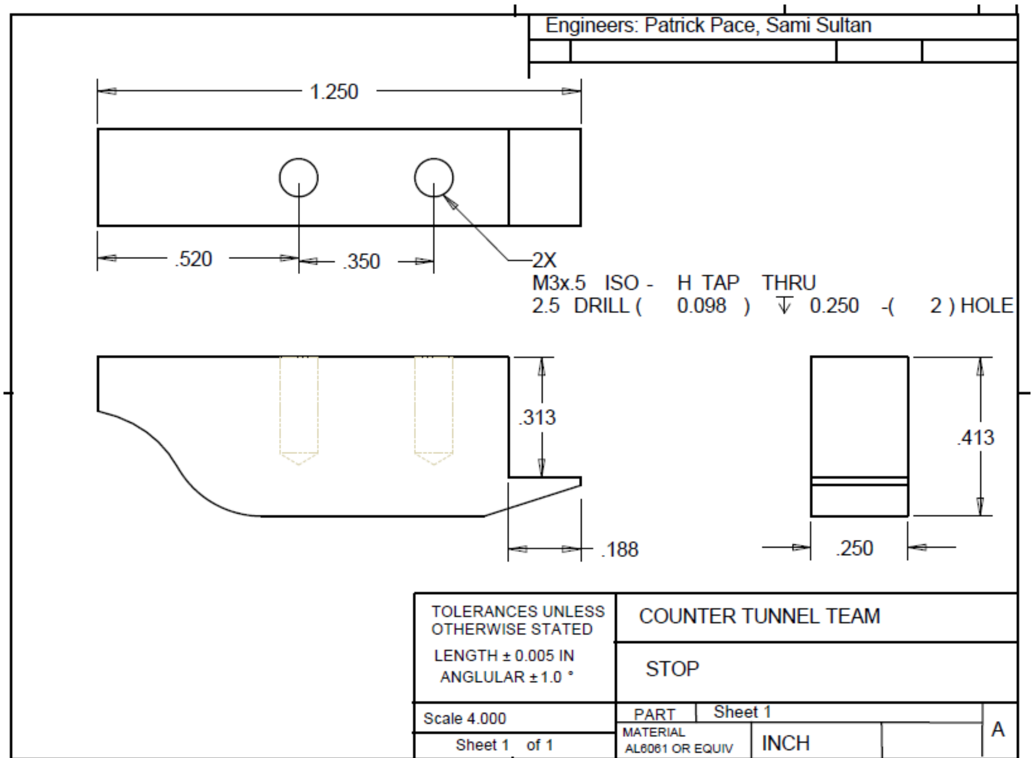

Engineers: Patrick Pace, Sami Sultan
2X M3x.5 ISO - H TAP THRU
2.5 DRILL (0.098) THRU -(2) HOLE
3.625
2.475
.27
HR
A1
A2
.365
2XR.125
15.500
2X.500
2XR.063
.500
.125
A1
A2
A3
.063
.938
HR
16.000
1.000
6X #52 DRILL (0.064) THRU- (2) HOLE
0.1 x 82.0
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
CHANNEL_1X1
Scale 0.500
PART
PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A
Sheet 1 of 2

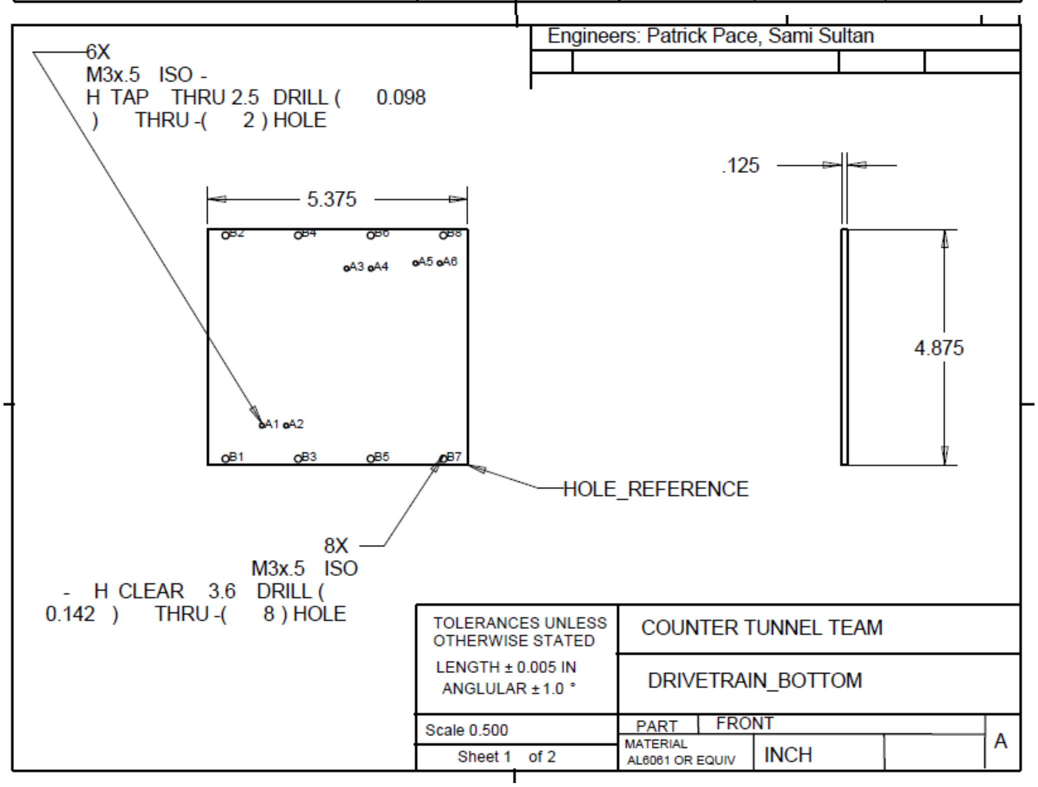

Engineers: Patrick Pace, Sami Sultan
2X M3x.5 ISO - H TAP THRU
2.5 DRILL (0.098) THRU -(2) HOLE
3.625
2.580
.270
HR
A1 A2
2XR.125
.240
14.000
.625
2X .500
.063
A1 A2
.313
.125
2XR.063
HR
14.500
.750
4X #52 DRILL (0.064) THRU- (2) HOLE
0.119 x 82.000
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
CHANNEL_3-4X3-4
Scale 0.500
Sheet 1 of 2
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A

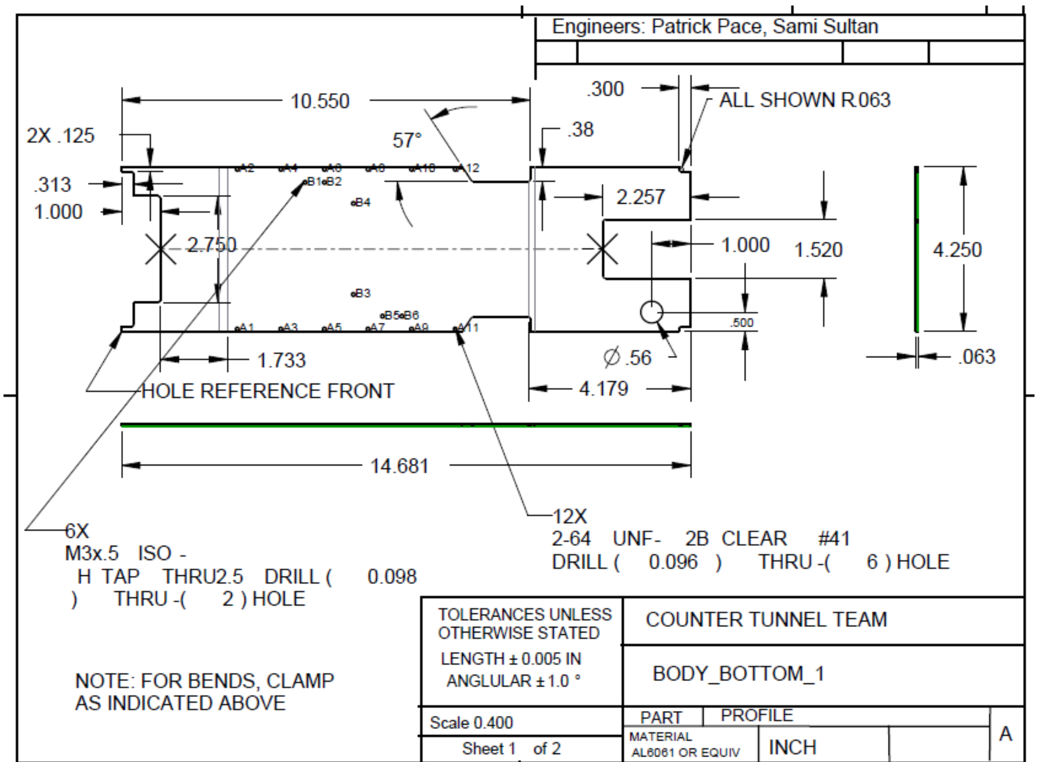

Engineers: Patrick Pace, Sami Sultan
.875
.063
.135
2X
0-80 UNF- 2B TAP THRU
3/64 DRILL (0.047) 0.250 -(1) HOLE
.250
1.000
.250
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
TRAVEL_STOP
Scale 2.000
Sheet 1 of 2
PART Sheet 1
MATERIAL AL6061 OR EQUIV
INCH
A

