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A Tread/Limb/Serpentine Hybrid Robot: Toward Hypermobility in Deconstructed Environments

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A TREAD/LIMB/SERPENTINE HYBRID ROBOT: TOWARD HYPERMOBILITY IN DECONSTRUCTED ENVIRONMENTS

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Submitted to the Faculty

of

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Joshua T. Lane

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of

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This research is dedicated to my family and friends for their endless support.

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LIST OF ABBREVIATIONS

DOF: Degree of Freedom

FPGA: Field Programmable Gate Array

GPIO: General Purpose I/O

HCRR: High Centering Rejection Ratio

MIPS: Million Instructions Per Second

UGV: Unmanned Ground Vehicle

USAR: Urban Search And Rescue

GLOSSARY

Holonomic: "A holonomic system is one in which the number of degrees of freedom is equal to the number of coordinates needed to specify the configuration of the system" (Holmberg & Khatib, 2000).

Hybridization: A synergistic combination of two or more different classes of actuation modes in a single platform (Doroftei, Conduraru, et al., 2014).

Hypermobile Robots: "A group of articulated mobile robots that typically comprise of several segments with powered wheels, tracks, or legs to propel the vehicle forward" (Granosik, 2014).

ABSTRACT

Lane, Joshua T. M.S., Purdue University, December 2015. A Tread/Limb/Serpentine Hybrid Robot: Toward Hypermobility in Deconstructed Environments. Major Professor: Richard M. Voyles.

According to the Red Cross, an average of over 600 disasters and 100,000 associated deaths occur annually throughout the world. This frequency of disasters strains an already overburdened disaster response effort. In the first 48 hours of a rescue operation, it is estimated that a responder will get less than three hours of continuous sleep as they need to work at full force to set up the operation and begin work in the field. This leads to sleep deprivation during the most critical time for search and rescue of victims. Therefore, robots are greatly needed as a force multiplier in USAR response to reduce some of the burden and workload placed on the human rescue workers to make for a more efficient and effective response.

This thesis outlines the development of a tread/limb/serpentine hybrid robot, built from a hybridization of a multiplicity of novel two-dimensional tread mechanisms interspersed with two dimensional articulating joints that combines the mobility strengths of wheels, treads, limbs, and snakes. This hybridization not only enables the robot to lift the tread mechanisms over obstacles with its joints, but also enables far greater capability through holonomic locomotion thanks to the novel two-dimensional tread mechanism design. The mobility of this hybrid robot was evaluated through experimentation and the design of the robot demonstrated both pros and cons compared to similar existing platforms.

CHAPTER 1. INTRODUCTION

The prevalence of robotics in urban search and rescue (USAR) efforts is ever expanding and being repeatedly justified as the frequency of natural and man-made disasters seems to rise and the capabilities of robotic platforms continue to increase. As of 2013, there had been 6,525 disasters reported worldwide throughout the previous decade. This includes both natural and man-made disasters ranging from earthquakes and tsunamis to terrorist attacks. From all of these disasters, a staggering 1,059,072 deaths were reported (Cross, 2014). Some of the most devastating disasters to occur in recent memory are the Fukushima earthquake and nuclear disaster, the Haiti earthquake, Hurricane Katrina, and the World Trade Center attack. It was the World Trade Center attack in 2001 that marked the first reported deployment of rescue robots in a live disaster and demonstrated the benefit of robots to emergency responders. More recently, a large scale deployment of USAR robots provided surveillance and damage assessment after the Fukushima Daiichi nuclear disaster. In this case, because of the damage to four nuclear reactors, radiation levels were far too high for humans to enter the plant and robots needed to be sent in their place (Yoshida, Nagatani, Tadokoro, Nishimura, & Koyanagi, 2014). Typically, robots are employed in disaster situations for that purpose; to extend human perception and to more effectively and efficiently locate survivors and assess damage without subjecting any more humans to potential harm and risk.

1.1 Problem Statement

The scale and frequency with which natural and man-made disasters can and do occur creates a strain on an already overburdened rescue response staff. Working in twelve hour shifts, these rescue workers must dig, drill, and otherwise excavate deconstructed structures to locate and extract victims. And the rescue staff must act fast. 48 hours after the onset of a disaster, the rate of victim mortality increases dramatically due to exposure, lack of food and water, and need of medical treatment (R. Murphy, 2000). As well, the threat against human life is not only restricted to the victims of the initial disaster. Emergency responders put their own lives at risk as they themselves may become victims of a secondary structural collapse, fires, explosions, or exposure to hazardous materials during their rescue efforts. Tragically in fact, over 400 emergency responders' lives were lost in the World Trade Center attack alone (Houser, Jackson, Bartis, & Peterson, 2004). By inserting robots into the rescue efforts, the human rescuers perception can be extended further into the hazardous environments without needing to put the rescuers themselves into harms way. It is with the hope that the human effort is multiplied for a more effective, efficient, and safe rescue response that these robots are utilized.

Because of the potential to preserve human life, USAR robotics research has gained a lot of ground and there have even been several instances in which robots have been deployed to alleviate some of the burden and risk to human rescue workers. However, the complex and unknown environments in disaster scenarios present a lot of challenges for robots and humans alike, and so up to this point there remain a lot of limitations on rescue robot mobility in these harsh environments. An instinctive solution to this issue of mobility could be to simply increase the size of the robot to the point that it can easily roll over any obstacle it encounters, but the size is constrained by the environment they operate in. Not only are there a myriad of obstacles littering the disaster area to overcome, there is also the added challenge of safely moving throughout a collapsed structure without causing further damage. Excavation to widen narrow passages and cavities to allow deeper penetration can further compromise the already weakened structure and lead to a secondary collapse, potentially further injuring or killing the victims or rescue workers. For that reason it is generally necessary to keep rescue robots small in size to limit any necessary alterations to the structure. Along the same lines, it is also necessary to keep robots light weight to limit added stress on the structure during the search. Therefore, the design of rescue robots often requires a more sophisticated approach than sheer size to achieve the necessary mobility for these environments.

1.2 Scope

In regard to search and rescue robotics, wheeled mobile robots like the Recon Scout (Drenner et al., 2002) are some of the simplest platforms to be deployed and they have exceptional mobility on smooth, engineered surfaces. Control of these robots is very simple to master and they are capable of reaching high speeds over flat terrain, but they quickly start to have issues with rough, unstructured terrain. In response to this limitation, treaded vehicles like the TALON (Wells & Deguire, 2005) wrap their wheels in a continuous, engineered surface and carry it with them, making them highly effective in traversing over rough, somewhat discontinuous terrain. But just like wheeled robots, treaded robots run into problems fairly quickly. When confronted with an obstacle greater than or equal to half the height of their tread, a treaded vehicle cannot proceed without intervention. Thus the operating environment for treaded vehicles is limited to terrain with obstacles small relative to their size.

The PackBot (Yamauchi, 2004) in turn recognized this limitation of traditional treaded vehicles and with the simple addition of a pair of single degree of freedom limbs, it achieved a radical leap in mobility paired with a trivial increase in complexity. By hybridizing the two locomotion modes of treads and limbs into a single platform, the PackBot was suddenly able to do things that neither mode could do on its own. The active limbs added the benefit of gearing traction to a treaded vehicle allowing it to lift itself over obstacles and up stairs, massively expanding its operating environment with only one additional degree of freedom.

Similarly, Quince (Nagatani et al., 2011) is another platform that hybridized a treaded vehicle with active limbs, but instead incorporated four independently controlled single degree of freedom limbs. Since its inception, Quince has shown really impressive performance and won a lot of competitions but it can also be difficult to control without full autonomy. And because of that, Quince is not often used outside of the research environment. The additional limbs and degrees of freedom only make it slightly more mobile than the PackBot, but they also make it much more complex than the PackBot. So the trade off between additional capability and complexity over the PackBot is not entirely there. This suggests that the massive increase in mobility afforded by the PackBot was not a function of the number of limbs a robot has, but a function of the hybridization itself.

Thanks to the hybridization of treads and limbs, the PackBot is one of the most effective and successful robots used in search and rescue applications. The PackBot was used in the aftermath of the World Trade Center attack, it was the only successful robot to be deployed in the Fukushima nuclear disaster, and it was even used to aid security at the 2014 World Cup. Despite all of its successes though, the PackBot still has limitations on what it can do in a disaster area, as evidenced in (Casper & Murphy, 2003). So to address the ongoing issue of mobility in the complex terrain of USAR environments, this research focuses on the hypermobility of adding yet another mode of locomotion in a novel mobile robot design. Just as the PackBot achieved a radical leap in mobility by hybridizing from one to two locomotion modes, this research leverages that same idea and hybridizes again from two to three locomotion modes for a second leap. Building off of a novel two dimensional tread mechanism, a tread/limb/serpentine hybrid robot is developed in this study to leverage the strengths of each of the locomotion modes, resulting in a synergistic combination that is greater than the sum of its parts.

1.3 Significance

It is estimated that in the first 48 hours of a rescue operation, a responder will get less than three hours of continuous sleep as they need to work at full force to set up the operation and begin work in the field (Burke, Murphy, Coovert, & Riddle, 2004). Unfortunately this leads to sleep deprivation during the most critical time for search and rescue of victims. Additionally, in a disaster response it will typically take ten workers ten hours to extract a single person trapped in a collapsed structure. So if a rescue worker finds themselves trapped during the course of the search, over 100 man hours are lost in an already time critical operation. Therefore, robots are greatly needed as a force multiplier in USAR response to reduce some of the burden and workload placed on the human rescue workers to make for a more efficient and effective response. For the rescue workers to be able to successfully use robots in these high stress situations and save time and lives, the supplied robots not only have to be capable of traversing through the complex terrain but they also need to be operable by a sleep deprived worker who may not have used the robot for several months. It is for that reason that this research focuses on hybrid robots as they have demonstrated an impressive leverage of mobility over complexity in the past, most notably with the PackBot.

1.4 Contributions

The principal contributions of this research are as follows:

- The development of a novel two-dimensional tread mechanism which uses a differential ring gear drive to propel the mechanism in two dimensions while keeping all motors and electronics stationary.
- The development of a tread/limb/serpentine hybrid robot, built from a hybridization of a multiplicity of two-dimensional tread mechanisms interspersed with two dimensional articulating joints that combines the mobility strengths of wheels, treads, limbs, and snakes.

1.5 Assumptions

The assumptions for this study include:

- The operating environment contains no open flames.
- The ambient temperature of the environment ranges from 0 to 85°C, as specified by the Xilinx Virtex 4 FPGA.
- Objects in the environment move sufficiently slow for the operator to react.
- The operator has normal dexterity in both hands.
- The operator never loses connectivity with the robot.

1.6 Limitations

The limitations for this study include:

- The circular cross section of the robot may result in some instability and undesired rolling over uneven surfaces.
- The non-treaded areas between modules of the robot can cause high centering and slow/hinder movement.
- The regularity of the robot may cause it to get stuck in obstacles with matching spatial frequency.

1.7 Delimitations

The delimitations for this study include:

- This study does not address water-proofing or dust-proofing for protection from the elements.

1.8 Summary

This introductory chapter has defined the problem addressed by this research to be a limitation on mobility of rescue robots in complex USAR environments and presents the proposed solution of a tread/limb/serpentine hybrid robot. Additionally the significance, assumptions, limitations, delimitations, definitions, and other background information for the research have been defined. The remainder of the thesis is structured as follows. Chapter 2 provides a review of the relevant literature, with a particular focus on hybridization in search and rescue robotics. Chapter 3 then provides an in depth description of the design for the two-dimensional tread mechanism and the tread/limb/serpentine hybrid robot as a whole, including the supporting electrical hardware and control software. Following the design, the methodology for testing and evaluation of the robot is presented. Chapter 4 presents the results of the testing procedures and finally analysis, conclusions, and future work for the developed robotic system are discussed in Chapter 5.

CHAPTER 2. REVIEW OF LITERATURE

As mentioned in the previous chapter, hybridization allows for great leaps in mobility, oftentimes with minimal additional complexity, and is therefore a focal point for USAR robotics research. Hybridization in this sense refers to a synergistic combination of two or more different classes of actuation modes in a single platform (Doroftei et al., 2014). Doing so extends the capabilities and task space of a robot by pooling together the strengths of the individual modes and results in a single platform that is greater than the sum of its parts. For instance, a traditional treaded mobile robot performs exceptionally well when traversing over relatively even ground at high speeds but it is next to impossible for this type of robot to overcome an obstacle nearing the height of its tread. Conversely, a limbed robot is far more capable of climbing over obstacles in its path, but at the cost of speed and far greater complexity in control and sensing. The most successful designs for traversing the highly rubbled and complex terrains characteristic of urban disaster sites have been those that incorporate some hybridization of the two into their design. In fact, two of the top three finishers at the 2015 DARPA Robotics Challenge used hybrid locomotion. Both CHIMP from CMU (Stentz et al., 2015) and the KAIST DRC-Hubo (Wang, Zheng, Jun, & Oh, 2014) used hybrid locomotion to enhance mobility and simplify control. Because this research focuses on hybridization of rescue robots to enhance mobility, this chapter presents a review of hybrid robots in the field of urban search and rescue.

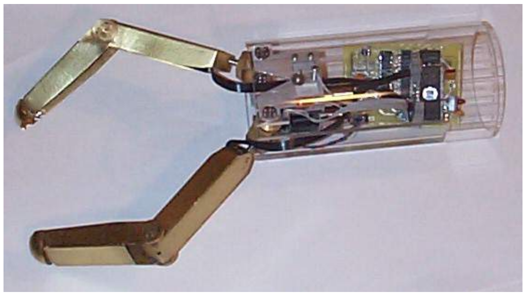
For hybrid designs that incorporate the use of both treads and limbs in a single platform, two subgroups have emerged based on which actuation mode is the dominant mode of locomotion and control. A hybrid design that uses treads as the dominant mode incorporates limbs in order to add finesse for fine locomotion such as in stair climbing and overcoming obstacles. Typically these tread/limb hybrid robots are large to accommodate locomotion over rubble and other obstacles. Conversely, a hybrid design that uses limbs as the dominant mode will add treads to provide bulk motive force to the platform to aid in locomotion. Typically these limb/tread hybrid robots are small to accommodate penetration into rubble.

