Hybridization of a 2-D Tread Module for Locomotion in USAR Environments

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Abstract— **Hybridization of robots has led to great leaps in capability, often with minimal additional complexity, and refers to a synergistic combination of different actuation modes within a single platform. 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. In this paper we present a novel 2-D tread module capable of exerting motive forces in two orthogonal directions. Hybridization of this mechanism is explored to create a holonomic differential drive configuration as well as a holonomic tread/limb serpentine hybrid robot. Some preliminary results of the tread module performance are presented as well.**

I. 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. Since the first use of rescue robots in a live disaster at the 2001 World Trade Center collapse [1], research in the field of search and rescue robotics has been unending as the potential to preserve human life has become apparent. Typically, robots are employed in these disaster situations to extend human perception and to more effectively and efficiently locate survivors and assess damage. 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. Therefore the potential to preserve human life is seen at both ends, both for the victim and the rescuer. To maximize this potential, what we need is the greatest leverage on mobility without too much complexity so that the robots are still controllable by the human rescue workers. Conventional wheeled and tracked robots are historically simple to control and operation can be mastered in hours or even minutes. However, oftentimes USAR environments prove impassible for conventional wheeled and tracked mobile robots, at least without time-consuming excavation methods such as digging and drilling. For this reason, hybridization of robot platforms has become a focal point in USAR robotics research as their combination of actuation types can provide far greater mobility without much added complexity.

Hybridization of robots refers to the synergistic combination of two or more different classes of actuation modes in a single platform [2]. 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. This is helpful for urban search and rescue applications due to the high complexity and uncertainty of the operating environment. For instance, a traditional tracked 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 the tread. Conversely, a limbed robot is far more capable of climbing over obstacles in its path, but at the cost of 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 such as this into their design. In fact, two of the top three finishers at the 2015 DARPA Robotics Challenge used hybrid locomotion. Both CHIMP from CMU [3] and the KAIST DRC-Hubo [4] used hybrid locomotion to simplify control.

In keeping with this pattern of success, we have developed a two-dimensional tread module capable of exerting motive forces in two orthogonal directions for integration into a tread/limb hybrid serpentine robot for locomotion in unstructured environments. Fig. 1 shows the 2-D tread module assembled into a three module hybrid serpentine configuration which we call the MOTHERSHIP.

Fig. 1. The 2-D tread module assembled into the MOTHERSHIP hybrid serpentine configuration.

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II. PRIOR WORK

Hybrid designs that incorporate the use of both treads and limbs in a single platform can be divided into two groups based on which of the two actuation modes is used as the dominant mode of locomotion and control. A hybrid design that uses treads as the dominant mode incorporates limbs 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. On the other hand, a hybrid design that uses limbs as the dominant mode will add treads to provide bulk motive force to the platform. Typically these limb/tread hybrid robots are small to accommodate penetration into rubble.

The Helios robot developed by Guarnieri et al [5] is a prime example of hybridization. They attached a manipulator to a treaded differential drive robot and use it as a leg to hoist it over obstacles. This is obvious tread/limb hybridization as the treads are dominant in locomotion. Aside from the manipulator, there is also a more subtle form of hybridization: there is an articulating joint between the two treads. This acts like a knee joint in some ways, but provides great capability with only one degree of freedom.

Likely the most widely known implementation of a tread/limb hybrid robot is the commercially available PackBot from iRobot [6]. Essentially, the PackBot consists of a main chassis with a pair of differentially driven treads as its main source of mobility and a pair of active flippers that allow the PackBot to lift itself over obstacles or lengthen its wheelbase by positioning them flat on the ground for greater traction. Redback [7] and Quince [8] are a few other implementations that similarly have one degree of freedom flippers that can be articulated to lift a tread-covered body over obstacles. The addition of limbs greatly enhances mobility in rubbled environments for these robots that would otherwise be limited by the height of their treads and introduces very little complexity to control and operation.

Previously, our lab has implemented a limb/tread hybrid robot based on the TerminatorBot [9], which was also developed in our 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 (a.k.a. "CRAWLER") typically has slow, precise movements. To improve the "brute force" capabilities of the miniature crawling robot, it was hybridized with a transverse tread module called the Crabinator [10]. With the tread attached, the TerminatorBot still uses its limbs as the dominant form of actuation, hence we call it a limb/tread hybrid (as opposed to a tread/limb hybrid) to reflect that dominance.