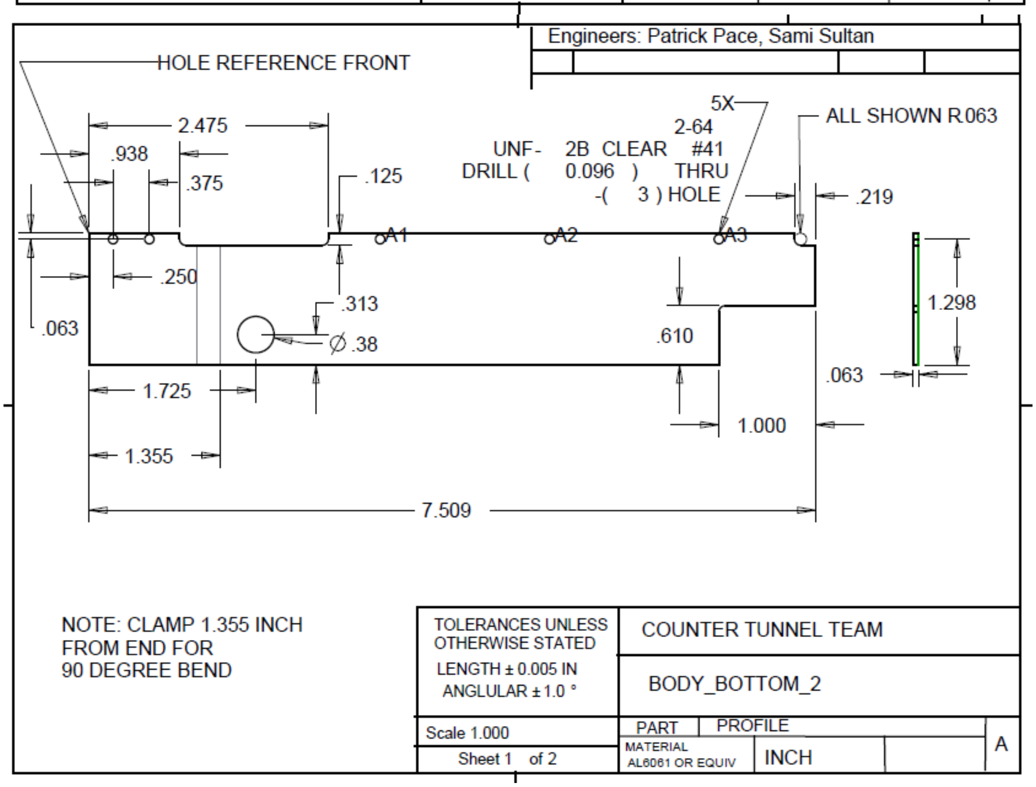

Engineers: Patrick Pace, Sami Sultan
.188
.135
.250
0-80 UNF- 2B TAP THRU
3/64 DRILL (0.047) ↧ 0.250 -(1) HOLE
.250
1.250
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
GUIDE_1
Scale 5.000
Sheet 1 of 1
PART
Sheet 1
MATERIAL
4130 STL OR EQUIV
INCH
A

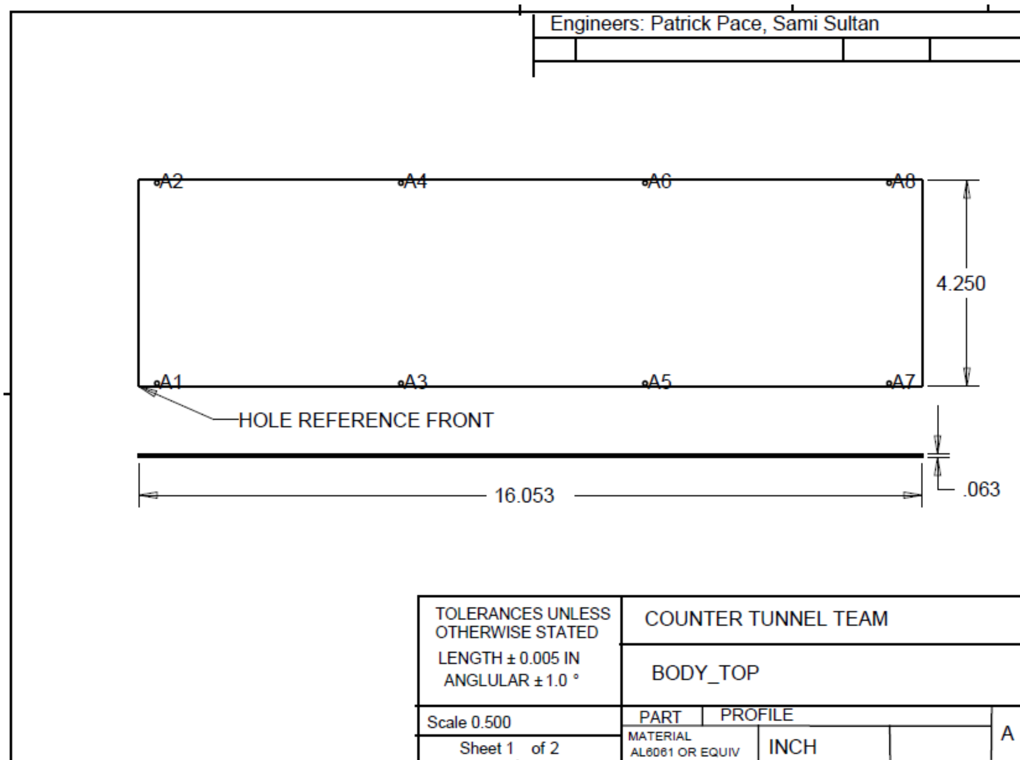

Engineers: Patrick Pace, Sami Sultan
.188
.135
2X
0-80 UNF - 2B TAP THRU
3/64 DRILL (0.047) ↧ 0.250 -(1) HOLE
.250
1.000
.250
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
GUIDE_3-4
Scale 5.000
Sheet 1 of 1
PART
Sheet 1
MATERIAL
4130 STL OR EQUIV
INCH
A

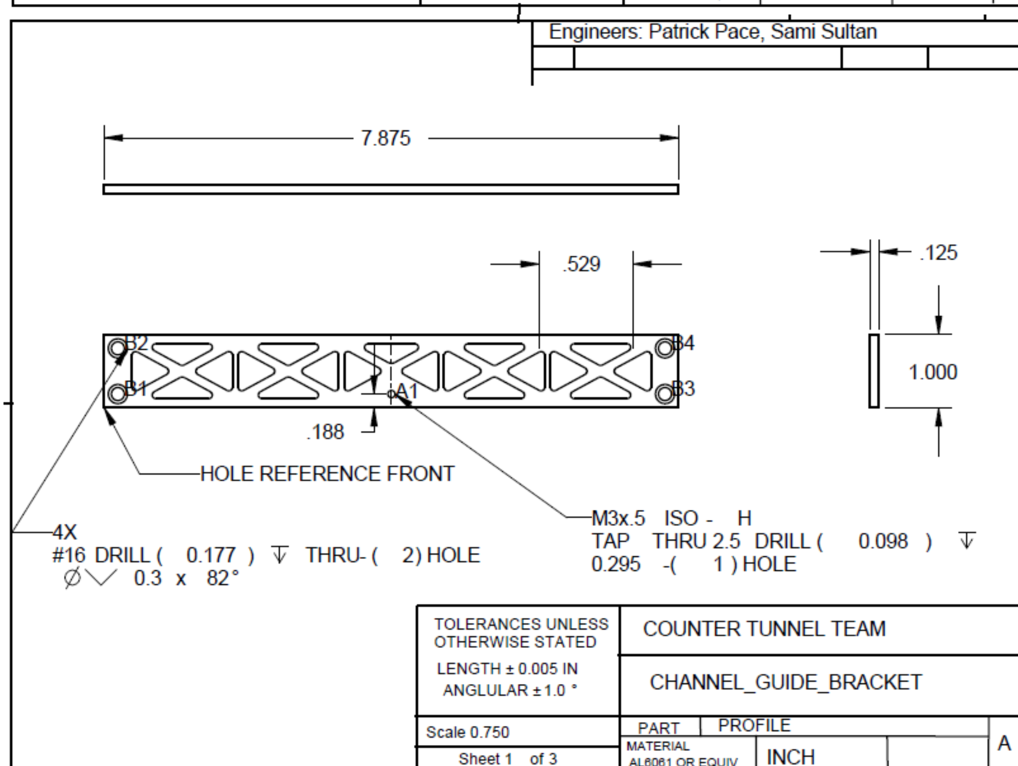

Engineers: Patrick Pace, Sami Sultan
1.250
.520
.350
2X
M3x.5 ISO - H TAP THRU
2.5 DRILL (0.098) ⊽ 0.250 -(2) HOLE
.313
.413
.188
.250
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
STOP
Scale 4.000
Sheet 1 of 1
PART
Sheet 1
MATERIAL
AL6061 OR EQUIV
INCH
A