2.1 Limb/Tread Hybrid Robots

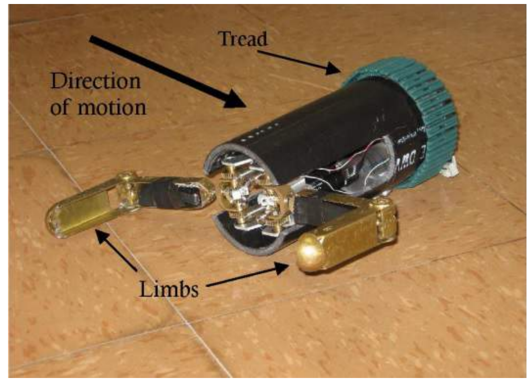
Previously, the Collaborative Robotics Lab has implemented a limb/tread hybrid robot based on the TerminatorBot ("CRAWLER") robot (Voyles & Larson, 2005), which was also developed in the same lab. The TerminatorBot is a small, crawling robot that uses a pair of three degree of freedom limbs to drag itself along the ground, similar to most cold-blooded animals. Due to the control complexity of the limbs, the TerminatorBot typically has slow, precise movements but is very effective for penetrating the narrow cavities of rubble and for core-bored search and rescue. To improve the "brute force" capabilities of the miniature crawling robot, it was hybridized with a transverse tread module called the Crabinator (Voyles & Godzdanker, 2008). With the Crabinator attached, the TerminatorBot continues to use its limbs as the dominant form of locomotion and control, hence we call it a limb/tread hybrid (as opposed to a tread/limb hybrid) to reflect that dominance. Figure 2.1 shows both the Terminatorbot robot itself and its hybridization with the Crabinator tread attachment.

2.2 Tread/Limb Hybrid Robots

As was introduced in the prior chapter, the most widely successful tread/limb hybrid robot is likely the commercially available iRobot PackBot, as shown in Figure 2.2, which was developed more than a decade ago (Yamauchi, 2004). Having been successfully used in military and civilian applications ranging from bomb disposal to search and rescue to surveillance of the 2014 FIFA World



(a) photo courtesy of Richard Voyles



(b) Copyright ©2007 IEEE

Figure 2.1: Terminatorbot without 2.1(a) and with 2.1(b) Crabinator attachment.

Cup, the PackBot epitomizes the class of tread/limb hybrid robots and the strength of hybridization. The PackBot combines a differentially driven treaded vehicle with a simple pair of active limbs, "flippers," that introduce gearing traction to allow the PackBot to lift itself over obstacles and up stairs, greatly enhancing its mobility. For years the Packbot has shown impressive performance in traversing through rough terrain, climbing stairs, and overcoming obstacles thanks to its hybrid limbs. It can also achieve high speeds of 5.8 mph over flat ground and surpass steep grades of 60 degrees thanks to its long differential tread base.

Quince (Nagatani, Yamasaki, Yoshida, Yoshida, & Koyanagi, 2008), also mentioned previously, is another tread/limb hybrid robot with a structural setup fairly similar to the PackBot, but it instead hybridizes the treaded base with two sets of active limbs instead of a single pair which can be seen in Figure 2.3. The main motivation for adding a second set of flippers is stability control. As the robot is susceptible to mission failures by rollover, it tries to minimize its chances of rolling over by incorporating four independently controlled flippers to maintain a desirable attitude of the treaded base. When operating on uneven terrain, Quince can actuate the left and right flippers separately to handle undesirable roll angles and it can actuate the front and back flippers to handle undesirable yaw angles.

Figure 2.2: iRobot PackBot 510 (photo courtesy of http://www.irobot.com)

Although the additional limbs provide a mechanism for stability control, they also increase the complexity of the system far more than the hybridization of the PackBot, thus diminishing the payoff.

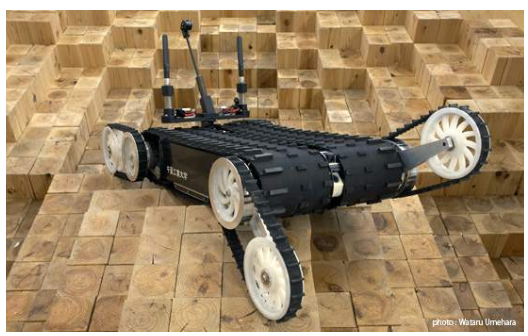


Figure 2.3: Quince Robot (photo courtesy of http://furo.org/)

Helios IX is configured somewhat similarly to the PackBot as well but with several deviations (Guarnieri et al., 2008). Helios IX has a differential tread base like the PackBot and Quince robots, but these treads themselves can be articulated about the main body, reminiscent of the flippers in the other two. The articulation of the main tracks enables the robot to maintain stable attitude of the base on uneven ground and to raise the base higher to allow its overhead camera to see over objects. As a second instance of hybridization, Helios IX incorporates a manipulator for interacting with the environment but which also has a dual use of aiding in vehicle mobility. The manipulator is useful as an active limb to push the main body of the robot up and over obstacles and also has a passive wheel mounted at the elbow so that the arm can be used as a caster wheel for the two main tracks. Another unique function of the manipulator is that it can be used to attach to a pivot point on a second Helios robot so they can cooperate to overcome particularly difficult terrain by working as an articulated skid steer vehicle (Guarnieri, Takao, Fukushima, & Hirose, 2007). The Helios robot is shown in Figure 2.4.

Figure 2.4: Helios IX robot. Copyright ©2008 IEEE

2.3 Serpentine Robots

Serpentine robots are slender, multi-segmented platforms which offer greater flexibility and mobility than traditional wheeled and treaded mobile robots (Maity & Mandal, 2009). The slender configuration makes serpentine robots ideal for the narrow openings common in USAR environments. These robots can be further divided into the subgroups of undulating serpentine robots and active skin serpentine robots. Undulating robots mimic the slithering, undulatory motion of biological snakes and rely on the motions of the joints between segments for propulsion. Active skin serpentine robots hybridize the serpentine structure with wheels, limbs, or treads to provide propulsion. As the platform defined in this research hybridizes treads, limbs, and serpentine locomotion, it falls into this category of active skin serpentine robots.

The pioneers of serpentine robotics were Hirose and Morishima, who developed KR-I, the first robot of its kind, in 1990 (Hirose & Morishima, 1990). The target application scenario of the platform was to carry out tasks in an atomic reactor with narrow passageways, which led to the implementation of an articulated body composed of multiple segments. An articulated body is of course far more slender and maneuverable in tight spaces than a traditional wheeled vehicle with comparable payload, but it also travels slowly on its own and requires specialized gaits, such as undulation, for mobility. To achieve the speeds necessary for operating in an atomic reactor, the designers hybridized the serpentine robot to ride each of the body segments on a crawler track for propulsion. This hybridization of serpentine and treaded locomotion modes combined the respective strengths of high maneuverability and high speed into a common platform to achieve previously unattainable mobility in a complex environment.

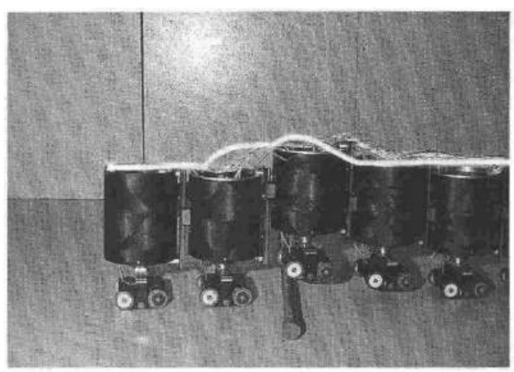


Figure 2.5: KR-I, the first serpentine robot. Copyright ©1990 Sage Publications.

Unlike the majority of serpentine robots developed these days, the KR-I robot incorporates a unique vertical slide between segments to raise a neighboring segment over obstacles and across voids rather than using an inflection joint for the pitch motion between segments. In this way, the individual modules can be positioned very close together to minimize dead area and the risk of high centering while the process for lifting the robot over obstacles is made very simple. From a high level, the overall design of the KR-I robot is a series of treaded modules connected via a swivel joint for yaw variation to steer and a linear slide to lift modules over obstacles which is shown in Figure 2.5. Testing of the robot platform showed that it has a max speed on level ground of 40 cm/s and can also cross gaps up to half the total body length as well as climb stairs which are small in comparison to the length of the treads. Following the example set forth by Hirose and Morishima, many researchers in the coming years expanded on this pioneering research to contribute to the serpentine robot effort. Many elements in recent robot platforms can be traced back to this initial design.

Hirose continued on after development of the KR-I serpentine robot to create many more serpentine platforms with varying capabilities and novel design elements but they all share a resemblance to his earliest work. From the year 2000 to 2012, Hirose and his research group developed nine versions of their successful Souryu serpentine robot [(Takayama & Hirose, 2000); (Arai, Tanaka, Hirose, Kuwahara, & Tsukui, 2008); (Suzuki, Nakano, Endo, & Hirose, 2012)]. Each robot has its own variation of design improvements and capabilities, but this review will focus on the fourth and fifth generations, Souryu-IV and Souryu-V, as these two have the most relevance to the research proposed in this thesis. Depictions of these two robots are displayed in Figure 2.6.

Souryu-IV and V were developed to address several issues experienced during operational testing with the third generation robot, namely controllability, terrain traversability, and durability (Arai et al., 2008). The fourth and fifth versions are very similar to each other but employ a few different design solutions to solve the same problems. Overall both platforms consist of three active propulsion tread modules serially connected by multi degree of freedom joints, similar to the design concept for the tread/limb/serpentine hybrid robot developed in this thesis. The difference in the tread modules between the two Souryu robots comes from the

(a) Souryu-IV. (photo reproduced from http://www.hibot.co.jp)

(b) Souryu-V. Copyright ©2012 IEEE

Figure 2.6: Two of the nine Souryu robots developed by Hirose.

tread configuration. Souryu-IV uses two independently actuated tracks at the sides of the module to allow for turning in place and better controllability through differential control of the tracks. Souryu-V on the other hand is more focused on minimizing the risk of high centering of the vehicle, which would inhibit mobility, and so its body modules are wrapped in a single wide tread for greater tread coverage. The second major difference in these two models lies in their joint mechanisms. Souryu-IV uses two linear rod screw axes, connected to each body segment by a universal joint, that extend and contract to push the joint to the desired angle. These joints also incorporate a novel "blade-spring" mechanism that both prevents debris from entering the joint and also adds some shock absorbency to the robot due to its elasticity. Souryu-V traded in the rigid rod based joint for a novel elastic rod joint in which four urethane rubber tubes are slid along rigid screw axes. By pushing the rubber tubes further off of the rigid screws, the tubes become more flexible and are able to bend about the more contracted tubes. The four elastic tubes allow for the necessary pitch and yaw motion control of the joint while also adding a third degree of freedom to extend or collapse the distance between two segments by extending or retracting all four rods, respectively. This allows the operator to shorten the joint and minimize dead area to prevent high centering or to extend the joint for greater reach.

Two common issues arise among this type of segmented robot and treaded vehicles in general. The first being a vulnerability to rollovers. Most segmented and treaded robots are designed to only operate with their body right side up and experience an enormous decline in mobility when rolled onto their side or upside down. If they do experience a rollover, which is common on terrains with steep grades and high variation, most either need to initiate a series of precise movements to correct itself or require human intervention before continuing the mission. Either way, mobility suffers. The second potentially mission fatal issue is the configuration of the propulsive treads. Most treaded vehicles like the Souryu robots wrap treads continuously around their entire body so that the treads are pulling in opposing directions on the top and the bottom of the robot. This becomes a problem in particularly tight passageways where both the bottom and top sides of the robot may contact the environment simultaneously. In this case the tread on the bottom works to move the robot forward, but the tread on the top pushes the robot back, greatly hindering mobility.

The OmniTread OT-4 and its predecessor OT-8, developed at the University of Michigan, solve these two issues by incorporating a square body cross section with application of treads to all four sides (Borenstein, Hansen, & Borrell, 2007). Many treaded and segmented robots attempt to limit potential rollovers by using a wide rectangular base, but rather than working to avoid rollovers, the OmniTread expects them and instead maintains its mobility in spite of them. To make the OmniTread compliant to the inevitable rollovers in the field and to ensure that mobility is not lost by falling on the side, the robot has a symmetric square cross section with all four sides of the body covered in active treads. This way, no matter the orientation of the robot, it will be able to continue locomoting. In addition to seven of these tread covered body segments, The OT-4 model also incorporates an active flipper at either end of the serpentine configuration to extend its reach, such as when crossing a large gap. Interestingly, whereas most serpentine robots drive each segment individually with its own motor to maintain a reconfigurable, modular design, the OT-4 uses a single drive motor to actuate all seven segments as well as the flipper tracks. The motive force from the single drive motor is transmitted to all of the other segments through a "drive shaft spine" that runs along the length of the robot. The single drive motor design is believed to be more efficient in terms of power and weight than dedicating a drive motor to each individual module. To increase power efficiency further, the designers cleverly use custom micro clutches in all of the robot body segments to disengage any tracks that are not in direct contact with a driving surface and therefore would contribute only friction and no motive force.

(a) OmniTread-OT8 (Borenstein et al., 2007). Copyright ©2007 Wiley Periodicals.

(b) OmniTread-OT4 (Borenstein et al., 2007). Copyright ©2007 Wiley Periodicals.

Figure 2.7: The OmniTread pair of robots from University of Michigan.

To hybridize the OmniTread robots, the tread modules are connected serially by active universal joints that are actuated by novel pneumatic bellows. Like most active joints found in serpentine robots, these bellows control the angular position of the joint, but unlike most active joints these can control the compliance of the joint as well. This allows the robot to conform to the complex shape of the environment for greater tread contact and traction while also giving the robot the added benefit of shock absorbency.

The majority of active skin serpentine robots, as evidenced previously, use discrete wheels or treads distributed along the body of the robot to provide propulsive forces. One robot developed by Howie Choset's research group at Carnegie Mellon University, on the other hand, uses a toroidal skin drive to propel the robot forward (McKenna et al., 2008). This toroidal skin drive wraps the entire circular cross section of the robot with a single flexible toroidal skin which slides on the surface of the robot from head to tail and then recirculates internally to close the loop. This serpentine robot can be seen in Figure 2.8. This design is quite advantageous as the single all enveloping tread gives the robot essentially 100 percent tread coverage so that the entire surface of the robot aids in propulsion. Another advantage seen in this design is that potential environmental hazards that may cause high centering for other robots, such as a protruding rock, actually provide greater traction by pressing into the skin, rather than hinder mobility. The internal shape of the skin drive robot is controlled by nine active universal joints for steering and lifting the robot over obstacles. The toroidal skin drive serpentine robot performs quite well for its miniature size, crossing gaps nearly 50 percent of its body length, climbing stairs of standard dimension, and overcoming a step height 25 percent of its body length.