III. FIELD MOTIVATION

Hybrid designs have led to great leaps in capability, often with minimal additional complexity. The PackBot mentioned previously is a great example of this. Just with the addition of a simple one degree of freedom flipper, the differential drive robot gains the ability to climb stairs and overcome obstacles, greatly expanding its task space. The 2-D tread similarly enables much greater capability. By replacing the Crabinator attachment on the TerminatorBot mentioned in the prior work with the 2-D tread module, we not only provide motive force in both the longitudinal AND transverse modes, but the hybridization results in so much more by enabling holonomic motion. In an actual mine disaster, a search attempt had to be aborted because the robot could not move sideways. This failure demonstrates the need for such holonomic capabilities in USAR targeted robotic platforms.

But in order for these capabilities to be beneficial, the platform that possesses them must be operable. A huge contributing factor to the success of the PackBot is its user interface and ease of operation. Typically, firefighters get 40 hours of training with a new tool, so if control of a robot can't be mastered in that time it won't do much good. Conventional tracked robots require only a video game level of interaction and are simple to control for people with little training. For USAR environments though, we need greater capability (and therefore complexity) than conventional tracked robots can provide. The TerminatorBot provides more capability but is too difficult to control for untrained operators. It is expected that complexity can be managed with the 2-D tread module. Since the tread module is modular, its hybridization can be as complex or as simple as the situation requires and the training of the operator allows. Also, because the tread module enables holonomic motion in a hybrid robot such as the MOTHERSHIP, the robot can move in any direction regardless of pose. This should allow a relatively inexperienced operator to control motion of the robot without worrying about the pose as well. Then as operators gain more experience they can take full control over the robot and command more complex tasks.

To allow for the expansibility, as well as the maintenance, of the 2-D tread module, its parts have been fabricated in large quantities by injection molding. This will also allow us to make multiple copies for field trials and experimentation.

IV. DESIGN AND INITIAL TESTING OF THE 2-D TREAD MODULE

A. Module Design

The initial design concept for the 2-D tread module was inspired by the Crabinator attachment mentioned in the Prior Work. This hybridization of the one DOF tread attachment with the TerminatorBot provided transverse brute force, but actually impeded motion in the longitudinal mode. Hence the need for the elaborate tread grouser design detailed in [10]. Unlike the Crabinator though, this 2-D tread mechanism can provide motive force in the longitudinal direction, as well as the transverse. The 2-D tread module presented in this paper is a scaled up version, first explored in [11], from a miniature 75mm diameter Terminatorbot attachment to roughly the diameter of a basketball. This enlarged version is targeted towards tread/limb 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 unstructured environments.

The 2-D tread module 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 supported by a pair of ring gears. These gears make up two opposing non-traditional planetary gear sets as shown in Fig. 2. One of the goals of this design was to eliminate moving motors. In [12], the motor mounted inside the tread must roll with the sideways motion of the crawler, requiring a slip ring arrangement for wiring. In our mechanism, the outer ring of treads is mounted onto a stationary motor core by a set of idler gears. Because the idler gears are mounted to the outer tread assembly, they can rotate about the stationary motor core as the ring gears rotate. Referring to Fig. 2; in the stationary motor core (1), torque is transmitted from the motor drive gear (2) to the inner ring gear (4) which is supported 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) 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). This gear arrangement is reflected on the reverse side of the tread module resulting in two opposing gear sets, giving the module two degrees of freedom.

Depending on the relative motion between the two drive gears, the tread assembly can rotate about the stationary core to provide transverse motion of the module or the treads can be driven to provide longitudinal motion or an arbitrary combination of the two can be achieved. The tread pulleys are driven in opposition, such that if both sets of ring gears are driven in the same direction, the treads are locked longitudinally since the ring gears are trying to pull the tread against itself. Because the treads are locked, the outer ring gears and intermediate idler gears cannot spin, so the entire tread assembly rotates with the motion of the inner ring gear as the motor core remains stationary, as illustrated in the top of Fig. 3. Conversely if the ring gears are driven in opposite directions, the treads do not rotate about the core but are instead driven longitudinally, as illustrated in the bottom of Fig. 3.