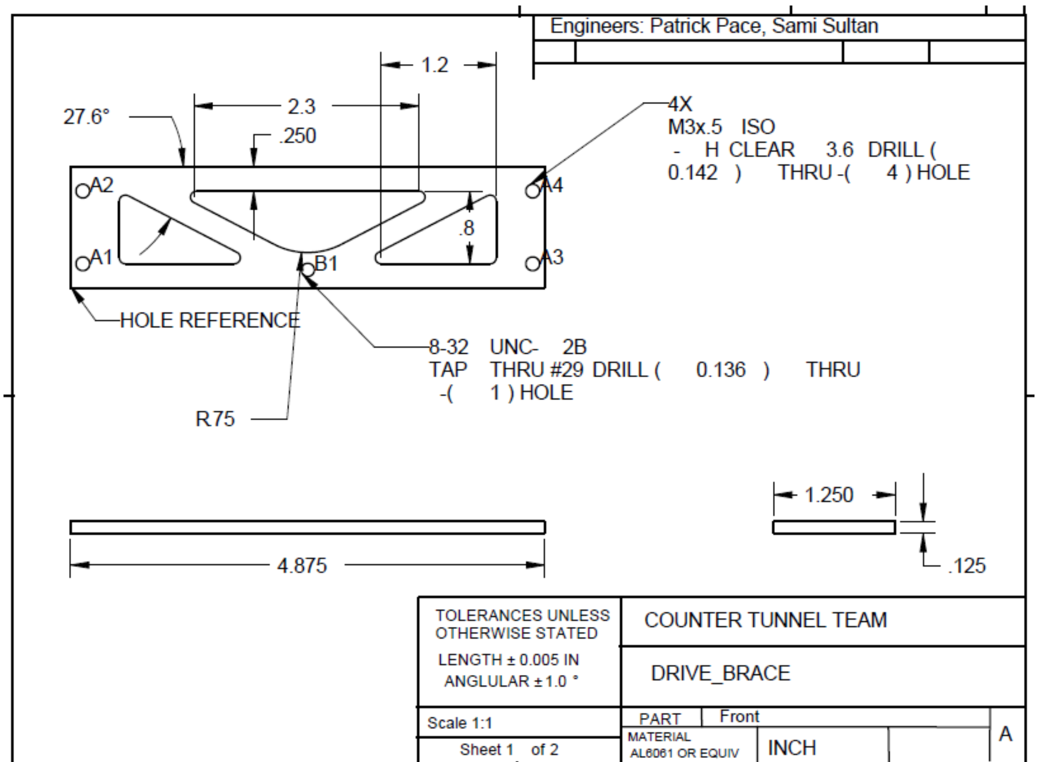

Engineers: Patrick Pace, Sami Sultan
6X
M3x.5 ISO -
H TAP THRU 2.5 DRILL (0.098
) THRU -(2) HOLE
.125
5.375
4.875
HOLE_REFERENCE
8X
M3x.5 ISO
- H CLEAR 3.6 DRILL (
0.142) THRU -(8) HOLE
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
DRIVETRAIN_BOTTOM
Scale 0.500
Sheet 1 of 2
PART
FRONT
MATERIAL
AL6061 OR EQUIV
INCH
A

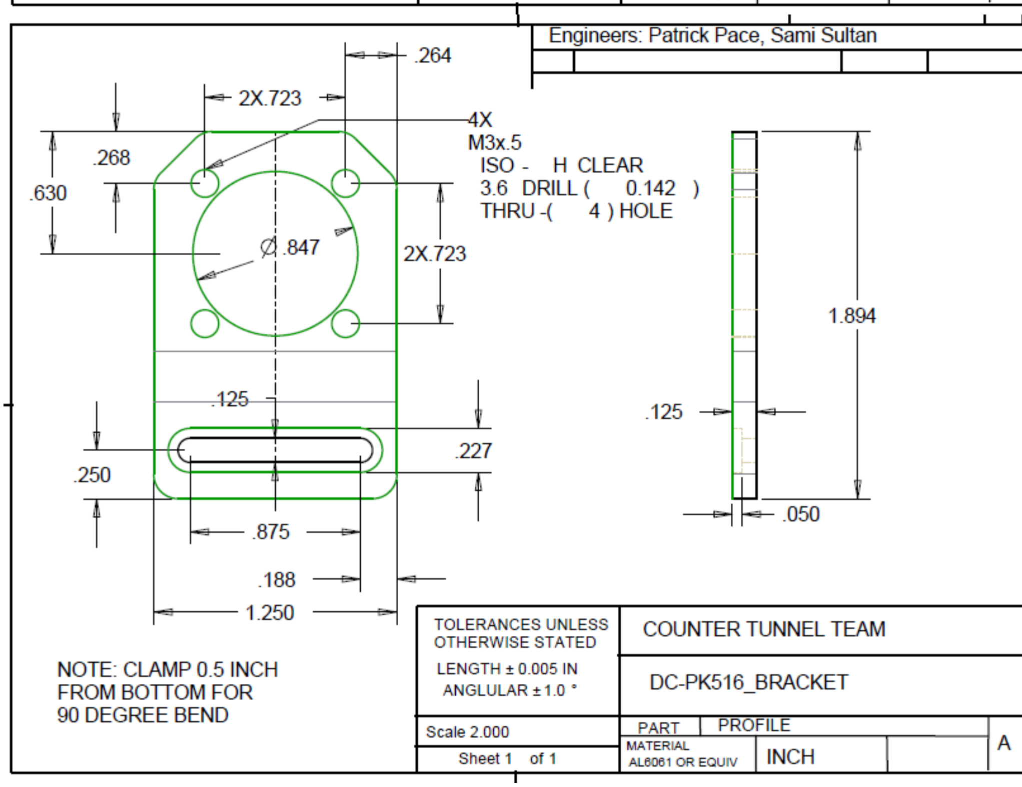

Engineers: Patrick Pace, Sami Sultan
10.550
57°
2X .125
.313
1.000
2.750
1.733
HOLE REFERENCE FRONT
.300
ALL SHOWN R.063
.38
2.257
1.000
1.520
4.250
.500
∅ .56
4.179
.063
14.681
6X
M3x.5 ISO -
H TAP THRU2.5 DRILL (0.098
) THRU -(2) HOLE
12X
2-64 UNF- 2B CLEAR #41
DRILL (0.096) THRU -(6) HOLE
NOTE: FOR BENDS, CLAMP
AS INDICATED ABOVE
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGULAR ± 1.0 °
COUNTER TUNNEL TEAM
BODY_BOTTOM_1
Scale 0.400
Sheet 1 of 2
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A