Although not a serpentine or a hybrid robot, the Omni-Crawler (shown in Figure 2.9) developed by Tadakuma et al. is a treaded robot that uses a tread mechanism that exhibits the same motion capabilities as the two dimensional tread mechanism presented in this thesis (Tadakuma, Tadakuma, & Berengeres, 2007). The tread mechanism on the Omni-Crawler is a sausage-like tread that advances in two halves on either side of the sausage. There is a small split between the two halves of the tread to allow a central shaft to penetrate the sausage-like tread along the body axis which the entire tread can rotate about. To achieve lateral motion in the tread mechanism, a motor mounted to the main chassis of the robot rotates this central axis, thereby rotating the tread as well. Just like our two dimensional tread mechanism, these two degrees of freedom contained in one actuation mechanism allows the crawler to translate both longitudinally and laterally on a plane. However, because the motor that controls longitudinal motion inside the

Figure 2.8: Toroidal skin serpentine robot from Carnegie Mellon University. Copyright ©2008 IEEE

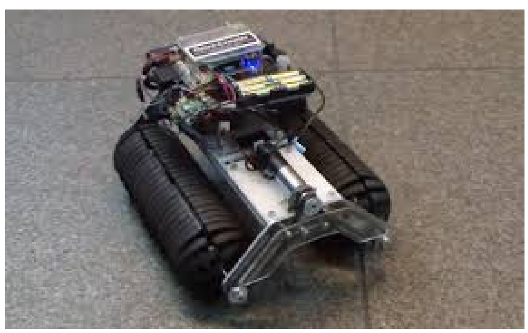


Figure 2.9: Omnicrawler robot. Copyright ©2008 IEEE

Omni-Crawler tread must rotate with the lateral motion of the tread, it requires a slip ring arrangement for wiring. The two dimensional tread mechanism in our research, on the other hand, manages to keep all motors stationary, eliminating that need.

The Omni-Crawler as it stands is not a hybrid as it doesn't incorporate multiple actuation mechanisms; however the developers have expressed the potential for adding active limbs, which incorporate the same two degree of freedom tread mechanism, in the same way the PackBot incorporates its flippers. This hybridization of the Omni-Crawler would allow it to overcome much larger obstacles and gaps, broadening its operating environment drastically.

2.4 Shared Autonomy and User Experience in USAR Robotics

Although hybridization has proven effective in leveraging mobility over complexity, since it is an addition of actuation modes, not a replacement, there is an inherent rise in complexity for these systems. The trick is therefore to mask the added complexity from the operator. Generally, hybridization brings with it more degrees of freedom, more sensors, and more control modes. With all of this, complexity of interfacing with the robot typically increases and thus, shared autonomy and user experience become important for success in a search and rescue situation.

Because of the unknown and complex environments characteristic of urban disasters, fully autonomous robot systems are difficult to achieve, and so a human operator needs to remain in the loop. In order to minimize the workload and maximize efficiency for rescue workers in disaster situations, efforts continue in the research community to improve the operability of rescue robots through shared autonomy and an improved user experience. In this section, some of the methods for improving the human-robot interface in rescue robotics are surveyed.

Serpentine robots can provide high flexibility and mobility thanks to their many degrees of freedom, but they can also require multiple operators to control all of the degrees of freedom. In the case of the Omnitread OT-8 robot mentioned previously, two operators are needed and three are needed for the OT-4. To make the OT-4 operable by a single person, the designers developed the Joysnake haptic controller (Baker & Borenstein, 2006). The Joysnake is a small scale replica of the OT-4 robot that the user manually manipulates to produce the same desired shape in the actual robot. Additional sliders on each of the replica segments control the forward speed of the robot and the stiffness in each of the six joints. By collapsing all of the control variables for the robot into a single intuitive controller, the operation of the OT-4 is reduced from three to a single operator. This makes it much easier to multiply the human effort when a single human is needed rather than three.

Several methods have been developed as well to coordinate the movements of the many segments of serpentine robots to reduce the workload on the operator. Follow-the-leader and n-trailer are two such methods (Granosik, 2014). In the follow-the-leader method, the operator controls only the front, or leader, segment of the robot which generally reduces the control burden to just three degrees of freedom and is far more manageable. All of the following segments then repeat the movement of the leader in the same exact spatial point. The n-trailer method imitates an actual truck hauling n trailers behind it. Unlike an actual truck though, the segments in a serpentine robot are active not passive. However this method still defines the control algorithm for all of the active joints and segments of the robot as if it were being pulled by a truck. Both of these are effective coordination methods, but they do rely on the assumption that speed relative to the ground is known, so there must either be no slippage or it must be able to measure slippage. Accounting for the slippage assumption, these methods generally work best on relatively flat terrain. Also, because these methods assume that all segments will pass through the same spatial point, they do not account for transverse motion, since with transverse motion this assumption is not necessarily true.

Another effective way of improving the user experience in robot operation is assisted remote operation (Granosik, 2014). In this case, the overall direction of travel and some high level path planning is controlled by a human operator while the robot takes direct automatic control over its individual degrees of freedom to produce the motion desired by the operator. Typically the operator will control the head of the robot and the movement of the rest of the body is automated according to the conditions of the terrain. The hybrid robot developed in this thesis incorporates assisted remote operation methods to map the operator's high level command inputs to the many degrees of freedom.

Maruyama et al. developed a serpentine robot which incorporates embodied intelligence in the physical design to simplify operation (Maruyama & Ito, 2010). Essentially, the authors designed the mechanical body of the robot such that it is able to adapt itself to the environment rather than using complex computations to directly command the desired body composition. In this way the operator only needs to control the macro-behavior of the robot (direction and speed) and not the micro-behavior (joint movements). This is a good example of masking some of the complexity of the system from the operator through clever design rather than software techniques. Our two dimensional tread mechanism similarly masks complexity from the operator by embedding the transverse degree of freedom in the mechanism itself.

Aside from these methods for simplifying the overall control of a robot to improve user experience, several algorithms have been developed to allow certain tasks to be carried out autonomously by the robot, completely independent from the operator. Mourikis, Trawny, Roumeliotis, Helmick, and Matthies (2007) have implemented an algorithm for autonomous stair climbing using only a 2D camera and a three axis gyroscope. The gyroscope is used to determine the orientation of the robot while the edges of the stairs are extracted from the camera images. Using only this information, the position of the robot relative to the center of the staircase is estimated and used in a controller to autonomously guide the robot upstairs.

The active limbs hybridizing the Quince tracked robot mentioned previously enable greater mobility for the robot but they also add more degrees of freedom for the operator to control. To mask this added complexity from the operator, the designers developed a method for autonomous control of the limbs to maintain stability of the robot over uneven terrain and to overcome obstacles (Okada et al., 2011). This method uses LIDAR sensors to model the terrain around the robot and uses this model to calculate the optimal limb positions to pass over obstacles and maintain stability. Using this method, the operator can simply direct the robot in the desired direction while the robot autonomously controls its body composition, thus enhancing the user experience through shared autonomy.

2.5 Summary

Several robotic platforms have been introduced in this chapter as a review of the literature relevant to hybrid and serpentine robots. All of the platforms discussed have exhibited impressive performance in the search and rescue domain, showing good mobility over rough terrain. However, with the exception of the Omni-Crawler, none of the ground robots are particularly effective for transverse motion. And although the Omni-Crawler is omnidirectional its mobility is somewhat limited by a lack of hybridization, which could improve its capability to navigate deconstructed environments. Therefore, there is still potential for research to enhance the mobility of rescue robots in complex disaster environments. The following chapter will provide a detailed design of the developed robotic platform and outline the methodology for testing its efficacy as a tool in USAR.

CHAPTER 3. RESEARCH METHODOLOGY

The goal of this research was to develop a mobile robot for use as an effective tool in USAR operations. In order to be an effective tool, this robot needs to leverage mobility over complexity so that a human rescue worker can easily operate it in the complex and stressful USAR environments. The developed design capitalizes on the strength of hybridization for enabling far greater mobility while keeping added complexity proportionally small. This is accomplished by serially linking several novel two-dimensional tread modules with articulating joint limbs to compose a tread/limb/serpentine hybrid robot called the MOTHERSHIP (Modular Omnidirectional Terrain Handler for Emergency Response, Serpentine and Holonomic for Instantaneous Propulsion). The operational complexity of the high degree of freedom MOTHERSHIP is reduced through assisted remote operation methods for a shared autonomy control structure. The efficacy of the MOTHERSHIP as a USAR tool was evaluated through functionality tests common for search and rescue robots to determine its level of mobility in harsh, disaster environments.

3.1 MOTHERSHIP Design

The MOTHERSHIP hybrid, mobile robot shown in Figure 3.1 is similar in structure to the OmniTread and Souryu platforms mentioned in the related work which both have relatively sophisticated tread mechanisms linked serially with relatively simple limb mechanisms. One of the key differences with this design is the circular cross section which allows holonomic locomotion, meaning that it can move instantly in any direction without changing its pose. The MOTHERSHIP is shown configured with three 2-D tread modules, but it is expandable to a four, five, or n link hybrid robot. Adding more links is expected to allow the MOTHERSHIP to cross wider gaps and overcome larger obstacles, but also increases power and computation requirements of the system. Because the MOTHERSHIP is a resource constrained platform, the initial configuration consists of the minimum number of links expected to enable the desired motion capabilities and can be extended from there in the future.

Figure 3.1: Three link configuration of the MOTHERSHIP hybrid robot.

3.1.1 2-D Tread Mechanism

The 2-D tread mechanism is a cylindrical arrangement of ten discrete treads that incorporates a dual ring gear differential drive to both actuate the treads to propel the mechanism along the body axis and rotate the entire tread assembly about the core for transverse motion. The initial design concept for the 2-D tread mechanism was inspired by the Crabinator attachment mentioned in the literature review. This hybridization of the one DOF Crabinator attachment with the

TerminatorBot provided transverse brute force, but actually impeded motion in the longitudinal mode due to increased frictional forces from the tread; hence the need for the elaborate tread grouser design detailed in (Voyles & Godzdanker, 2008). Unlike the Crabinator though, the 2-D tread mechanism detailed here can provide motive forces in the longitudinal direction as well as the transverse. The 2-D tread is advantageous in part because it enables transverse motion with no added complexity for the operator. Although the mechanism design itself increased in complexity from the original Crabinator attachment, the complexity is not perceived by the operator, thereby making planar motion control much easier. The 2-D tread module here is scaled up from the miniature 75mm diameter Terminatorbot attachment to roughly the diameter of a basketball. This enlarged version is targeted towards tread/limb/serpentine hybridization wherein the 2-D tread is the dominant form of actuation, as opposed to the previous limb/tread hybridization of the TerminatorBot. This alternative hybridization enables a robot, assembled from a serial link of tread modules with articulating joints as limbs, to overcome larger obstacles in deconstructed environments.

As stated in the literature review, a common issue among treaded robots is their configuration of the treads. Generally with rectangular robots, the treads pass continuously around the entire surface of the vehicle such that the tread and propulsive forces move in opposing directions on the top and bottom faces. This can be problematic in the event that the robot contacts the environment on both its top and bottom, such as in a narrow crevice. Our 2-D tread solves this issue in the same manner as the OmniTread serpentine robot, by circulating multiple treads inside the robot rather than wrapping a single tread around the body surface. This ensures that all propulsive forces in the mechanism move cooperatively in the same direction so there are no conflicting forces as demonstrated in Figure 3.2.

The second issue mentioned in the literature review was a vulnerability to rollovers. Our 2-D tread mechanism handles this issue similarly to the OmniTread as well, by incorporating a symmetric cross section and applying treads to the entire

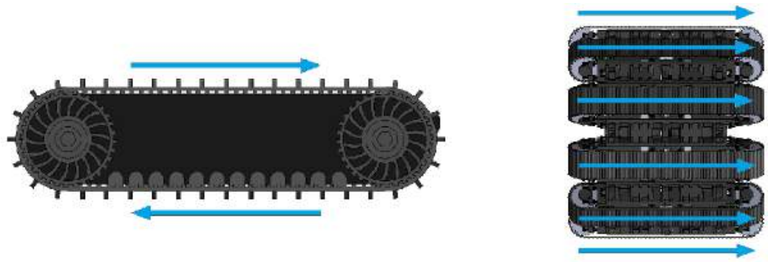


Figure 3.2: Demonstration of tread configuration for uniform propulsion.

outer surface. In our case though, the symmetric cross section is circular which affords us smooth and efficient transverse motion, like a wheel. Although the circular cross section permits smooth transverse motion, it also complicates the tread configuration. Ideally, the mechanism would have 100% tread coverage so that there is always a gripping surface in contact with the environment, but because the treads in our mechanism circulate internally, in order to have a single continuous tread around the entire circumference, the tread would have to be smaller on the inside than the outside. The toroidal skin serpentine robot mentioned in the literature review presents a sophisticated method to incorporate a single continuous tread for nearly 100% tread coverage, but the 2-D tread mechanism instead uses its advanced motion capabilities in place of maximal tread coverage. Because the 2-D tread places ten discrete, linear treads around the circumference of a circle, there are also ten discrete bare areas between the treads accounting for roughly 50% absolute tread coverage. However, it is not enough to only consider tread coverage as treads are not the only mode of locomotion in the mechanism. Instead we consider high centering rejection to describe the 2-D tread mechanism.

High centering in a mobile robot can occur when the robot falls into equilibrium on a surface patch incapable of any non zero body referenced velocity. We define such a patch as having zero degree high centering rejection. In contrast, a patch of one degree high centering rejection can resist high centering in one dimension and two degrees can resist high centering in two dimensions. As an example, high centering often occurs on a large rock or other obstacle that comes to somewhat of a vertex for the vehicle to get propped up on. Only one degree high centering rejection is needed to overcome this pyramid like geometry as moving in any direction will cause the vehicle to fall off of the vertex. However, high centering can also occur on a roof like structure where two planes come together to make a ridge. High centering can be avoided with one degree rejection as long as that degree is not in line with the ridge. Imagine a traditional treaded vehicle that comes to equilibrium on the ridge of a roof. If the only tread in contact with the surface is parallel to the ridge, the vehicle can only move along the obstacle rather than overcome the high centering. In this case, two degree high centering rejection would be desired, such as a tread mechanism capable of two degrees of motion. Because our 2-D tread mechanism can rotate the entire tread assembly transversely about its core, the entire surface has at least one degree high centering rejection and so we say the one degree high centering rejection ratio (HCRR) of the mechanism is 100%. The roughly 50% tread coverage of the mechanism then provides a two degree HCRR of 50% for the mechanism. Therefore, although the 2-D tread has only about 50% tread coverage, the entire mechanism can resist high centering in at least one dimension.