B. Design Considerations

In the design of the 2-D tread module, we had to consider high centering and tread coverage, which are common issues for mobile, treaded robots. High centering occurs when a ”dead” area of a robot, which does not actively drive it forward, gets stuck on an obstacle and prevents the robot from moving. This issue can potentially immobilize a robot in the field and cause a mission failure. To limit the chance of high centering most robots attempt to minimize ”dead” areas, for treaded robots this means getting as much tread coverage as possible. The OmniTread robot [13] covers all four sides of its square cross section with synchronized treads that are driven by a single motor so that they move in unison, regardless of which side is in contact. Souryu [14] rather than wrapping treads around all sides of its body, has a much flatter rectangular cross section. This body composition minimizes the chance that the robot will get stuck on its side and so it only needs one wide tread wrapped around the top and bottom sides to maximize tread coverage.

Fig. 3. Illustration of (top) transverse motion due to like ring gear velocities and (bottom) longitudinal motion due to opposing ring gear velocities.

Ideally, our 2-D tread module would have 100% tread coverage, but that is a difficult feat with a circular cross section as the tread would have to be narrower on the inside of the tread assembly. The toroidal skin drive snake robot by McKenna et al [15] and the Omnicrawler by Tadakuma et al [12] exhibit impressive solutions to this problem and achieve nearly 100% tread coverage over a circular cross section. The toroidal skin snake wraps its entire body with a flexible skin that runs from head to tail and then recirculates internally to provide continuous propulsion over the entire body. The Omnicrawler has a sausage-like tread that runs in two halves on either side. Both treads are driven in unison, but have a narrow split between them to allow a central shaft to penetrate the tread lengthwise. Rather than strive for 100% tread coverage, the 2-D tread module takes advantage of its longitudinal and transverse motion capabilities to minimize the potential for high centering. The 2-D tread uses ten discrete treads spread over its circular cross section, which makes up only about 50% tread coverage. Normally this