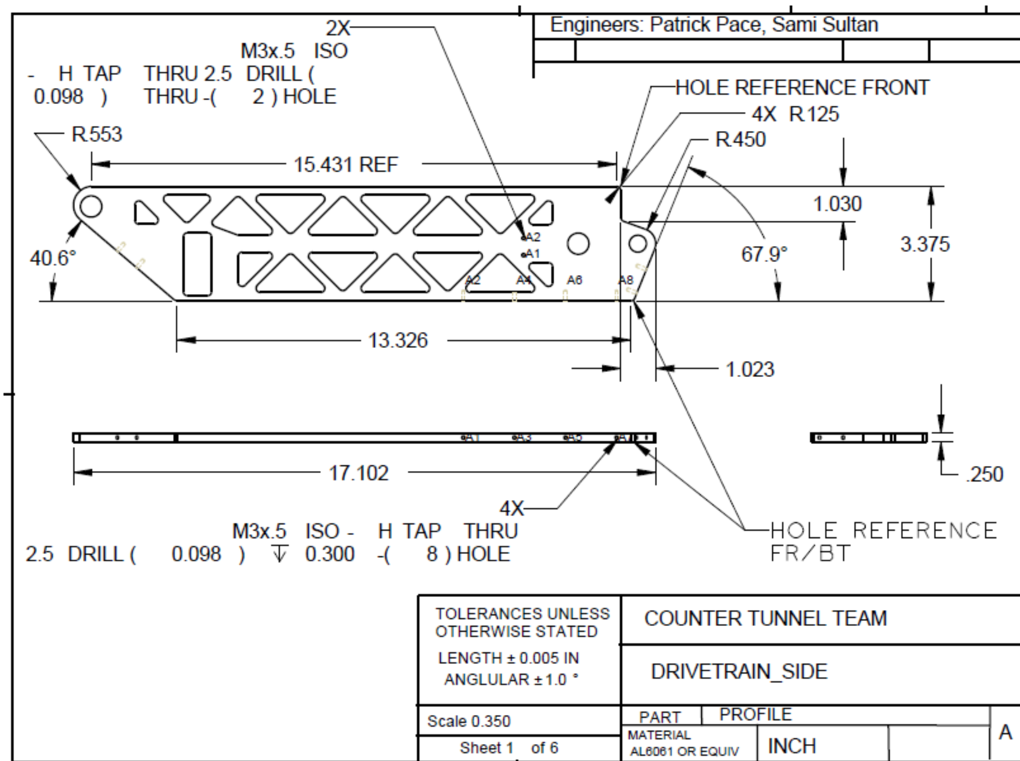

Engineers: Patrick Pace, Sami Sultan
HOLE REFERENCE FRONT
2.475
.938
.375
.125
5X
2-64
UNF- 2B CLEAR #41
DRILL (0.096) THRU
-(3) HOLE
ALL SHOWN R.063
.219
A1
A2
A3
.250
.313
∅ .38
.063
.610
1.298
.063
1.725
1.355
1.000
7.509
NOTE: CLAMP 1.355 INCH
FROM END FOR
90 DEGREE BEND
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGULAR ± 1.0 °
COUNTER TUNNEL TEAM
BODY_BOTTOM_2
Scale 1.000
Sheet 1 of 2
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A

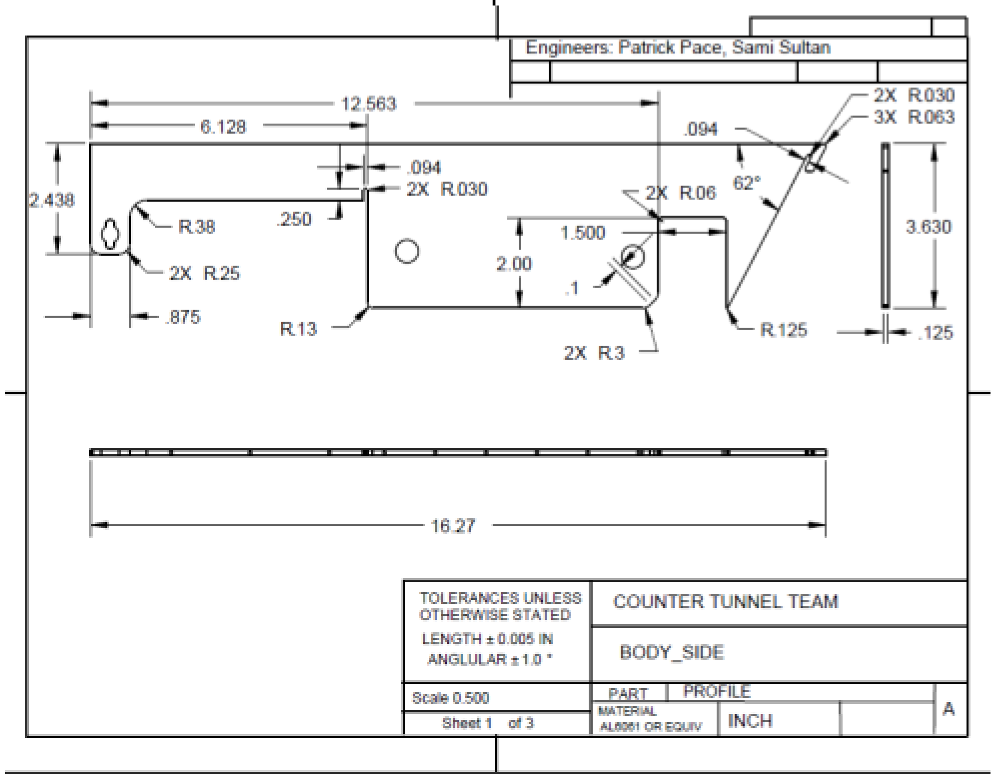

Engineers: Patrick Pace, Sami Sultan
A2
A4
A6
A8
A1
A3
A5
A7
4.250
HOLE REFERENCE FRONT
16.053
.063
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
BODY_TOP
Scale 0.500
Sheet 1 of 2
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A

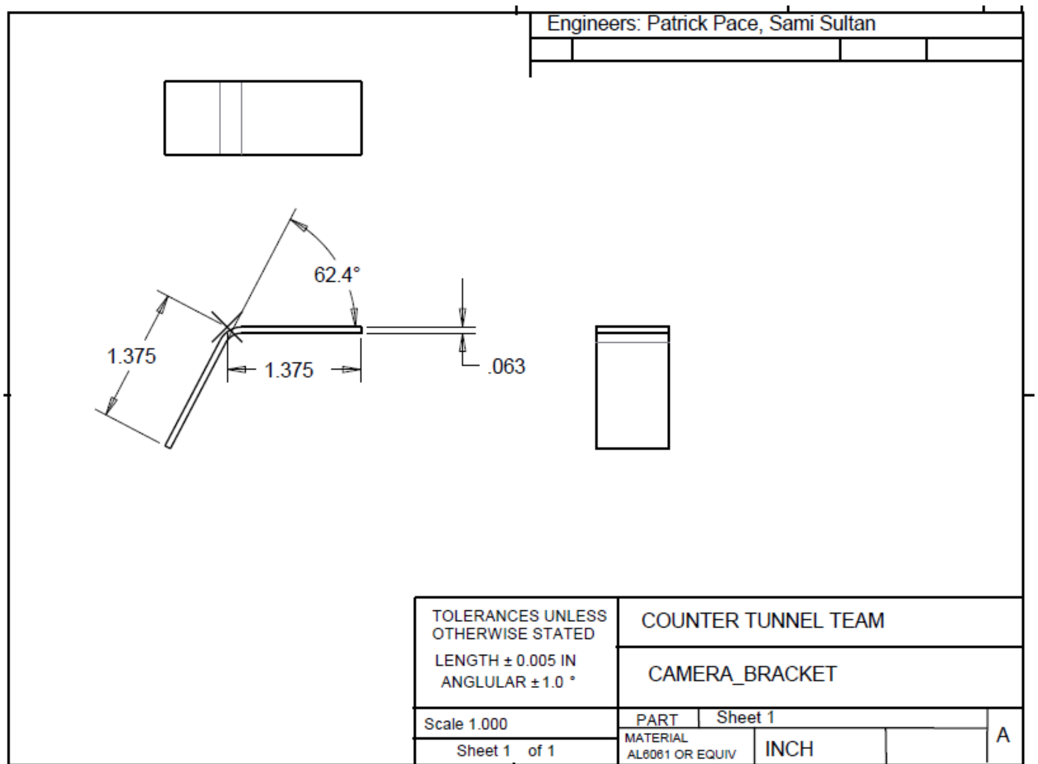

Engineers: Patrick Pace, Sami Sultan
7.875
.529
.125
B2
B1
B4
B3
A1
1.000
.188
HOLE REFERENCE FRONT
4X
#16 DRILL (0.177) THRU- (2) HOLE
0.3 x 82°
M3x.5 ISO - H
TAP THRU 2.5 DRILL (0.098)
0.295 -(1) HOLE
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
CHANNEL_GUIDE_BRACKET
Scale 0.750
Sheet 1 of 3
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A