Expanding to the entire MOTHERSHIP, we calculated the HCRR for each degree of high centering rejection with the body frame centered on the center tread module. Because the MOTHERSHIP has so many degrees of freedom, there are few places on the surface that are incapable of a non zero body referenced velocity and so the zero degree HCRR is quite small at 9.3%. This means that 90.7% of the body of the MOTHERSHIP has at least one degree HCRR and can resist high centering. With the 2-D treads and two DOF articulating limbs, a majority of the surface, 80.4%, is actually capable of resisting high centering in two degrees. To compare this result, we also approximated the HCRR for the PackBot using the standard model without a manipulator and the body frame centered at the center of the chassis. The majority of the PackBot is not covered in treads which allows for plenty of room for additional components, sensors, and other payloads but it also means a majority of the surface has zero degree high centering rejection. According to our definition, the PackBot has a 55% zero degree HCRR. This means that the treads and the active limbs provide a one degree HCRR of 45%. There are also treaded areas on the limbs that account for a 9% two degree HCRR for the PackBot. We expect that the high HCRR for the MOTHERSHIP will greatly reduce our chances of high centering in the field.

3.1.1.1. Detailed Design

From a high level, the 2-D tread mechanism consists of a series of ten discrete treads spaced evenly around the circumference of a hollow cylinder that rides on a set of idler gears interposed between a pair of ring gears. These ring gears transfer torque from two drive motors to the tread pulleys on either end of the treads. Rather than driving each of the ten treads individually with its own motor and using an additional motor to realize the transverse motion, the 2-D tread mechanism incorporates a novel dual ring gear differential drive system to drive all ten treads in unison and to provide transverse motion from only two stationary motors. With this drive system, the mechanism realizes the desired two degrees of freedom with the minimum possible number of motors. An illustration of this drive system is presented in Figure 3.3.

Referring to the same figure; in the motor core (1), torque is transmitted from the motor drive gear (2) to the inner ring gear (4) which is supported on the core by two inner pinion gears (3). Torque is then transmitted from the inner ring gear to a set of intermediate idler gears (5) mounted to the tread assembly. Within the tread assembly, torque is transmitted from the intermediate idler gears to the outer ring gear (6) that passes through all the treads and then to the bevel gears (7) mounted in each of the ten treads. The torque is transmitted 90 degrees to the tread pulleys (8) by a 3D belt configuration, which in turn drives the treads (9).

The entire gear train has an effective gear ratio of 1.49 from motor to tread. This gear arrangement is reflected symmetrically on both ends of the tread module resulting in two differentially driven gear sets which gives the module its two degrees of freedom. The motors used to drive the tread mechanism are Maxon DCX32L 48V motors with a GPX32A 28:1 planetary gearhead. This motor was selected under the criteria that the treads be able to reach a top speed of 1 m/s and that the treads be able to propel the tread mechanism up a 35° incline at 0.3 m/s to give the tread mechanism similar performance to the PackBot.

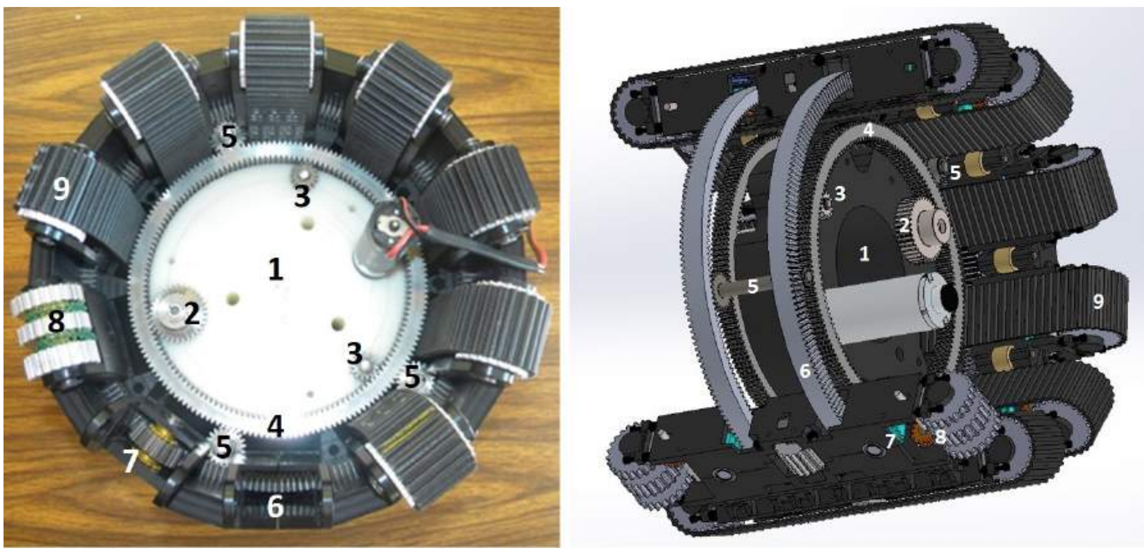


Figure 3.3: Closeup of the 2-D tread module, highlighting the gear arrangement.

A primary goal of this design was to eliminate moving motors. In (Tadakuma et al., 2008), the motor mounted inside the tread must roll with the transverse motion of the crawler, requiring a slip ring arrangement for wiring. To avoid slip rings in this mechanism, the outer tread assembly is mechanically isolated from the stationary motor core by a second pair of ring gears inside the outer pair. This inner pair of ring gears allows the treads to rotate around the stationary motor core as the ring gears rotate, keeping the motors fixed in the body frame of the mechanism.

The tread rollers at each end of the mechanism are driven in opposition such that if both of the ring gears are driven in the same direction, the rollers want to pull the tread against itself so they lock longitudinally. Instead of actuating the treads, the entire tread assembly then rotates transversely about the stationary motor core, as illustrated in the left of Figure 3.4. Conversely, if the ring gears are driven in opposite directions, the tread assembly does not orbit around the core, but instead the tread rollers pull the tread cooperatively to actuate the treads longitudinally, as illustrated in the right of Figure 3.4. Arbitrary combinations of longitudinal and transverse motion of the mechanism then result from arbitrary superposition of the differential ring gears.

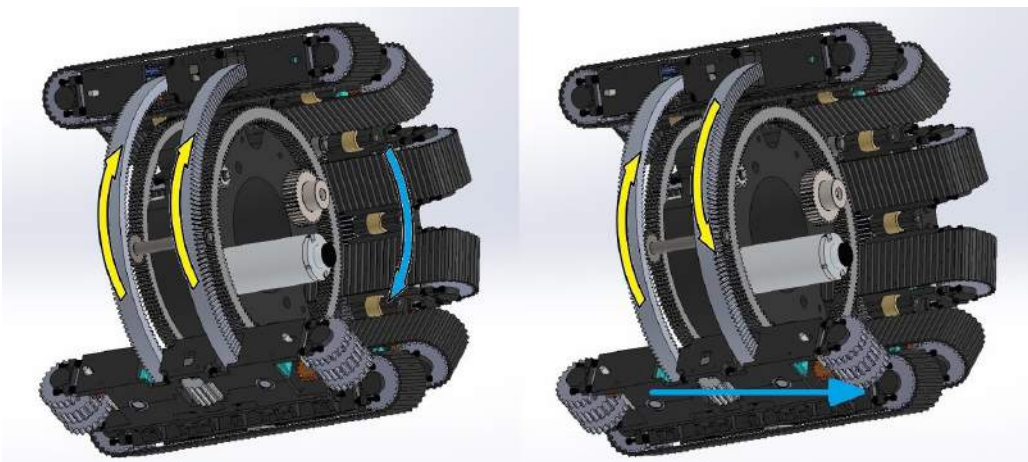


Figure 3.4: Illustration of (left) transverse motion due to like ring gear velocities and (right) longitudinal motion due to opposing ring gear velocities.

Because the motion of the tread mechanism is dependent on the differentially driven ring gears, the motors are coupled such that the longitudinal body velocity of the mechanism is related to the average of the motor velocities and the transverse body velocity is related to the relative motion between the two motor velocities. If we define the frame of the 2-D tread mechanism according to Figure 3.5 with x pointed along the longitudinal axis and y pointed along the transverse axis, the following equations of body motion result.

$$V_x = \frac{\omega_F + \omega_B}{2} \tag{3.1}$$

$$V_y = \frac{\omega_F - \omega_B}{2} \tag{3.2}$$

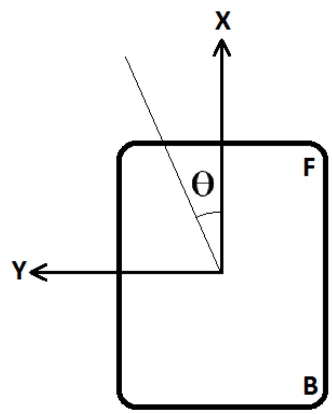


Figure 3.5: Frame definition for the 2-D tread mechanism. The x axis is directed longitudinally, the y axis is directed transversely, F refers to the motor driving the front ring gear set, and B refers to the motor driving the back ring gear set.

Inversely, the motor velocities can be determined from the body velocities by,

$$\omega_F = V_x + V_y \tag{3.3}$$

$$\omega_B = V_x - V_y \tag{3.4}$$

By considering the motor and body velocities as a percentage of top speed, we can say ω_F, ω_B, V_x, and V_y range from -100 to +100. With this distinction, V_x and V_y are constrained by equations 3.5 and 3.6 as the motors cannot exceed their own maximum velocity. Based on this, Figure 3.6 shows the absolute bounds of the two dimensional velocity of the tread mechanism.

$$-100 \leq V_x + V_y \leq 100 \tag{3.5}$$

$$-100 \leq V_x - V_y \leq 100 \tag{3.6}$$

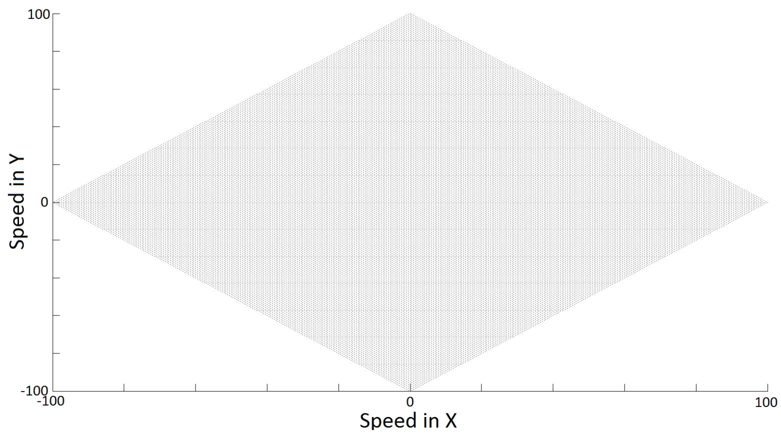


Figure 3.6: Two dimensional velocity bounds of the 2-D tread mechanism.

This data can be represented as a function of the angle θ between the velocity vector and the x axis of the 2-D tread body as in Figure 3.7. From this graph it is obvious that the maximum attainable velocity for the 2-D treads occurs along the body axes. The maximum velocity along a diagonal of the mechanism can be reduced to a minimum of 70.7% of the top axial speed.

Taking a detailed look at the tread assembly, we can see it is comprised of ten individual tread carrier units positioned alternately with ten wedge units. Figure 3.9 shows a detailed view of a single tread carrier with the tread removed. At the midsection of the tread carrier is a spring loaded tread roller (1), designed to keep the tread taut and to also provide some shock absorption to the sides of the mechanism. There are also two bevel gear shaft assemblies (2) which convert torque from the outer ring gears and transfer it to a 3D belt at each end. The 3D belt arrangement (3) rotates the torque in the bevel gear shaft 90 degrees to the tread pulley shaft (4) at the end of the tread carrier. Unlike a common twisted belt design, like that of Figure 3.8(a), the 3D belt configuration rotates the torque while keeping a zero angle of attack between the belt and the pulleys, thereby minimizing the risk

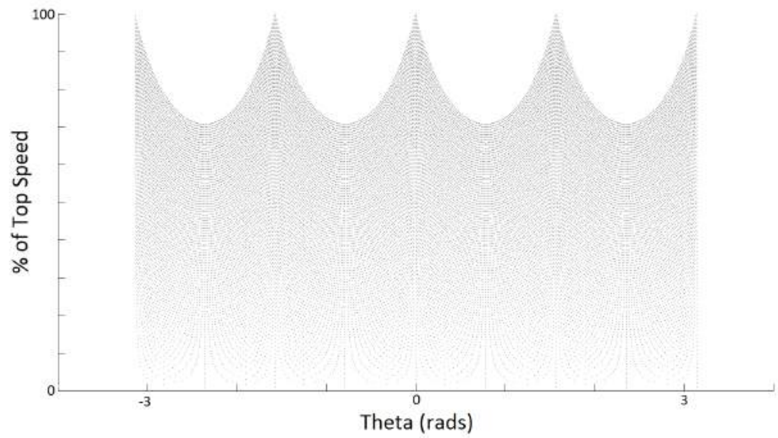
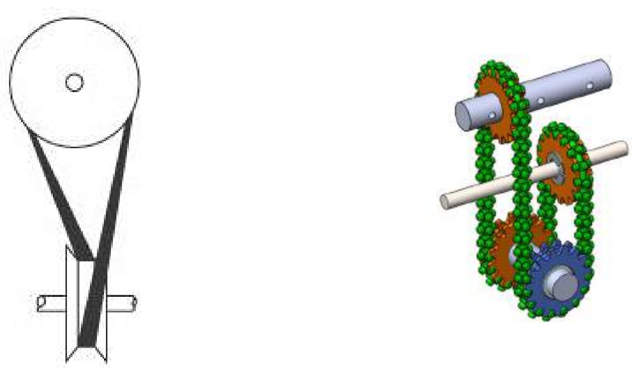


Figure 3.7: Velocity bounds as a percentage of top ground speed as a function of the angle θ.

of the belt jumping off the pulley. Because the 3D belt passes around the bevel gear shaft twice to maintain zero angle of attack, one of the 3D pulleys is fixed to the shaft while the other floats on a bearing as the two loops pull in opposite directions.