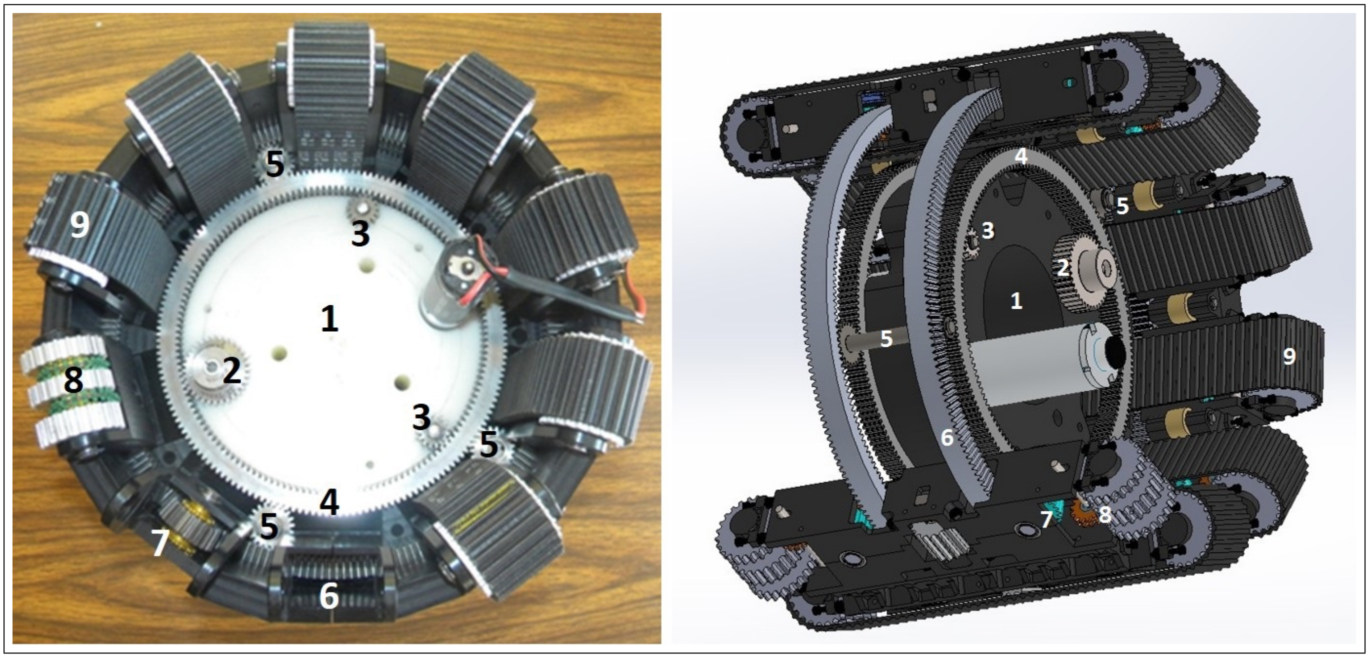

Fig. 2. Closeup view of the 2-D tread module, highlighting the gear arrangement.

would result in nearly half of the surface area being a ”dead” spot. However, since we have control over the transverse motion, we can simply rotate the module so that at least one tread is always in contact with the ground. Because we can ensure that the treads of the module will always be in contact, we can assume an apparent tread coverage of 100%.

C. Preliminary Testing

Some preliminary tests have been conducted to determine the performance of a single tread module and are outlined in this section. These tests include a pull test to determine the maximum pull force a tread module can exert by actuation of the treads on a variety of surfaces commonly found in USAR environments. Also we have determined the top speed at which the tread module can travel on level ground in both the longitudinal and transverse directions. Finally we constructed a test bed to confirm the expected holonomic locomotion capabilities of the 2-D tread module. The results of these tests as well as some dimensional specifications of the tread module are displayed in Table I.

To determine the maximum pull force on each of the three surfaces, a scale was grounded and immobilized then attached to the tread module. The motor velocities were steadily increased to ramp up the tread (longitudinal) speed of the module until the treads began to slip and the maximum pull force was recorded immediately before the treads began to slip. Increasing the traction between the treads and surface would allow for a greater pull force, as the limiting factor here was slippage.

TABLE I

SINGLE MODULE PRELIMINARY RESULTS

Module Length	240 mm
Module Diameter	270 mm
Module Weight	9.23 kg
Max Pull (carpet)	5.65 kg
Max Pull (plywood)	3.11 kg
Max Pull (linoleum)	3.12 kg
Top Longitudinal Speed	0.847 m/s
Top Transverse Speed	1.219 m/s

The top speed in the two dimensions was recorded on level, linoleum tile flooring. 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. 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 traveled a distance of four feet.

To confirm the expected holonomic motion capabilities of the tread module, the test bed shown in Fig. 4 was used to immobilize the motor core of the module while the treads were actuated. It was observed that for arbitrary sums and differences of the two motor velocities, the tread module produced arbitrary combinations of longitudinal and transverse motion.

V. MODULARITY AND VERSATILITY OF THE 2-D TREAD MODULE

The 2-D tread module is designed in a modular way to allow for varied configurations so that an operator can tailor the configuration to the specific task space they are presented with as well as to introduce as much or as little complexity into the system as is needed and as they are comfortable with. Generally we have been exploring the hybridization of the 2-D tread module with simple two degree of freedom articulating joints due to the success other platforms have had with similar limb mechanisms. We have

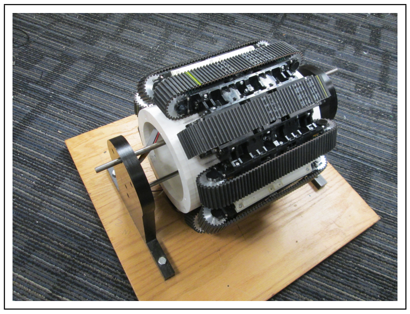

Fig. 4. The 2-D tread module test bed for confirmation of holonomic capabilities.

also explored a differential drive configuration, pictured in Fig. 5, consisting of two tread modules with a rigid center link. This configuration is similar in scale and functionality to the UMN Mega Scout [16] with the added benefit of holonomic locomotion.

Fig. 5. The 2-D tread module configured as a holonomic differential drive platform.