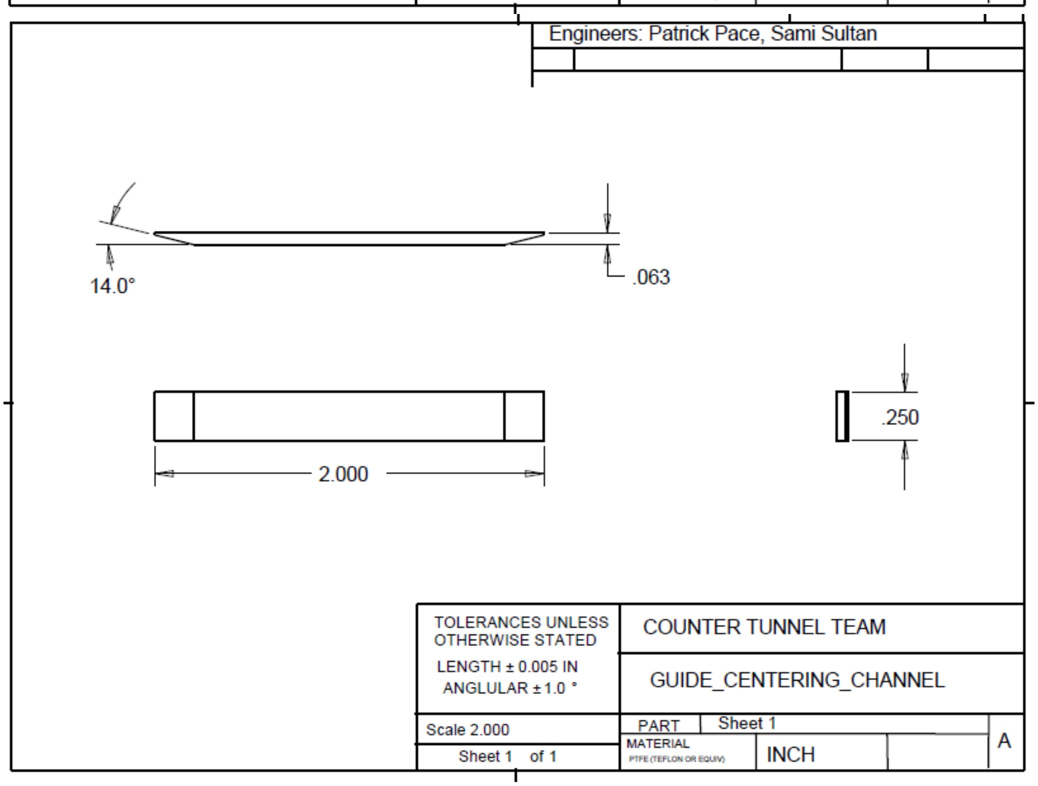

Engineers: Patrick Pace, Sami Sultan
1.2
2.3
27.6°
.250
4X
M3x.5 ISO
- H CLEAR 3.6 DRILL (
0.142) THRU -(4) HOLE
A2
A4
.8
A1
A3
B1
HOLE REFERENCE
8-32 UNC- 2B
TAP THRU #29 DRILL (0.136) THRU
-(1) HOLE
R75
1.250
.125
4.875
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
DRIVE_BRACE
Scale 1:1
Sheet 1 of 2
PART Front
MATERIAL AL6061 OR EQUIV
INCH
A

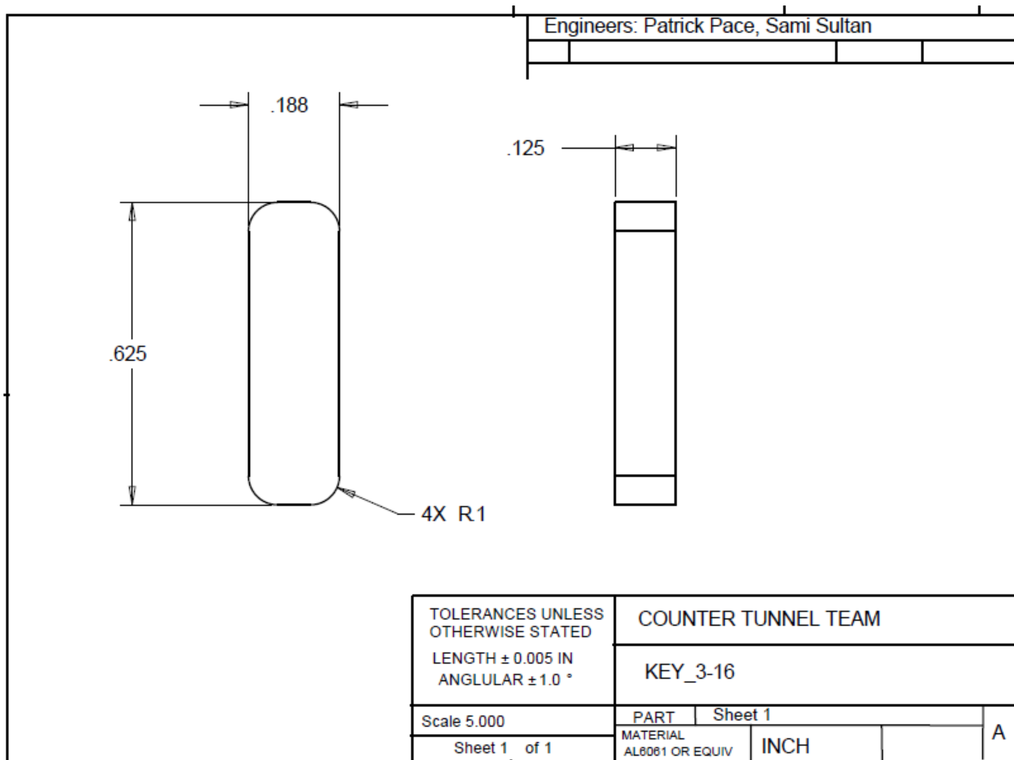

Engineers: Patrick Pace, Sami Sultan
.264
2X.723
4X
M3x.5
ISO - H CLEAR
3.6 DRILL (0.142)
THRU -(4) HOLE
.268
.630
Ø.847
2X.723
1.894
.125
.125
.227
.250
.050
.875
.188
1.250
NOTE: CLAMP 0.5 INCH
FROM BOTTOM FOR
90 DEGREE BEND
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
DC-PK516_BRACKET
Scale 2.000
Sheet 1 of 1
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A

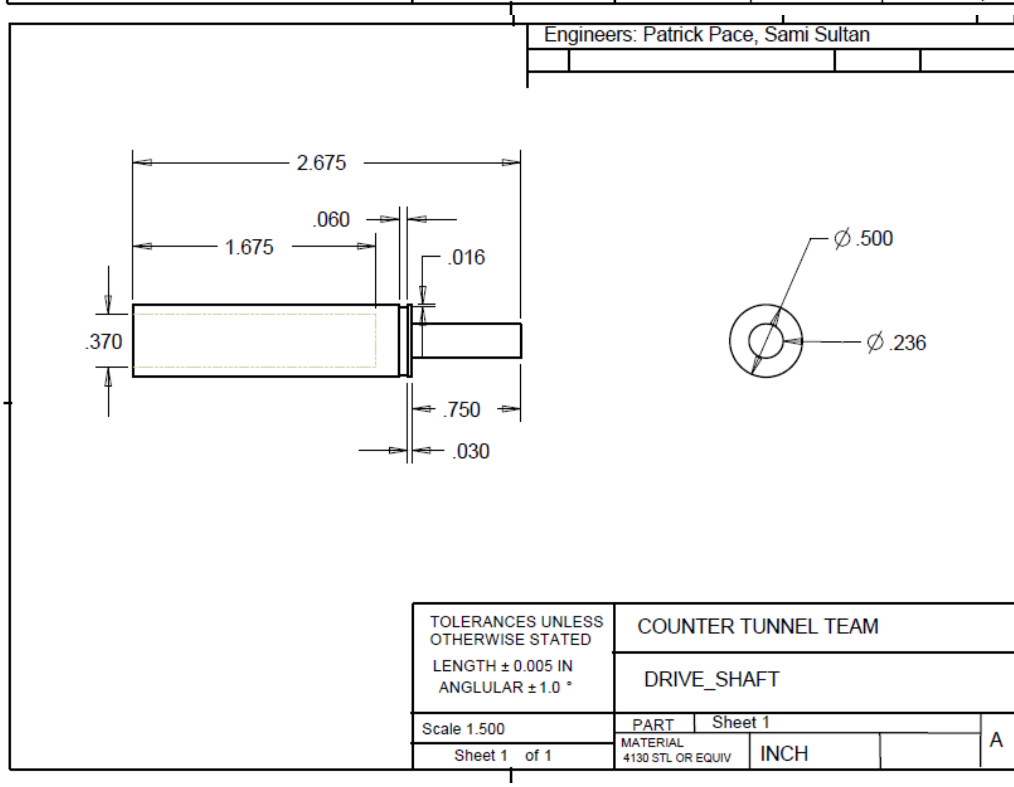

Engineers: Patrick Pace, Sami Sultan
2X
M3x.5 ISO
- H TAP THRU 2.5 DRILL (
0.098) THRU -(2) HOLE
R.553
15.431 REF
HOLE REFERENCE FRONT
4X R.125
R.450
1.030
3.375
67.9°
40.6°
13.326
1.023
17.102
.250
4X
M3x.5 ISO - H TAP THRU
2.5 DRILL (0.098) ↧ 0.300 -(8) HOLE
HOLE REFERENCE FR/BT
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
DRIVETRAIN_SIDE
Scale 0.350
Sheet 1 of 6
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A