(a) Twisted flat belt.

(b) 3D belt arrangement with zero angle of attack.

Figure 3.8: Comparison of a twisted flat belt with high angle of attack and the 3D belt configuration with zero angle of attack.

To keep the 3D belt properly tensioned, a 3D belt tensioner shaft (5) is incorporated which has a free spinning 3D pulley and 3.75mm of travel between the bevel gear shaft and the tread pulley shaft. This tensioner shaft engages with a tensioning screw mechanism mounted on the neighboring wedge units. Similarly, to keep the tread properly tensioned, the tread pulley shafts on either end of the tread carrier are mounted on sets of pillow blocks (6) that can be translated out from center by a separate screw tensioning mechanism. Also to keep the tread properly centered on the pulleys, a pair of tread guides (7) are mounted near the center of the tread carrier.

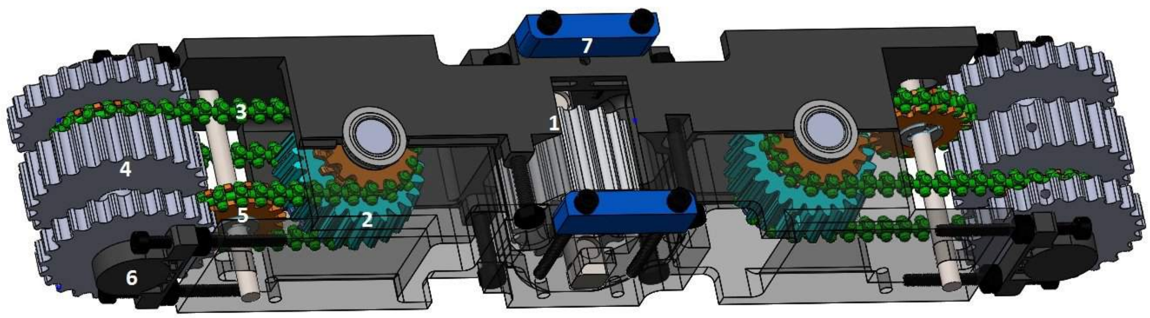


Figure 3.9: Semi-transparent view of a single tread carrier unit highlighting: (1) spring loaded tread roller, (2) bevel gear shaft assembly, (3) 3D belt configuration, (4) tread pulley shaft, (5) 3D belt tensioner shaft, (6) pillow blocks, (7) tread guides.

To give the 2-D tread mechanism its circular cross section and enable smooth transverse motion, the tread carriers are joined together by wedge units shown in Figure 3.10. Aside from making the tread circular, the wedge unit provides other functions to support the mechanism. At each end of the wedge unit, a rubber guide roller (1) provides additional points of contact between the core and the tread assembly to stabilize the treads on the core. By incorporating these additional points of contact, the two sets of ring gears can be positioned close to each other near the center of the tread which allows for more empty space in the core for additional payload. Also at the ends of the wedge unit are sets of 3D shaft pillow blocks (2), similar to the pillow blocks of the tread carrier, which engage with the neighboring tread carriers to tension the 3D belts.

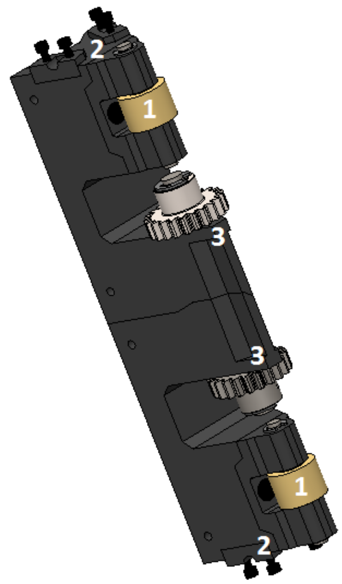
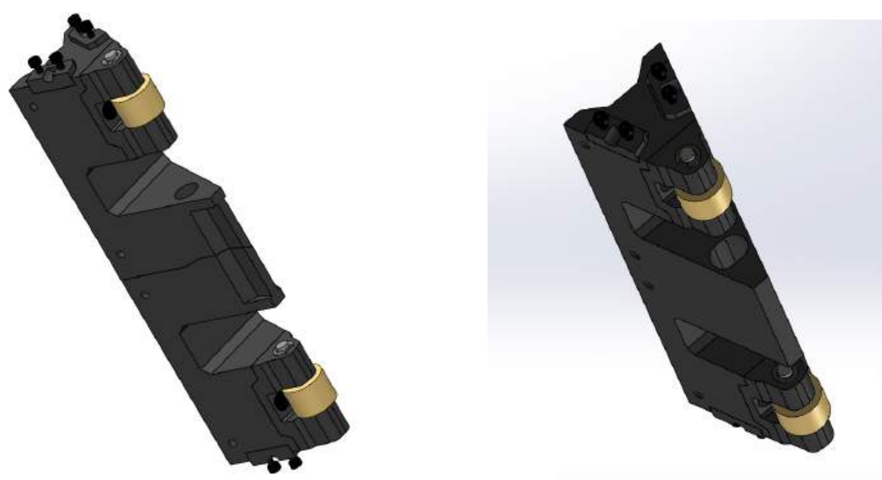


Figure 3.10: A single wedge unit highlighting: (1) rubber guide rollers, (2) 3D shaft pillow blocks, (3) intermediate idler gear shaft.

The intermediate idler gears of the drive system are mounted on the wedge units (3) and act as the junction between the motor core and the tread assembly; they both transfer mechanical power between the two and are the only points of contact besides the passive guide rollers. For a rigid connection between the core and tread assembly at least three intermediate idler gears are needed, distributed uniformly around the tread assembly. Therefore, seven wedge units are passive without an idler gear and only three house an idler gear. Since the intermediate idler gears are interposed between the inner and outer ring gears, they have to mesh with both ring gears simultaneously. Due to the discreteness of mechanical gear teeth, there are discrete points around the circumference of the ring gears that the idlers can properly mesh, it is not a continuum. There are also only ten discrete points on the tread assembly where the wedge units are that the idler gears can be mounted, which do not match the discreteness of the ring gears. Also, because the gears experience some thermal expansion during operation and because of manufacturing tolerances, additional degrees of freedom are needed in the gear train to ensure proper meshing of the idler gears.

Of course, one of the three idlers can always fall into proper mesh by rotating it into position, but the remaining two need some freedom of movement to fall into mesh. For that reason, two of the three idler gear shafts are mounted in an arc slot on the wedge unit with an arc length equal to one full pitch of the ring gears. This arc slot provides enough freedom for all three idler gears to properly mesh in the gear train. The third idler gear shaft is then mounted in a straight, through hole in the wedge unit keeping its location rigid. This static idler gear grounds the two floating ones and holds them rigid once assembled. Figure 3.11 contrasts the two wedge unit configurations for a static and a floating idler gear.



(a) Static idler wedge unit without idler gear.

(b) Floating idler wedge unit without idler gear.

Figure 3.11: Wedge unit configurations used in the tread mechanism.

As a complete mechanism, the 2-D tread is highly effective for planar translations, but the true potential of the mechanism is realized when combinations and hybridizations are built from it. Because the mechanism is modular, it can be easily integrated into a larger system. A particularly simple, yet highly effective configuration of the tread mechanism is a differential drive robot similar in scale and functionality to the UMN Mega Scout (Kratochvil et al., 2003). By joining two tread mechanisms with a rigid center link, as in Figure 3.12, the result is a differential drive robot that not only can translate forward and spin in place, but due to the 2-D treads it can also translate sideways enabling full holonomic motion from a simple combination of tread mechanisms.

Figure 3.12: Differential drive configuration of the 2-D tread mechanism.

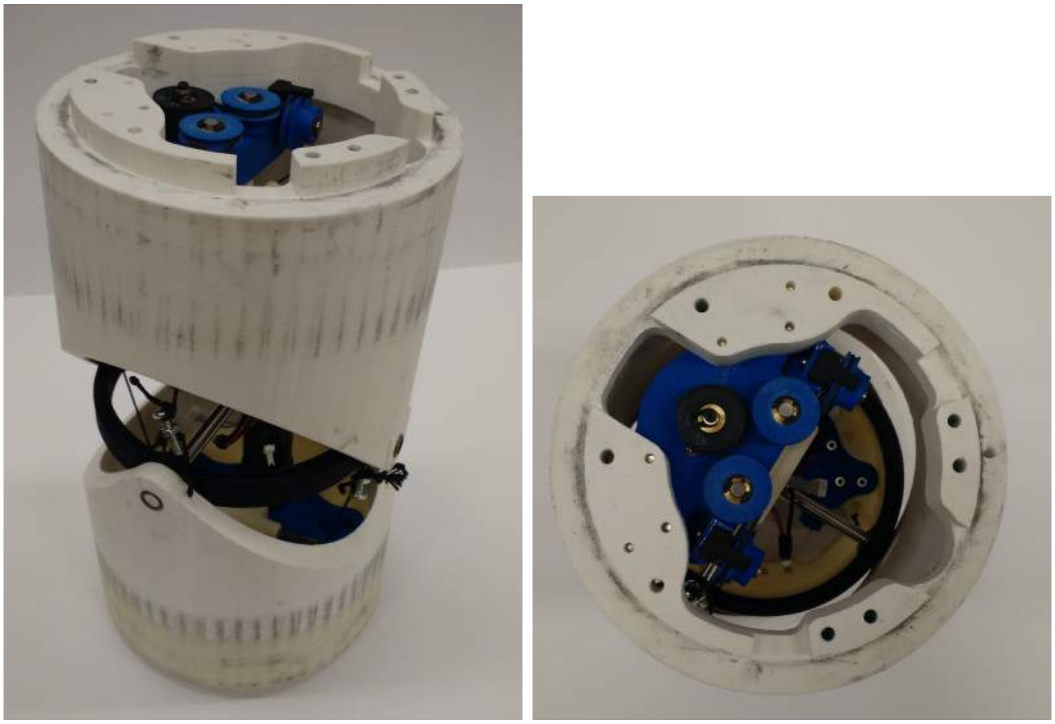
Although this differential drive configuration is highly mobile over rough, relatively flat terrain, it would not be able to overcome most of the complexities of USAR environments. For that we need the radical leap in mobility that comes from hybridization. Therefore, the MOTHERSHIP hybridizes a multiplicity of these 2-D tread mechanisms with a series of two degree of freedom articulating joint limbs.

3.1.2 Articulating Joint Limb

The articulating joint of the MOTHERSHIP hybridizes the tread mechanism to enhance its mobility and extend its task space to make it effective in USAR environments. To minimize additional complexity in the system, the articulating joint is implemented as a simple active universal joint as shown in Figure 3.13. Being a universal joint it has two degrees of freedom which account for the pitch and yaw motion of the neighboring tread mechanism. To drive the two degrees of freedom there is a cable pulley system at each end of the joint which actively pulls on the opposing half. The motors used in the articulating joint are different from the drive motors in the tread mechanism as greater torque and less speed are required in the joint. The joint motors are Maxon RE30 48V motors with GP32C 66:1 planetary gearheads. These motors were selected under the criteria that they be able to lift a 2-D tread mechanism 40° in one second. The two halves of the joint are held together at the inflection point by steel crossing shafts and a solid ABS ring. The total length of the joint is 31.2 cm but most of this length is contained inside the neighboring tread mechanisms to minimize the distance between treads.

In the pulley system a 400 pound test braided Kevlar cable passes through a hubcap on the drive motor shaft and passes over a series of v-pulleys to terminate on the opposite joint half. This pulley system is configured to direct the cable such that the angle of attack is always zero to minimize the chances of a cable rolling off of a pulley, similar to the 3D belt configuration in the tread carrier. Cable guides on the outermost pulleys help to reduce the likelihood of a cable jumping off even further.

To tension the cable and minimize backlash, a screw tensioner with 11 mm of travel is connected in line with each of the cables. As the joint is articulated in either direction, one end of the cable pulls on the opposing joint half which in turn keeps the other end of the cable tight as it is wound off of the drive motor pulley. To eliminate any slack that might occur from this unwinding of the one end of the cable, an extension spring is connected between the two ends of the cable. Not only



(a) (b)

Figure 3.13: Articulating joint 3.13(a) isometric view and 3.13(b) end view.

does this keep the cable taut during operation, it also provides a small amount of elasticity to the joint which reduces shock on impact.

By linking multiple tread modules together with these joints, the system not only gains the ability to navigate over obstacles and uneven terrain, it also results in far greater capability by enabling holonomic locomotion, allowing it to instantaneously move in any direction without altering its pose. Because the 2-D tread mechanism can move with two degrees of freedom, linking several of them together in a serpentine configuration affords the same holonomic motion capabilities as the differential drive configuration. However, in order for the tread mechanism to provide transverse motion, it needs a reaction arm to keep the motor core from spinning inside the tread assembly. Attaching an external reaction arm to the MOTHERSHIP though is not ideal as it could potentially interfere with locomotion particularly through narrow passageways. Instead, the MOTHERSHIP uses the articulating joints to create a reaction arm between modules. By reverting to the zig zag configuration in Figure 3.14, each tread module uses its neighboring modules as a reaction arm. Therefore, the MOTHERSHIP can take advantage of the two degrees of motion of the tread mechanism and enable full holonomic locomotion. This is extremely advantageous given that in an actual mine disaster, a search attempt had to be aborted because the robot could not move sideways (R. R. Murphy, Kravitz, Stover, & Shoureshi, 2009). This failure demonstrates the need for such holonomic capabilities in USAR targeted robotic platforms.

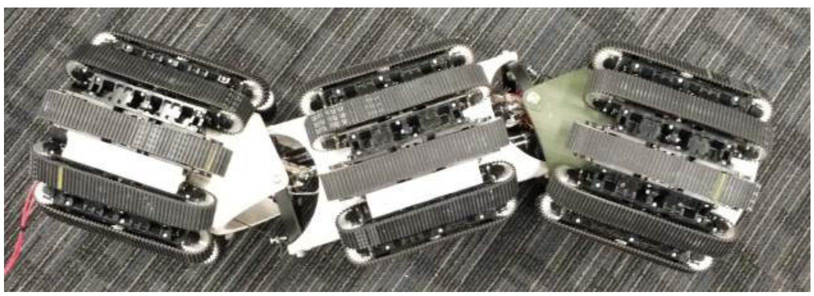


Figure 3.14: Zig zag configuration providing a self induced reaction arm.