The MOTHERSHIP hybrid serpentine configuration shown in Fig. 1 is similar to the OmniTread and Souryu platforms which both have relatively sophisticated track mechanisms linked serially with relatively simple limb mechanisms. The MOTHERSHIP configuration is shown with three 2-D tread modules, but it is easily expandable to a four, five, or n link hybrid robot. In fact, because of the circular cross section of the module, it may prove necessary to add additional modules from a stability stand point. The circular cross section allows the tread module to move transversely, but it also essentially reduces contact to a line contact, as opposed to the large plane of contact gained from a rectangular cross section. In certain situations, the MOTHERSHIP may exhibit some undesired rolling depending on where the center of gravity is located relative to the base of support. For example, if the MOTHERSHIP is positioned in a straight line, the base of support will just be a line along the central body axis making the robot marginally stable. It wouldn't take much to send the robot rolling in this case. By positioning the MOTHERSHIP in a zigzag configuration, we can expand the base of support to be a wider area and make the robot far more stable. But as soon as a module is raised to overcome an obstacle, the base of support shrinks and can cause the robot to fall into the position of lowest energy. Adding a fourth module would help with stability by expanding the base of support.

When developing hybrid configurations for the tread module we must also consider regularity. By regularity we mean constant frequency of tread modules and limbs. Regularity can prove troublesome if the spatial frequency of the robot matches that of the environment. An example of this is shown in the top of Fig. 6 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, it would be far less efficient and far more complex than simply rolling. By introducing some irregularity into the hybrid configuration, such as in Fig. 7, 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. 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.

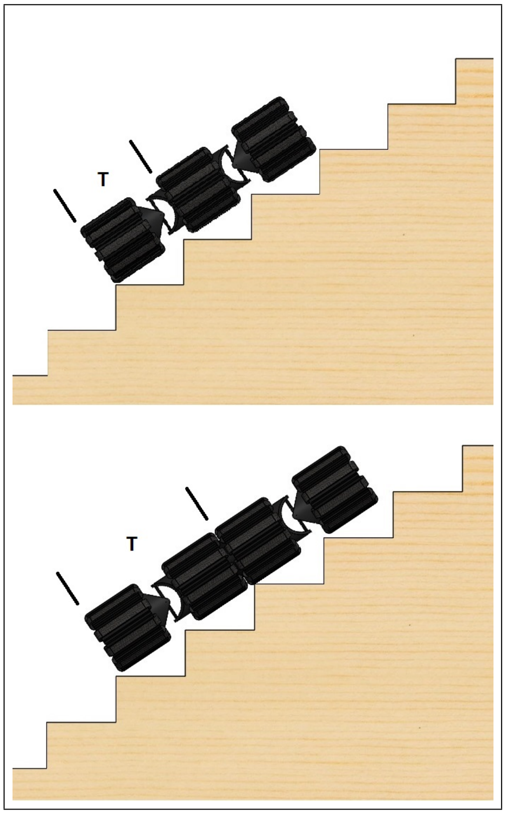

Fig. 6. Illustration of the potential benefit of breaking up regularity in a hybrid configuration. T denotes the period of the robot configuration.

VI. CONCLUSIONS

In this paper, we have presented a novel tread mechanism with a circular cross section that is capable of exerting

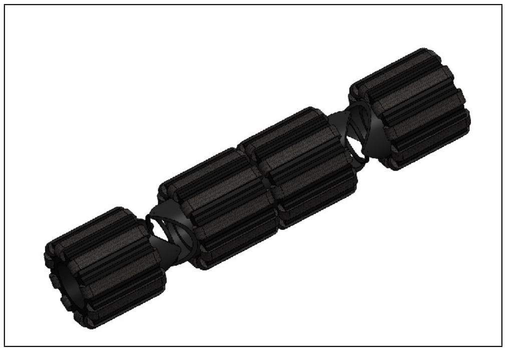

Fig. 7. The 2-D tread module configured as an irregular four link hybrid robot.

motion in two orthogonal directions. Hybridization of this tread module can greatly expand its capabilities. We have presented a tread/limb serpentine hybrid configuration based on this 2-D tread module which we call the MOTHERSHIP. By adding simple articulating joints to the modules, we enable capabilities for holonomic motion as well as overcoming obstacles and climbing up stairs. With these added capabilities the MOTHERSHIP is suitable for urban search and rescue applications. We also expect that the modularity of the tread mechanism design and the holonomic capabilities it enables will allow the operator to manage the level of complexity of the hybrid system, making it as simple or complex as the situation requires and the skill of the operator allows.

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