Engineers: Patrick Pace, Sami Sultan
12.563
6.128
.094
2X R.030
3X R.063
.094
2X R.030
62°
2.438
R.38
.250
2X R.06
1.500
3.630
2X R.25
2.00
.1
.875
R.13
2X R.3
R.125
.125
16.27
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
BODY_SIDE
Scale 0.500
Sheet 1 of 3
PART PROFILE
MATERIAL AL6061 OR EQUIV
INCH
A


Engineers: Patrick Pace, Sami Sultan
62.4°
1.375
1.375
.063
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
CAMERA_BRACKET
Scale 1.000
Sheet 1 of 1
PART
Sheet 1
MATERIAL
AL6061 OR EQUIV
INCH
A


Engineers: Patrick Pace, Sami Sultan
14.0°
.063
2.000
.250
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
GUIDE_CENTERING_CHANNEL
Scale 2.000
Sheet 1 of 1
PART
Sheet 1
MATERIAL
INCH
A


Engineers: Patrick Pace, Sami Sultan
.188
.125
.625
4X R1
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
KEY_3-16
Scale 5.000
Sheet 1 of 1
PART
Sheet 1
MATERIAL
AL6061 OR EQUIV
INCH
A


Engineers: Patrick Pace, Sami Sultan
2.675
.060
1.675
.016
.370
.750
.030
∅ .500
∅ .236
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
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Scale 1.500
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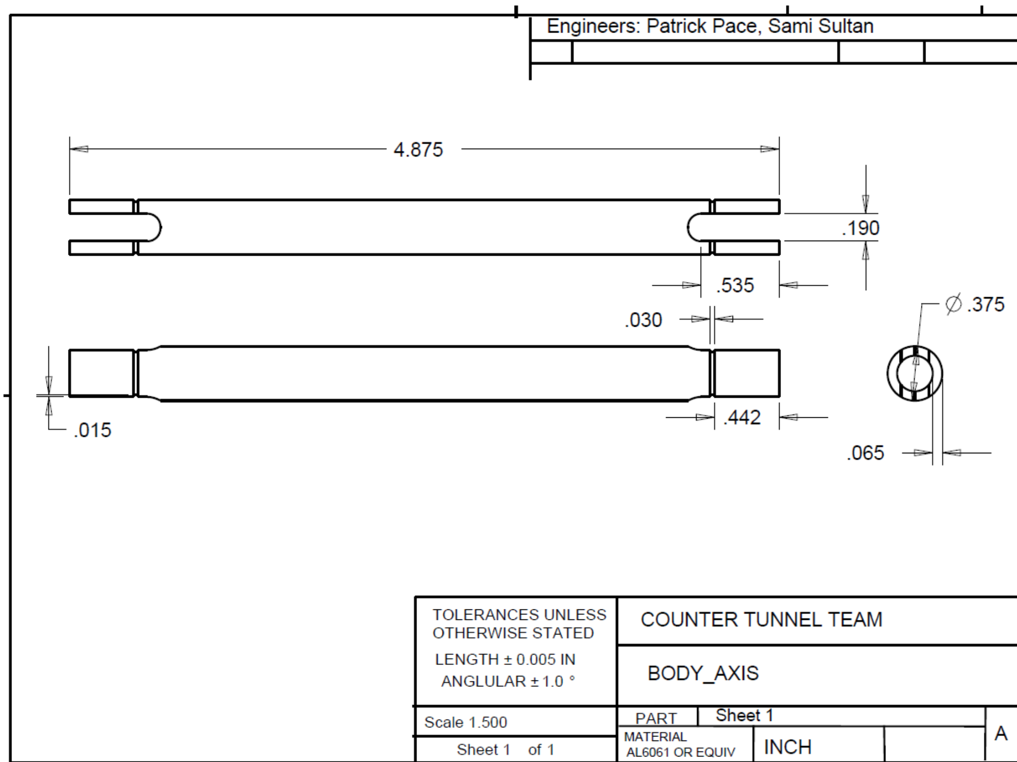
PART
Sheet 1
MATERIAL
4130 STL OR EQUIV
INCH
A