Because this hybridization provides holonomic locomotion, the MOTHERSHIP does not need to rely on slithering or follow-the-leader motion, typical in many serpentine robots. Instead the MOTHERSHIP can travel in any direction without needing to change the joint configuration. This feature can simplify operation for the user as they can set a command velocity vector for the entire robot to follow without being burdened by joint angles. But as soon as the robot needs to climb over an obstacle, the joints can be articulated to lift the tread modules.

3.1.3 Electronics

To support the physical mechanisms of the MOTHERSHIP, the RecoNode custom FPGA board and its custom peripheral wedges provide a platform for sensing, actuation, and computational software and control. The RecoNode is a custom FPGA platform developed by the Collaborative Robotics Lab that is designed for reconfigurable hardware and software computation in resource constrained robotics (Voyles, Povilus, Mangharam, & Li, 2010). Along with the RecoNode, several peripheral wedges have been developed which stack compactly on top of the board in a double helix arrangement to expand the capabilities of the RecoNode. A demonstrative RecoNode stack is shown in Figure 3.15 to display the compactness and small foot print of the structure. The boards and wedges associated with the RecoNode are listed as follows:

- TRC1000 RecoNode baseboard: a dual processor Xilinx Virtex 4 FPGA board running at 400 MIPS.
- TRC1005 power board: this board regulates supply voltage to provide the required 1.2, 2.5, 3.3, and 5 volt supplies to the RecoNode and peripheral wedges. Powered by a 3.7V, 1.75Ah Ultralife li-ion battery, this board can provide power for approximately 75 minutes of run time on a single charge.
- TRC1120 motor wedge: a motor amplifier wedge built around the L6205D dual H-bridge motor driver capable of driving two DC motors.
- TRC1121 servo wedge: this wedge provides access to the general purpose I/O pins of the RecoNode to interface additional external sensors and peripherals.
- TRC1140 IMU wedge: built around the MPU6000 IMU and HMC5883L compass IC's, this wedge provides motion tracking and orientation measurement capabilities.

- TRC1150 ZigBee wedge: this wedge provides an interface to the CC2520 ZigBee chip to provide wireless communication to other ZigBee enabled devices.

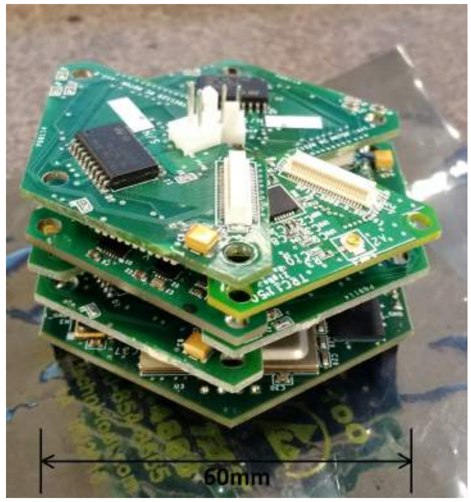


Figure 3.15: Example RecoNode and peripheral stack.

The RecoNode stack used in the MOTHERSHIP consists of five TRC1121 servo wedges to interface with ten DC motor drivers, a TRC1140 IMU wedge to sense the orientation of the MOTHERSHIP, and an additional TRC1121 servo wedge to interface with an external XBee module. Note that a third party motor driver module is used in place of the TRC1120 motor wedge and interfaced with the RecoNode through a TRC1121 servo wedge. This is due to the fact that the existing thermal management of the H-bridge IC on the motor wedge is insufficient for the current draw of the MOTHERSHIP. There are an additional fifteen available GPIO pins on the RecoNode that can be used to integrate a camera or air quality sensor to enhance capabilities for search and rescue applications.

All of the electronics of the MOTHERSHIP are housed in the stationary core of the head module with wiring leading to each motor through the core of each 2D tread mechanism and articulating joint. Since the novel 2D tread allows the entire core to remain stationary during operation, no slip ring arrangements are needed for the wiring, only simple direct connections are used. Electric power for the MOTHERSHIP is supplied by two separate li-ion batteries. A small 3.7V, 1.75Ah battery is stowed with the RecoNode to power the electronics while a 24V, 10Ah battery pack is stowed in the other end of the robot to power all of the DC motors. This on board power along with the wireless communication capabilities allow completely tetherless operation of the MOTHERSHIP and enhance mobility by eliminating a tether as a potential catch point.

3.1.4 Control Software

The software to control the MOTHERSHIP runs on the port based object real time operating system (PBO/RT). PBO/RT is a library of routines that provide task scheduling and task dispatch functions for the RecoNode platform and uses a simple scheduler to run periodic real time tasks. These real time tasks are contained in reusable code blocks called modules that run at a user defined frequency.

Since both the 2D tread mechanism and the articulating joint limb have two degrees of freedom, the three link MOTHERSHIP consisting of three tread modules and two joints has ten controllable degrees of freedom. It would be quite burdensome for a human operator to have to directly control all ten degrees of freedom and would likely require more than one operator to manage them all. To ease the operational complexity of the MOTHERSHIP, assisted remote operation methods are used to implement shared autonomy control. In this shared autonomy system, the operator provides control at the robot level, designating the desired direction of travel, speed, and rotation while the robot autonomously controls the individual degrees of freedom.

Table 3.1 summarizes the key specifications of the MOTHERSHIP that have been presented in this design section.

Table 3.1: Specifications for the MOTHERSHIP hybrid robot

Parameter	Value
2-D Tread Length	24 cm
2-D Tread Diameter	27 cm
2-D Tread Weight	12 kg
Joint Length	31.2 cm
Joint Diameter	17.5 cm
Joint Weight	2 kg
Joint Max Deflection	$\pm$ 35°
Distance between tread modules	11 cm
MOTHERSHIP Body Length	94 cm
MOTHERSHIP Weight	40 kg
Tread Motor	Maxon DCX32L motor & GPX32 gearhead
Joint Motor	Maxon RE30 motor & GP32C gearhead
Motor Power Supply	24V, 10Ah Li-ion battery pack
Electronics Power Supply	3.7V, 1.75Ah Li-ion battery pack
Wireless Communication	XBee Series 1

3.2 Test Methodology

The developed robot platform was designed to be a tool in USAR applications where it is expected to encounter obstacles consistent with deconstructed urban environments. To determine the effectiveness of the MOTHERSHIP in traversing such environments, it was subjected to mobility tests wherein its ability to accomplish common USAR tasks was evaluated. These tasks included traversing an incline, crossing a gap, and stair climbing. In addition, the robot was tested to determine basic ground robot performance metrics; namely top ground speed and minimum turning radius. The results of these mobility tests are presented in the next chapter alongside published data for similar robotic platforms in the research community to give some context to the data and to provide a measure of success.

3.2.1 2-D Tread Mechanism Test Procedures

Prior to the completion of the full MOTHERSHIP platform, a series of tests were performed on a single 2-D tread mechanism to confirm the expected behavior and to characterize the individual mechanism. As the main function of the 2-D tread is to provide motive force in two dimensions, the initial test was performed to confirm that the mechanism could in fact exhibit this behavior. To do so, the test bed shown in Figure 3.16 was constructed to fix the motor core in place by feeding two steel rods through it and suspending the tread mechanism above the ground. With the tread mechanism in place, the DC voltage supplied to each of the drive motors was varied between $\pm$ 30V while the motion of the mechanism was observed.

Following testing of the desired motion capabilities of the mechanism, several tests were performed to characterize the performance of the tread mechanism. These tests determined 1) the no load current draw of the drive motors, 2) the maximum pull force the module could exert using the treads, and 3) the top ground speed of the mechanism in both the longitudinal and transverse directions.

Figure 3.16: 2-D tread mechanism test bed to confirm motion capabilities.

The test procedure to determine the no load current draw of the mechanism began again with mounting the mechanism securely on the test bed. With the mechanism secure, a three DOF joystick was used to input command velocities to the mechanism, initially ramping up to the top transverse speed with 24V supply voltage. The input command velocity vector of the mechanism was then steadily rotated from pointing along the transverse body axis to pointing along the longitudinal body axis. Readings of the current draw for each drive motor under this no load condition were taken at several points during the test.

A potential application for the MOTHERSHIP is to deliver medical supplies and/or food and water to victims trapped under a collapsed structure, therefore it is important to determine the maximum pull force this tread mechanism can exert as it relates to payload capacity. To determine the maximum pull force, a scale was grounded and immobilized then affixed rigidly to the tread module. The drive motor velocities were steadily increased to ramp up the tread (longitudinal) speed of the module until the treads began to slip along the driving surface. The maximum pull force was recorded immediately before the treads began to slip. This test was repeated for three trials on three different driving surfaces (carpet, plywood, and linoleum tile) and the average force was recorded for each of the three surfaces.

It was shown in Section 3.1.1 that the maximum velocity of the tread mechanism is aligned along the longitudinal and transverse body axes due to the coupling of the drive motors. Therefore the top speed for the mechanism was only recorded along those two axes. The top speed in the two dimensions was recorded on a level, concrete floor. For both the longitudinal and transverse directions, the tread module was raised off the ground while the motor velocities were increased to their maximum value at the motor specified voltage of 48V. This allowed the tread module to start from a known location while already traveling at top speed. The elapsed time was then recorded as the tread module was released on the ground and traveled a total distance of four feet at top speed. This test was repeated for three trials in both the longitudinal and transverse direction and the average speed was recorded for both.

3.2.2 MOTHERSHIP Test Procedures

Again, the top speed of the 2-D tread mechanism is directed along the principal body axes, the transverse and longitudinal directions. However, without a reaction arm the MOTHERSHIP cannot drive all tread modules purely transversely as the core would simply rotate inside of the stationary tread assemblies. Therefore the maximum attainable speed for the MOTHERSHIP hybrid robot occurs in a straight line configuration with all velocities directed along the longitudinal axis. For this reason, the top speed of the MOTHERSHIP was examined in the straight line configuration by measuring the time elapsed traveling over four feet after it reached top speed.

In addition to speed, the minimum turning radius for a mobile robot is important in characterizing mobility, especially in complex environments, as it pertains to how much open space the robot needs in order to maneuver. Because the MOTHERSHIP is holonomic, it can rotate in place and so it has a theoretical minimum turning radius of zero. This expected behavior was confirmed through experimentation.

To determine the maximum angle of ascent that the MOTHERSHIP can handle, a test apparatus was built to provide a variable height ramp ranging from five to sixty degrees above horizontal. The ramp consists of a stable base with six foot high vertical posts and a six foot by four foot reinforced plywood board as the driving surface. The vertical posts have holes every six inches through which a half inch aluminum rod is bridged between the posts. These six inch increments in the posts relate to five degree increments in inclination angle. The driving surface is hung on the aluminum rod to create a stable inclined plane. In the test, the MOTHERSHIP was set in its initial position at the bottom of the ramp and, starting at five degree inclination, was driven up the ramp. The inclination angle was increased in five degree increments and the experiment was repeated until the MOTHERSHIP failed to propel itself up the ramp.

The RoboCup Rescue League is a popular competition that tests the mobility and functionality of search and rescue robots. As part of the competition there is an "orange" test arena for autonomous and teleoperated rescue robots that uses 15 degree ramps as an obstacle. Therefore the maximum angle of ascent experiment is considered a success if the MOTHERSHIP can overcome a fifteen degree incline. However many similar robots such as the OmniTread and Souryu can traverse thirty degree slopes or more, so the target for this test is a thirty degree incline.

To determine the widest gap the MOTHERSHIP can cross, the same reinforced board used in the inclination test was elevated to a height of 6 inches to be level with an existing step. The board was initially situated 6 inches away from the step and the MOTHERSHIP was driven across the gap to end up on the other side. The gap was enlarged in 3 inch increments until the MOTHERSHIP failed to cross on its own.

A common obstacle found in urban disaster environments is stairs. Stairs generally present a lot of difficulties for traditional treaded robots as the step height is generally larger than the tread itself. The hybridization of the articulating joints in the MOTHERSHIP should enable it to lift the 2-D treads and overcome the step height. Starting with a flight of stairs with tread length 36 inches and riser height 6 inches, the MOTHERSHIP was tested for it ability to successfully climb the stairs. The pitch of the stairs was then increased after each successful trial until the robot failed the task.

3.3 Summary

The design of the developed MOTHERSHIP robot has been presented in detail, highlighting the aspects of the design that address the stated problem of mobility in this research. The novel two-dimensional tread mechanism is central to the design and has the advantage of omnidirectional planar motion with very little operational complexity. The articulating joint then hybridizes the two-dimensional tread mechanism to create a tread/limb/serpentine hybrid robot and greatly expands on the capabilities and task space of the tread mechanism. After presenting the design of the MOTHERSHIP, this chapter laid out the test procedures for determining the potential effectiveness of this robot in urban disaster areas. The results of these tests are presented in the following chapter.

CHAPTER 4. RESULTS

The results of the test procedures laid out in the previous chapter are presented in this chapter alongside some published results for similar platforms to provide a frame of reference. The results are further analyzed in this chapter to elaborate on the effectiveness of the 2-D tread mechanism and the MOTHERSHIP hybrid robot.

4.1 2-D Tread Mechanism Test Results

The preliminary test of the tread mechanism confirmed the desired motion behavior by suspending a single module on a testbed and altering the supply voltages of the motors. The mechanism was observed to exhibit smooth two dimensional motion by actuating the treads and rotating the tread assembly about the core. This motion can be observed through video at http://www.purdue.edu/crl.

With the two dimensional tread still mounted on the testbed, the no load current of the mechanism was observed during operation. Because the treads are locked longitudinally in purely transverse motion, the bevel gears in the tread units as well as the outer ring gears and the intermediate idler gears are not driven and remain stationary. In this case, the drive motors only drive the inner ring gears as the entire tread assembly rotates with the ring gear. Therefore the motors have to drive far fewer gears and the no load current is at a minimum during transverse motion. The no load current in the transverse direction was observed to be 0.4 amps for each motor. In the longitudinal direction however, the motors have to drive all of the gears in the system as well as the treads which account for greater friction and inefficiencies. Therefore the no load current is at a maximum in the longitudinal direction and was observed to be 1.9 amps for each motor. As the current draw for the motors is at a minimum in the transverse direction, it would suggest that the most efficient way to operate the MOTHERSHIP to extend battery life and operation time would be to operate it purely in the transverse direction. However, the MOTHERSHIP cannot operate purely in the transverse mode without a reaction arm and the MOTHERSHIP also requires far less area to move longitudinally, which is important in confined areas. Therefore, we sacrifice some efficiency in order to take full advantage of the capabilities of the MOTHERSHIP.

The drawbar pull test for a single 2-D tread mechanism demonstrated how much force the treads can exert in order to carry a payload. The test showed that the treads can exert an average of 55.3N of force operating on carpet, 30.4N on plywood, and 30.5N on linoleum tile. This relates to an average payload capacity of 5.65kg on carpet, 3.11kg on plywood, and 3.12kg on linoleum tile. It is important to note however that the limiting factor in this test was not motor strength. For each surface the treads began to slip far below the maximum operating current of the drive motors. In each case, the treads slipped at less than 3 amps which is well below the maximum current of 6 amps for the motors. So although the motors are capable of exerting greater torque, the traction of the treads along the driving surface limits the pull strength. This result is not surprising as we are currently using timing belts for the treads, similar to the very early versions of the Souryu and PackBot. Both of those development efforts went to extreme lengths in later versions to develop custom treads with special grousers to achieve much higher drawbar pull strength.

This low result is also attributed to the geometry of the test surface. This test used a planar surface which is the ideal case for rectangular vehicles that have wide flat treads, but for a circular cross section, like the 2-D tread, a planar surface is the worst case. As demonstrated by Figure 4.1, the amount of tread that the 2-D tread mechanism can contact with a planar surface is far less than a rectangular vehicle. However, because the target environment for the MOTHERSHIP is disaster areas, smooth planar surfaces are not expected to be the norm. Instead, rubbled, uneven, and complex surfaces are more likely to be encountered. These types of surfaces, as illustrated in Figure 4.2, should provide multiple points of contact and increased traction for the 2-D tread. Based on this, we extended the drawbar pull test to determine the best case result. We replaced the planar surface with a circular duct that contoured the shape of the 2-D tread and lined the duct with carpet as this surface provided the greatest traction in the previous test. This ideal case resulted in a pull strength of 160.8N for a payload capacity of 16.4kg at the maximum safe operating current of 6 amps for a 190% increase over the worst case conditions.

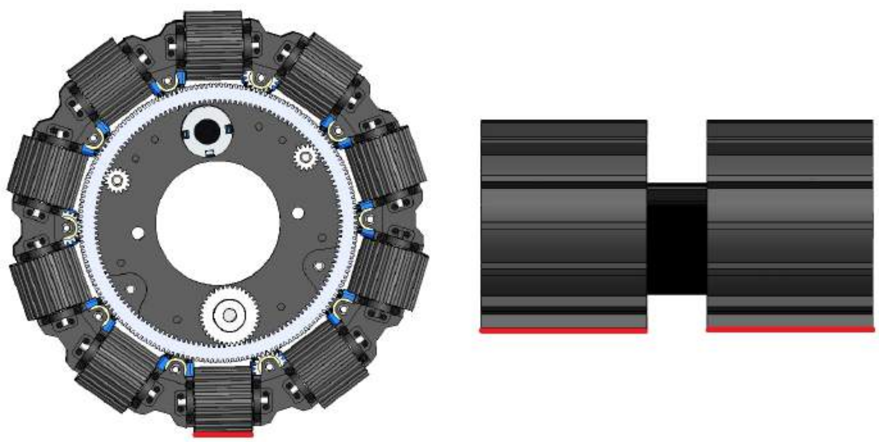


Figure 4.1: Comparison of tread contact for a circular tread mechanism and a rectangular tread mechanism on a planar surface. Red is used to highlight contact.

As described in the design section, the theoretical maximum attainable velocity for the tread mechanism is directed along the principal transverse and longitudinal axes. Therefore the speed was only tested along these two directions. In the transverse direction, the tread mechanism acts as a large diameter wheel and wheels of course excel at delivering high speeds on level ground. The maximum speed recorded for the transverse direction was recorded as 1.22 m/s, which equals 5.08 body lengths per second for a single tread module. In the longitudinal

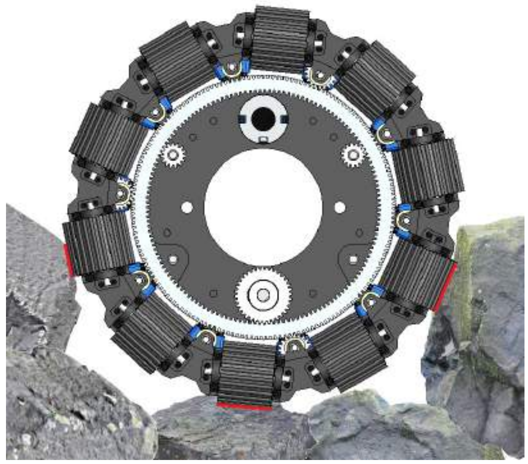


Figure 4.2: Sample driving surface in USAR which provides multiple contact points and greater traction for the circular 2-D tread mechanism.

direction, the mechanism relies on the treads to propel itself forward and as the treads incur greater inefficiencies through driving more gears, the longitudinal top speed is slightly less at 0.85 m/s, or 3.54 body lengths per second. The drive motors of the tread mechanism were designed to give the mechanism a top longitudinal speed of 1 m/s but due to higher than expected frictional forces and gear inefficiencies, the actual speed attained is slightly less.

The results of these tests as a characterization of the 2-D tread mechanism are summarized at the end of this chapter in Table 4.1.

4.2 MOTHERSHIP Test Results

The previous results aim to characterize the 2-D tread mechanism while the results in this section pertain to the effectiveness of the MOTHERSHIP in locomoting through harsh USAR environments.

Urban search and rescue is a highly time sensitive operation as the victims need to be located and extracted as soon as possible to increase their chances of survival. For that reason, maximum velocity is a useful metric to evaluate a rescue robots effectiveness. As the top speed of our 2-D tread mechanism is observed in the longitudinal and transverse axes and the MOTHERSHIP is not able to use pure transverse motion of all mechanisms without a reaction arm, the top ground speed of the MOTHERSHIP is observed along the longitudinal axis in the straight line configuration shown in Figure 4.3. As expected, the top speed of the MOTHERSHIP is the same as the top speed of the tread mechanism along the longitudinal axis, 0.85 m/s. For the full length, three module MOTHERSHIP this equates to 0.9 body lengths per second. To give a frame of reference to this result, the maximum velocity of the OmniTread OT8 is 0.1 m/s (0.08 body lengths per second), that of the Souryu IV is 0.105 m/s (0.09 body lengths per second), and of the Souryu V is 0.25 m/s (0.22 body lengths per second). The body length of each individual robot is used to calculate each speed. All of these other platforms are similar in scale and structure to the MOTHERSHIP yet the MOTHERSHIP can travel up to eight times faster. This higher speed capability gives the MOTHERSHIP the potential to cover far more ground in the search for survivors.

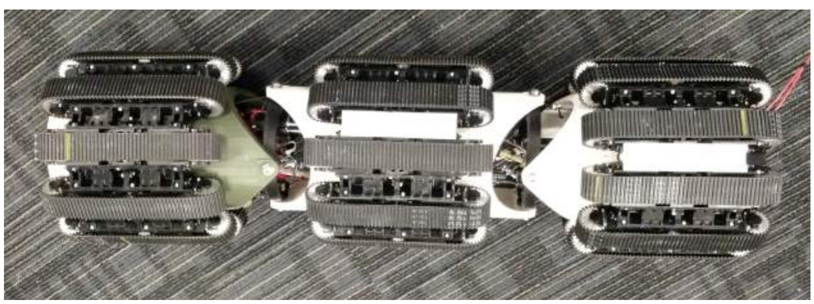


Figure 4.3: Straight line configuration associated with maximum velocity.

Besides speed, minimum turning radius is a useful metric to determine mobility of ground robots, particularly in cluttered environments such as disaster sites. Because the MOTHERSHIP has holonomic locomotion capabilities it has a theoretical zero turning radius. This theoretical result was confirmed through experimentation and it was observed that the hybridization of 2-D tread mechanisms and two degree of freedom articulating joints enables the

MOTHERSHIP to spin in place with zero turning radius. This behavior can be observed through video at http://www.purdue.edu/crl.

In comparison, the OmniTread serpentine robot has a minimum turning radius of 53 cm which is equal to 42% of its total body length. This inability to turn in place can potentially limit the mobility of the system as it can have difficulty turning in a confined space without sufficient open area. The Souryu IV and V robots however are capable of spinning in place as well, giving them a zero turning radius like the MOTHERSHIP. The Souryu IV incorporates differentially driven treads on each of its segments, so by lifting the two end segments off the ground it can rotate the center module in place. The Souryu V on the other hand wraps its segments in a single wide tread so it cannot accomplish the same motion as the Souryu IV. Instead, to turn in place, the Souryu V has to run through a sequence of precise, choreographed joint manipulations which is much slower and more difficult to control than the spot turning of the MOTHERSHIP. Compared to these other mobile robot platforms, the MOTHERSHIP appears to have the most advantageous spot turning. Not only can the MOTHERSHIP spin in place, it can do so quickly and in any pose without regard to the joint angles. This allows the MOTHERSHIP to keep all of its body segments on the ground during spot turning which makes it more stable, especially on non-flat ground.

For the gap test, the same straight line configuration used to determine maximum velocity was used. The straight line configuration for the MOTHERSHIP is expected to have the greatest reach as the shortest distance between two points is a line. Upon completion of the test, the widest gap that the MOTHERSHIP was able to successfully cross on its own was 28 cm, which is approximately 30% of the total body length. It was at this width that the MOTHERSHIP began to lose stability from having such a small contact area to support it. Comparatively, the OmniTread OT8 can cross a gap width of 66 cm (52% body length), the Souryu IV can cross 59 cm (49% body length), and the Souryu V can cross 68.6 cm (59% body length). Generally speaking, a robot should be able to cross a gap width of roughly

50% its body length before the robot will tip forward, assuming weight is evenly distributed. However, because the MOTHERSHIP doesn't have a wide base to keep it steady, disturbances such as hanging over a ledge can cause it to lose stability sooner. Figure 4.4 shows the MOTHERSHIP during one of the trials of the gap test.

Figure 4.4: MOTHERSHIP crossing a gap of 28 cm.

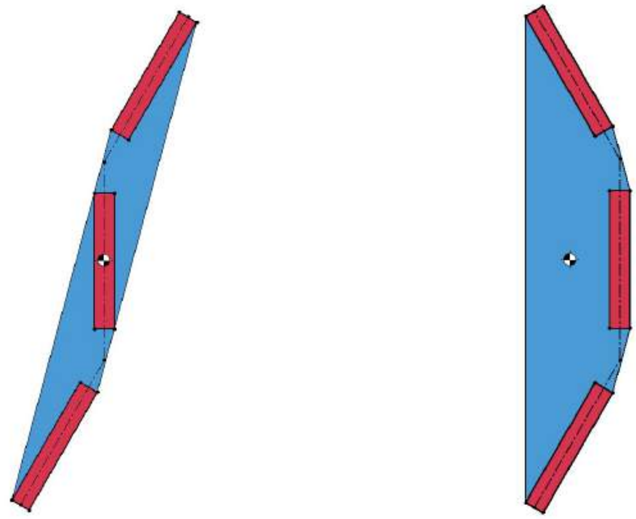
Stability also became an issue in the test for maximum angle of ascent. This problem with stability is a consequence of the inherently small support polygon for the MOTHERSHIP. The support polygon of an object, in this case a robot, is the convex hull of contact points with the supporting surface (Siciliano & Khatib, 2008). To maintain stability, it is necessary for the robot's center of mass to stay within this support polygon. Therefore, the larger the support polygon is, the more resistant it will be to becoming unstable due to outside disturbances. Because the 2-D tread mechanism has a cylindrical geometry like a wheel, its support polygon is small, smaller than a traditional rectangular tread vehicle, so it doesn't take much to send the 2-D tread rolling. This is highly beneficial when our desire is to roll as the 2-D tread can very efficiently roll transversely to locomote. But this can also cause problems in the event of undesired rolling.

By linking a multiplicity of the 2-D treads together with articulating joints, as in the MOTHERSHIP, we can enlarge the support polygon of the entire robot by offsetting the modules from the central axis for a more stable system. Next we compare the stability of three basic configurations of the MOTHERSHIP: the straight line, the zig zag, and the arc configurations. In a straight line, the MOTHERSHIP has the geometry of an elongated wheel and as such can easily incur undesired rolling. This is because the support polygon in this case is a thin strip right below the center of mass as illustrated in Figure 4.5.

Figure 4.5: Support polygon representation for the straight line configuration. Red shows contact area and the combination of red and blue shows the support polygon.

The support polygon for the MOTHERSHIP is enlarged by changing the joint angles. The support polygons for the zig zag and arc configurations are shown in Figure 4.6. As can be seen in the figure, both support polygons are larger than the straight line with the arc being the largest. Also since the center of mass shifts toward the center of the support polygon for the arc, the arc is the most stable configuration.

This assessment was confirmed in the incline test as all three of the configurations were attempted for the ascent and the arc was able to climb the steepest incline. Initially, the straight line configuration was attempted as the treads provide the most friction in the longitudinal direction. However because of the small support polygon, the MOTHERSHIP had a tendency to roll down the incline like a



(a) Zig zag (b) Arc

Figure 4.6: Support polygon representations for the zig zag and arc configurations.

wheel. The zig zag was able to maintain stability more so than the straight line, but the joint configuration gave it a tendency to twist like a screw about its central axis on steeper inclines. The arc configuration on the other hand was able to maintain stability throughout the entire test and it was in this configuration that the MOTHERSHIP ascended its maximum inclination angle of 20°. This result is greater than the 15° inclines used in the Robocup Rescue League orange arena but it does not match the performance of the OmniTread OT8 which can climb up to 30° inclines. Just as it was for the pull test for the 2-D tread mechanism, this deficiency is attributed to the limited tractive forces that are a consequence of the circular cross section. Figure 4.7 shows the MOTHERSHIP climbing an incline of 20° during the inclination test.