Engineers: Patrick Pace, Sami Sultan
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.535
.030
Ø .375
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.442
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TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGULAR ± 1.0 °
COUNTER TUNNEL TEAM
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PART
Sheet 1
MATERIAL
AL6061 OR EQUIV
INCH
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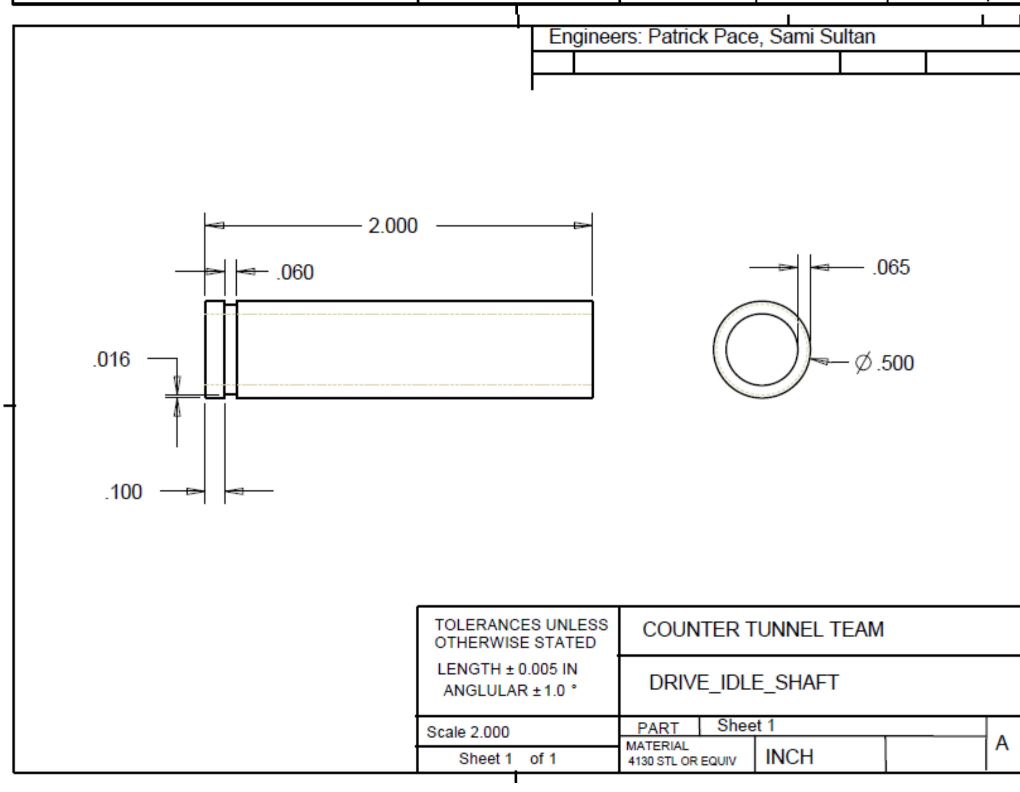
Engineers: Patrick Pace, Sami Sultan
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Ø .500
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ANGULAR ± 1.0 °
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Sheet 1
MATERIAL
4130 STL OR EQUIV
INCH
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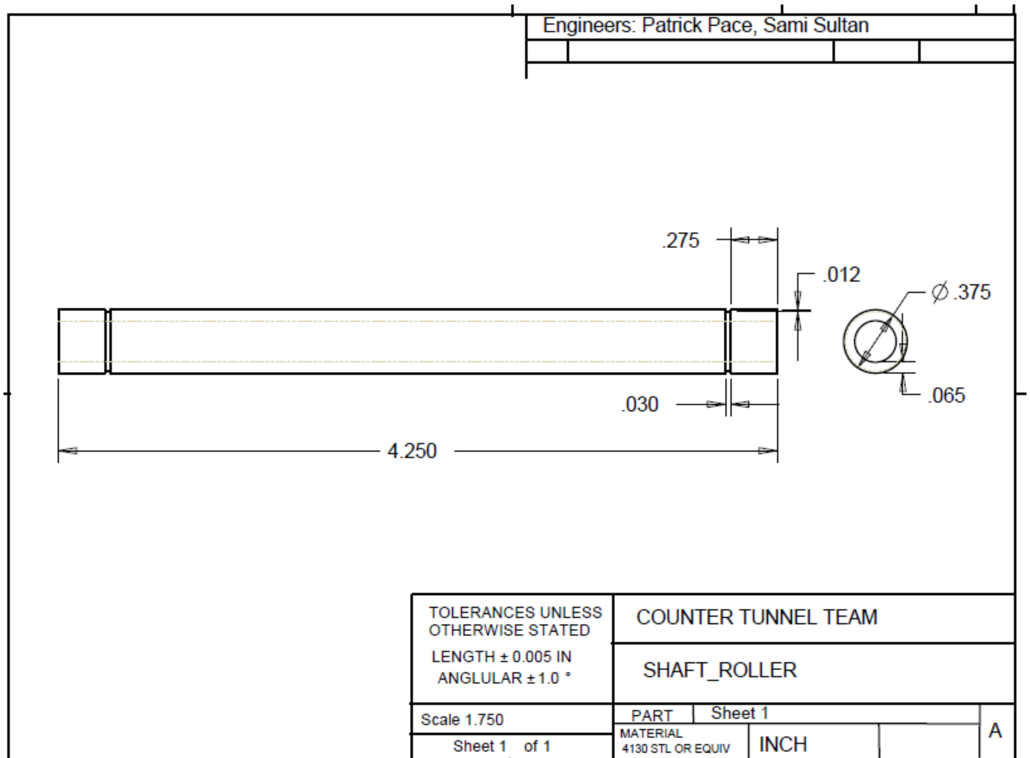
Engineers: Patrick Pace, Sami Sultan
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TOLERANCES UNLESS OTHERWISE STATED
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Scale 1.750
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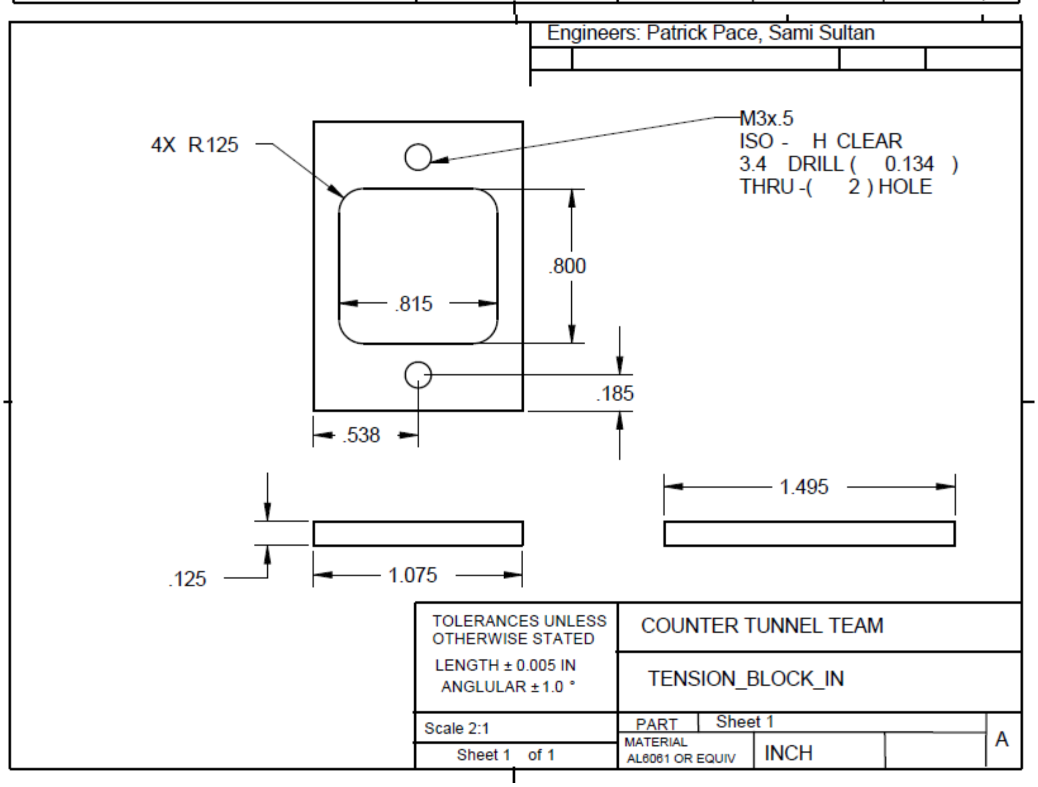
PART
Sheet 1
MATERIAL
4130 STL OR EQUIV
INCH
A


Engineers: Patrick Pace, Sami Sultan
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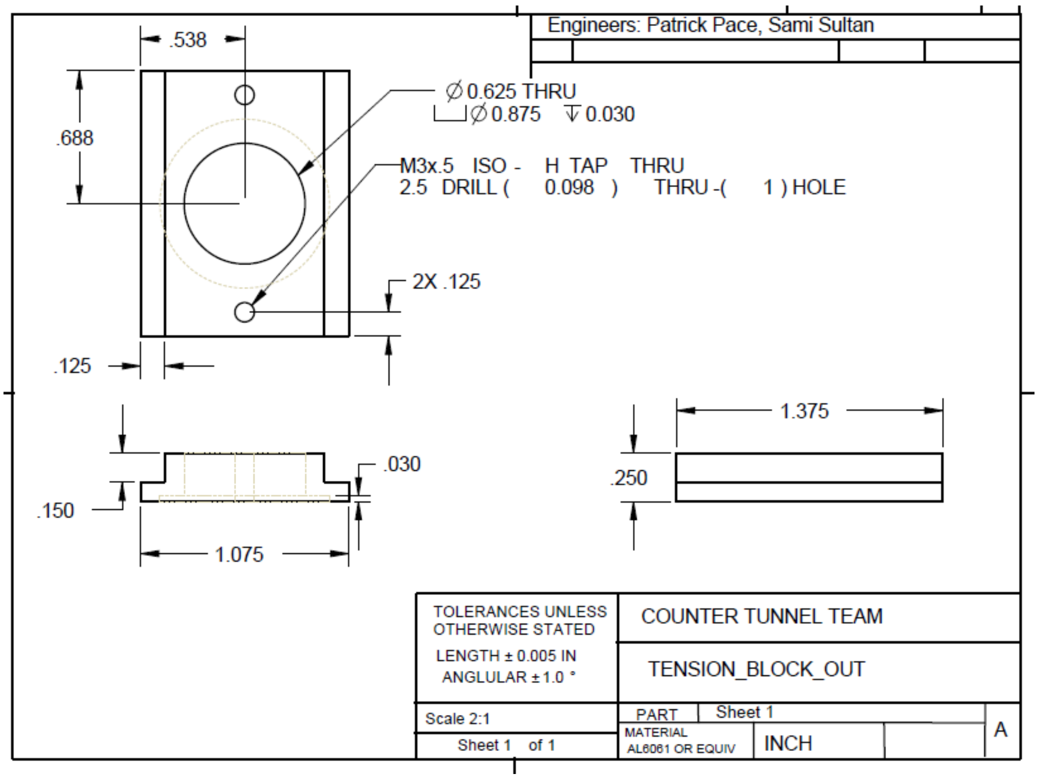
M3x.5
ISO - H CLEAR
3.4 DRILL (0.134)
THRU -(2) HOLE
.800
.815
.185
.538
1.495
.125
1.075
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
TENSION_BLOCK_IN
Scale 2:1
Sheet 1 of 1
PART
Sheet 1
MATERIAL
AL6061 OR EQUIV
INCH
A

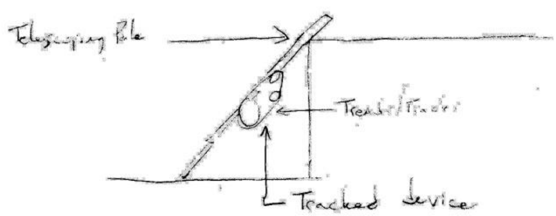

Engineers: Patrick Pace, Sami Sultan
.538
.688
Ø 0.625 THRU
⌴ Ø 0.875 ↧ 0.030
M3x.5 ISO - H TAP THRU
2.5 DRILL (0.098) THRU -(1) HOLE
2X .125
.125
1.375
.030
.250
.150
1.075
TOLERANCES UNLESS OTHERWISE STATED
LENGTH ± 0.005 IN
ANGLULAR ± 1.0 °
COUNTER TUNNEL TEAM
TENSION_BLOCK_OUT
Scale 2:1
PART
Sheet 1
MATERIAL
AL6061 OR EQUIV
INCH
A
Sheet 1 of 1