The stair climbing test had to be aborted as a structural weakness was exposed in the joint motor mount shown in Figure 4.8. As the cable rolls over the indicated pulley to lift the neighboring tread segment, a large torque is induced on the pulley shaft causing it to break through its mounting hole rendering the joint

Figure 4.7: MOTHERSHIP ascending an incline of 20°.

inoperable. Due to time constraints associated with this research, a full stress analysis on the entire robot was not possible as the fabrication and assembly of the MOTHERSHIP required significant time and resources. Therefore, a compromise was made between simulation and product development and so some parts had to be analyzed through experimentation. The joint motor mount was fabricated from ABS plastic in an effort to keep weight low but to rectify this structural weakness, the mount may need to be machined from aluminum or a stronger metal still. Additionally the design of the mount may need to be modified to support the pulley shaft at both ends to eliminate the torque that caused the break.

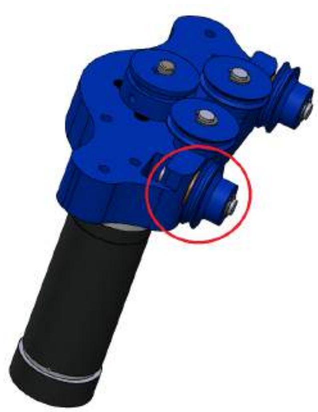


Figure 4.8: The joint motor mount with the weak cable pulley circled.

Prior to the part breakage though, additional difficulties with stability were observed. The joint was able to lift the segment roughly 10° before the breakage occurred and in that time the MOTHERSHIP had a tendency to turn on its side to return the lifted segment back into contact with the ground. As can be seen in Figure 4.9, the support polygon of the MOTHERSHIP shrinks greatly by lifting a segment off the ground. Only in the zig zag configuration does the center of mass stay in the support polygon, but even so it is at the edge of the polygon making it vulnerable to outside disturbances. This suggests that a minimum of four tread segments will be required to lift a segment while maintaining a stable base of three segments. This situation is demonstrated for both the arc and zig zag configurations in Figure 4.10. With both configurations, the support polygon is large enough to provide a stable base for the lifted segment and it also creates some freedom to position the lifted segment. Having only three segments, the position of the lifted segment is constrained to keep the center of mass within the support polygon, but the enlarged base with four segments allows a range of motion for the lifted segment which should make it easier to climb stairs and other obstacles.

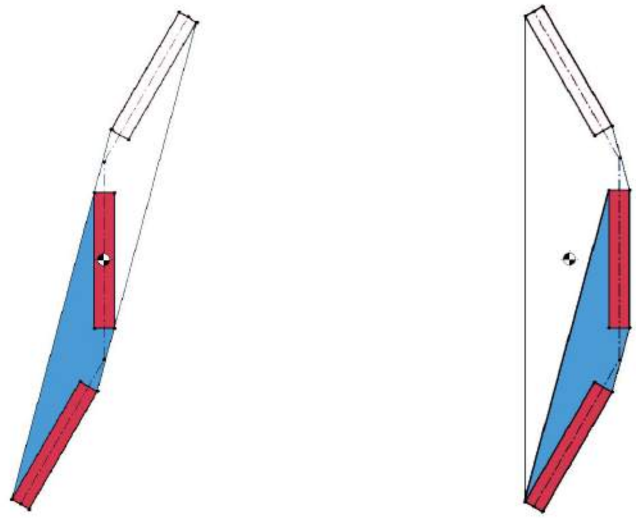
Table 4.1 in the chapter summary section summarizes the performance results for the 2-D tread mechanism and the MOTHERSHIP hybrid robot.

4.3 Summary

This chapter has presented and analyzed the results of the testing performed to both characterize the novel two dimensional tread mechanism and to determine the effectiveness of the MOTHERSHIP hybrid robot. The tests have shown that the platform excels at ground motion, moving both at high speeds with high maneuverability, but also that the geometry of the robot coupled with the current three link configuration can cause difficulties with maintaining stability while going over obstacles. A summary of the results of the completed experiments are presented in Table 4.1.

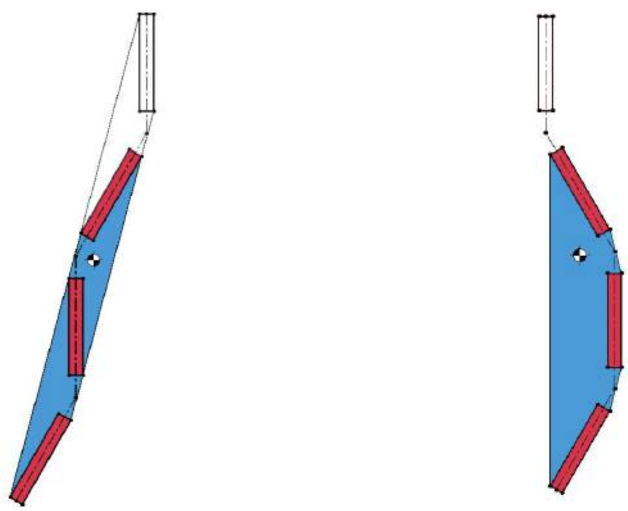
Table 4.1: Results of mobility tests for the 2-D tread and the MOTHERSHIP

Platform	Test	Result
Tread Mechanism	Top ground speed (longitudinal)	0.85 m/s
	Top ground speed (transverse)	1.22 m/s
	Average pull force (carpet)	55.3 N
	Average pull force (plywood)	30.4 N
	Average pull force (linoleum)	30.5 N
	Average pull force rounded surface	160.8 N
	No load current per motor (longitudinal)	1.9 amp
	No load current per motor (transverse)	0.4 amp
MOTHERSHIP	Top ground speed	0.85 m/s
	Minimum turning radius	Zero
	Maximum angle of ascent	20°
	Largest Gap	28 cm



(a) Zig zag (b) Arc

Figure 4.9: Support polygon representations for the three segment zig zag and arc configurations with one lifted segment.



(a) Zig zag (b) Arc

Figure 4.10: Support polygon representations for the four segment zig zag and arc configurations with one lifted segment.

CHAPTER 5. SUMMARY, CONCLUSIONS, and RECOMMENDATIONS

The ultimate goal of this research was to develop a tread/limb/serpentine hybrid robot, based on a novel 2-D tread mechanism, that combines the strengths of wheels, treads, limbs, and snakes to make it effective for locomotion in urban search and rescue applications. This research successfully developed and confirmed the expected motion behaviors of the MOTHERSHIP robotic platform as well as the novel 2-D tread mechanism and, through experimentation, exposed some potential limitations of the platform that can be addressed through future work.

5.1 Mobility Assessment

Through experimentation and observation, the MOTHERSHIP proved to excel at ground locomotion, it has great mobility as it can move at highs speeds and is highly maneuverable thanks to its holonomic locomotion capabilities. It is able to move about the ground plane very efficiently and with almost no operational complexity. However, moving out of the ground plane presented some difficulties with maintaining stability. Stability was a potential concern at the onset of this research and was identified as a potentially limiting factor because the circular cross section of the MOTHERSHIP has a smaller base than traditional rectangular tread vehicles.

The three link configuration of the MOTHERSHIP was chosen for this research as a compromise between resource consumption, complexity, stability, and capability. A rudimentary preliminary analysis of stability through support polygons suggested that the pose of the three link MOTHERSHIP can be configured to maintain stability when moving out of the ground plane. This initial assessment proved true during experimentation as long as outside disturbances were kept small.

The biggest issue observed with the MOTHERSHIP was that lifting segments off of the ground to overcome obstacles greatly reduced the support polygon and hurt stability. This caused some difficulty for the three link MOTHERSHIP because lifting one segment leaves only two to support the entire robot. Expanding the length of the MOTHERSHIP to four or even five segments would likely increase stability greatly and allow it to overcome larger obstacles.

Despite the difficulties experienced with stability, the MOTHERSHIP was still able to handle each of the obstacles it was tested on, with the exception of stair climbing. Though it did not perform as well as similar rectangular robot platforms in the gap, incline, and stair climbing tests which we attribute to the circular cross section providing less traction and a smaller base of support. It did however perform more effectively in ground plane locomotion than similar rectangular robot platforms as the circular cross section also enables holonomic locomotion in the MOTHERSHIP.

Overall the MOTHERSHIP was shown to have both pros and cons compared to similar robotic systems. The circular cross section does result in less contact area with the driving surface and a smaller support polygon than similar rectangular vehicles which presented some issues with stability and traction. But the circular cross section also enables the benefit of holonomic locomotion and also allows us to take advantage of the locomotion strengths of wheels, that being high speed and high efficiency motion. We believe that this platform has demonstrated good mobility for use in USAR applications and by addressing the stability and traction issues in future work it has the potential for far greater mobility.

5.2 Future Work

It was observed through experimentation that traction is a major limiting factor for the MOTHERSHIP. The circular cross section of the MOTHERSHIP enables smooth and efficient holonomic locomotion, but it also results in less contact area between the robot and the driving surface, particularly over planar surfaces. To increase the pull strength, the payload capacity, and the maximum angle of ascent for the MOTHERSHIP, increasing the tractive forces of the robot should be investigated. This could potentially be achieved through reevaluating the tread grouser geometry and material or by examining how to get greater contact area between the MOTHERSHIP and the driving surface.

The second limitation observed in the MOTHERSHIP is its susceptibility to undesired rolling and inversions again due to the limited contact area with support surfaces. Extending the MOTHERSHIP by adding more tread mechanism segments would result in a larger support polygon and make the robot more stable and resistant to undesired rolling. This would make the robot especially more stable when lifting segments to cross gaps or climb stairs where in the current configuration only two segments remain in contact with the ground. As seen in Figure 4.9(a), the center of mass of the MOTHERSHIP is situated at the edge of the support polygon during a segment lift in the zig zag configuration, making it marginally stable and vulnerable to outside disturbances. Figure 4.9(b) shows that, for the arc configuration, the center of mass is actually outside of the support polygon which results in unstable tipping during a segment lift in the three segment MOTHERSHIP. Expanding to a five segment configuration should alleviate some of this instability by creating a larger support polygon as well as increasing the size of obstacles and gaps that the robot could overcome.

Additionally, in adding segments to the configuration it could prove beneficial to break up the regularity of the MOTHERSHIP. By regularity we mean the constant pattern of tread mechanisms and limbs. This regularity can prove troublesome if the spatial frequency of the robot matches that of the environment.

An example of this is shown in the left of Figure 5.1 where the spatial frequency of the MOTHERSHIP is very near the spatial frequency of the stairs. In this case, the joints of the MOTHERSHIP would fall into the stairs. Although the MOTHERSHIP could still use its limbs to climb out and make its way up the stairs in a serpentine fashion, it would be far less efficient and far more intensive from a control stand point than simply rolling up the stairs. By introducing some irregularity into the hybrid configuration, such as in the right of Figure 5.1, we can lower the spatial frequency of the robot, thus lowering the required spatial frequency of the stairs. This is analogous to the Nyquist rate in signal processing. Consider the robot as a signal to be sampled and the stairs as the sampling rate. To prevent "aliasing," the frequency of the stairs must be at least twice the frequency of the robot. By introducing irregularity and lowering the frequency of the robot, we lower the Nyquist rate of the stairs and expand the set of stairs that the robot can more efficiently roll up. This irregularity could come in the form of rigidly connecting two tread mechanisms in the middle to mimic an elongated tread as in Figure 5.1, or in some other form that can be investigated with future work.

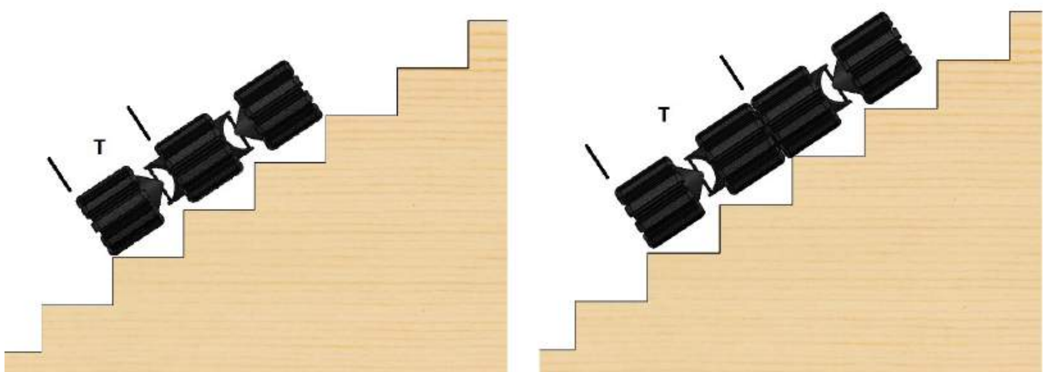


Figure 5.1: Illustration of the potential benefit of disrupting regularity. T denotes the period of the robot configuration.

In order to extend the MOTHERSHIP with additional tread segments, the computation will need to be decentralized. Already with the three segment, ten motor configuration of the MOTHERSHIP, nearly all of the available GPIO pins on the RecoNode computing platform are occupied, so there is not enough space to add many more motors. To overcome this, the computation of the MOTHERSHIP can be decentralized such that each tread segment incorporates a cheap, low power microcontroller while the MOTHERSHIP connects to all of them and acts as the master. The individual microcontrollers would control the individual segment's motors and two dimensional motion while the RecoNode would only need to communicate with each of the segments through a CAN bus or similar to send command signals. This decentralized control would free up the majority of the pins currently occupied on the RecoNode by the motor drivers. With more available connections, the RecoNode could interface with a sophisticated sensor cluster, such as an infrared camera, air quality sensor, and LIDAR to enhance the capabilities of the MOTHERSHIP in search and rescue applications.

By also decentralizing the power supply to instead have each tread mechanism carry its own smaller battery to power itself, the tread mechanism can be made to be completely self-contained. This would make the tread mechanism truly modular so that multiple mechanisms could be linked by a single connector for communication. This is advantageous from a wiring aspect as wires don't need to be fed through the entire robot to make connections. Also, this decentralized, modular design would make maintenance of the MOTHERSHIP far more efficient such that if a segment has a break, the operator can swap it out without taking apart the entire robot. This ease of maintenance is important for field robots as Figure 5.2 from (Carlson & Murphy, 2005) shows that the operation time for most field robots is quite small compared to downtime. Also important for field robots is robustness against the environment, this means water proofing and dust proofing the MOTHERSHIP to make it field ready.

Manu.	# of Failures	% of Usage	MTBF(hrs)	Availability	Average Downtime (hrs)
Inuktun	34	94%	6.14	90%	177
iRobot	12	28%	6.27	36%	207
Overall	46	58%	6.17	64%	185

Figure 5.2: Table showing the average downtime and operational (MTBF) time for the Inuktun and iRobot field robots. Copyright ©2005 IEEE

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