Appendix F: Bond Graph Development and Code

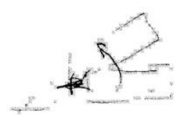
Term Project | J83Q | Patrick Pace

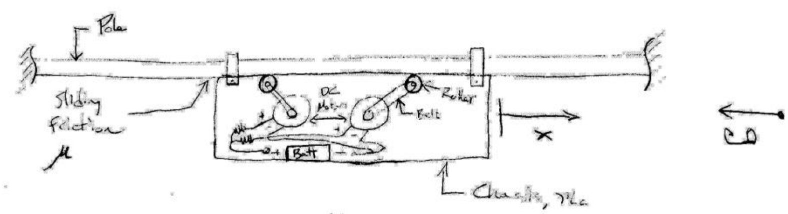
Project Description: Model a robotic device to obtain the required torque and current during transient motion.

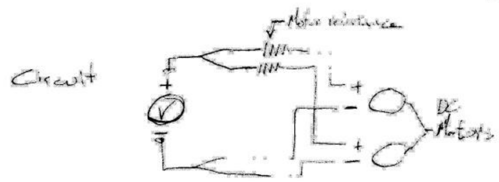
Device Description: The device is a tracked robot that is required to surmount relatively large obstacles. To accomplish this, the device can deploy a telescoping pole, and then by driving rollers attached to the pole with DC motors, the device can "climb" to the top of an obstacle.



Simplified Model for Bond Graph:







Calculations to verify and "tune" model

Dynamic climbing, no friction

— the voltage should cause current + momentum flow to rise until equilibrium with gravity is reached.

$P = VI = R_m I^2 + mg(V_{ei})$ + $E = mgh$

$\dot{E} = mg\dot{h} \approx 13 W$

$0 = R_m I^2 - VI + mg(V_{ei})$

$0 = 2(I^2) - 12I + 14$

$P_{min} = VI = 13W$

$\therefore I_{min} = 13/9.2$ or ... 1.4 / ...

*Estimated current ≈ 2A

With no gravity, damping terms should force velocity to stabilize ~10 mph or 14 fps or 4.4 m/s

or use b_R to limit v to 4.4 + 25% = 6 m/s

b_f to limit v to 4.4 + 75% = 17.6 m/s

Now activate gravity and examine results.

Speed check @ 12 in/s = 0.3048 m/s

$\omega_R = \frac{v}{r} = \frac{12}{.5} \approx 24$ rad/s × $\frac{1 rev}{2\pi rad} \frac{60 s}{1 min}$ = 229.2 rpm

$\omega_m = 1.5(14)\omega_R = 504$ rad/s × = 4813 rpm
(27) 972 ≈ 9282

$T_R = 9.40/2.2 (.5 \cdot .0254) = 0.56$ $T_m = T_R/(1.5 \cdot 14) = 0.0267$ N·m

$i = \frac{T_m}{K_t} \frac{N \cdot m}{A}$ = 1.7 A ?
= 2.9 ... 27

$K = 21$

BOND GRAPH MOTOR SIMULATION CODE

Simulation Code M-File

```
close all
clear all
clc
global Rm L rg rm ra rr re k m g Jm v_nom

initial = [0;0];
[time answ] = ode45(@motorfun_fb, [0 2], [initial]);

plot(time, answ(:,1)/L)
xlabel('time (s)')
ylabel('Current (amps)')
figure(2)
plot(time, answ(:,2)/m)
xlabel('time (s)')
ylabel('Velocity (m/s)')

for i = 1:length(answ)
   wm(i) = (k/rr)*(answ(i,2)/m);     % motor vel, rad/s
   wm_rpm = wm*(1/(2*pi)*60);        % motor vel, rpm
   w_roll(i) = (answ(i,2)/m)/rr;     % roller vel, rad/s
   w_roll_rpm = w_roll*(1/(2*pi)*60); % roller vel, rpm
end
figure(4)
plot(time, wm_rpm, time, w_roll_rpm)
xlabel('time (s)')
ylabel('Rotational speed (rpm)')
legend('w motor(rpm)','w roller(rpm)')

for i = 1:length(answ)
   p2(i) = (answ(i,1)/L)*rg*wm(i);
   pow(i) = (-m*g)*(answ(i,2)/m);
%    p3(i)  = v_nom*(answ(i,1)/L);
end
figure(3)
plot(time, p2, time, pow)
xlabel('time (s)')
ylabel('Power (W)')
legend('Power w/ Losses (effot*flow using solved vars)','No Loss
Power(m*g*h-dot)','Location','SouthEast')
```

Variables and Equations Defined, M-File

```
function [xdot] = motorfun_fb(t, x)
global Rm L rg rm ra rr re k m g Jm

%x(1) = Lamda
%x(2) = Momentum, P
```

```
%Variables Defined for lambda dot
%v Controlled voltage output defined in function "v(vel,tar)"
tar = 6*.0254;           %Target velocity, m/s
Rm  = 1.8;               %Winding resistance, Ohm
L   = 1.1;               %Motor Inductance, Henry
rg  = .01534;            %Torque constant, Nm/Amp
rm  = (0.92/2)*0.0254;   %Motor gear radius, m
ra  = (1.08/2)*0.0254;   %Roller axis gear radius, m
rr  = (1.5/2)*0.0254;    %Roller radius, m
re  = 35;                %Motor reduction ratio
k   = (ra/rm)*re;        %Transformer constant, m/m (accounts for gear
head and roller-motor ratio)
m   = 12*(4.448/9.81);   %Robot mass, kg (modeling 1 motor assuming they
share load)

%Additional Variables for Pdot
g   = -9.81;        %acceleration of gravity, m/s2
bf  = 10;           %Friction viscous coefficient
Jm  = 1.2E-6;       %Motor rotor inertia, kg*m^2
%br - nonlinear rolling friction of roller, defined in function "br"

    xdot=zeros(2,1);
    xdot(1)  = v(x(2)/m,tar)-(x(1)/L)*Rm-rg*k*(1/rr)*(x(2)/m);
    xdot(2)  = m*g+(k*rg/rr)*(x(1)/L)+(x(2)/m)*(-bf-((k^2)/rr^2)*Jm-
(br(x(2)/m)/rr^2));

end
```

Voltage Controller, M-File

```
function [vo] = v(vel,tar)
%vo is the output voltage calulated with the desired method
global v_nom
v_nom =12;
%Various basic controlling methods
% Uncomment the method desired

%$-Constant Value-$%
% vo=v_nom;

%$-Bang Bang Controller-$%
% if vel<=tar
%     vo=v_nom;
% end
% if vel>tar
%     vo=0;
% end

%$-Restricted Percentage of Velocity-$%
if vel<=tar
    per=(vel/tar);
    vo=v_nom-v_nom*per;
```

```
end
if vel>tar
    per=(vel/tar);
    vo=v_nom-v_nom*(per-1);
end
 if vo>v_nom
    vo=v_nom
end
if vo<0
    vo=0
end
vo=vo
```

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Vita

Patrick Pace was born in Lake Charles, Louisiana, as a blend of a third generation engineer and contractor. Growing up in Albuquerque, New Mexico, he was constantly occupied with LEGOs®, toy cars, and tools. This would progress into power tools, real cars, bicycles, and gadgetry all mixed with healthy doses of the great outdoors. He is a graduate from Eldorado High School and finished his B.S. in Mechanical Engineering at The University of New Mexico. During his college career he gained hands on business and engineering experience at Eclipse Aviation, Kirtland AFRL, and Sandia National Laboratories, as well as maintaining a small landscaping business. Upon completion of his degree at UNM and internship at SNL, he started his M.S. in Mechanical Engineering at The University of Texas at Austin in the Design and Manufacturing group, serving as a research assistant under Dr. Kristin L. Wood learning and expanding the fields of design methodology and highly mobile robots while collaborating with Cadets of the United States Air Force Academy. Future plans include his home and church family, a career as a mechanical design engineer, hobby entrepreneurship, exploration of the great outdoors, and ever tinkering on personal vehicles and bicycles.

Carguy68@msn.com

This thesis was typed by the author.