Using Manipulation to Enable Adaptive Ground Mobility

Raymond Kim[1], Alex Debate[1], Stephen Balakirsky[2], and Anirban Mazumdar[1]

***Abstract*— In order to accomplish various missions, autonomous ground vehicles must operate on a wide range of terrain. While many systems such as wheels and whegs can navigate some types of terrain, none are optimal across all. This creates a need for physical adaptation. This paper presents a broad new approach to physical adaptation that relies on manipulation. Specifically, we explore how multipurpose manipulators can enable ground vehicles to dramatically modify their propulsion system in order to optimize performance across various terrain. While this approach is general and widely applicable, this work focuses on physically switching between wheels and legs. We outline the design of "swappable propulsors" that combine the powerful adhesion forces of permanent magnets with geometric features for easy detachment. We provide analysis on how the swappable propulsors can be manipulated, and use these results to create a functional prototype robot. This robot can use its manipulator to change between wheeled and legged locomotion. Our experimental results illustrate how this approach can enhance energy efficiency and versatility.**

***Index Terms*— Mechanism design, mobile manipulation, wheeled robots.**

I. INTRODUCTION

Mobile robots can aid search and rescue, explore remote locations, and scout conflict zones [1]–[3]. To execute such missions, terrestrial mobile robotic platforms must traverse through unpredictable terrain that can have large variations in height, friction properties, and grade. While autonomous mobility on paved roads has progressed considerably, off-road and rugged terrain remain challenging due to their highly variable physical properties. Off-road terrains are particularly difficult for autonomous robotic systems because an individual mode of locomotion may degrade when conditions change.

This paper presents a new approach to adaptive terrestrial locomotion. The core contributions of this work are: 1) formulating a new manipulation based framework for adaptation, 2) designing a magnet-based design for swappable propulsors, 3) experimental results illustrating the energy efficiency and versatility benefits from using this method of adaptation. To the best of our knowledge, this paper is the first to use manipulation to enable adaptive mobility of unmanned ground vehicles.

Existing terrestrial locomotion strategies can be categorized into three different areas: static, passive-adaptive, and active-adaptive. Static methods consist of mechanical systems that are designed to perform well on a range of surfaces, but do not modulate their physical form for different terrain. Biologically inspired cockroach robots are good examples of such systems, and can operate on varying terrain [4], [5]. Similarly, the RHex robot uses six semicircular legged wheels to walk over a range of surfaces [6]. Because static methods do not adjust their behavior on different surfaces, they can be simple and robust. However, fixed structures cannot be easily changed and therefore are suboptimal on one or more types of terrain.

Fig. 1. A prototype implementation of the swappable propulsor robot.

In contrast, passive-adaptive methods adjust their properties without centralized sensing or control. Wheels that can passively change their radius have been developed to better traverse their given environment [7], [8]. Other systems offer the ability to completely change their physical configurations for new modes of locomotion [9]–[11]. The inability to control these adaptation behaviors means that they may deploy in conditions where such changes are undesirable. Additionally, these approaches add mass and mechanical complexity to wheels or legs. This can modify the vehicle dynamics and risk failure.

Active-adaptive methods require energy and control to modify their mode of locomotion. These approaches offer the greatest degree of flexibility and optimality. Recent works have presented vehicles that can actively change their wheel diameter or articulate their suspension on different terrains [12], [13]. Other designs are capable of actively lengthening or repositioning their mechanical components to better traverse a given terrain [14]–[19]. Active methods also provide the capacity to transform between wheels and legs [20]–[23]. Active-adaptive designs hold great promise, but in order to maximize performance they must use low power, have minimal complexity, and be physically robust.

In this paper, we propose a new approach that uses manipulation to combine the simplicity and robustness of static methods with the controllable versatility of active-adaptive

[1]R. Kim, A. Debate, and A. Mazumdar are with the G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332 email: rsk@gatech.edu

[2]S. Balakirsky is with Georgia Tech Research Institute, Atlanta, GA 30318 email: Stephen.Balakirsky@gtri.gatech.edu

approaches. We explore how robots can utilize multi-purpose manipulators to modify their legs or wheels for different terrain. To ensure generality, we refer to features that propel the vehicle as "propulsors." Propulsors can include wheels, legs, propellers, whegs, or tracks. The use of manipulation enables discrete switching between propulsors. This concept of "swappable propulsors" enables a broad range of adaptations. We liken this approach to how humans change shoes for different types of terrain. The ability to change shoes enables a broad range of locomotion capability. This can enable motion over varying terrain (running shoes and cleats), to different modes of locomotion (shoes and roller skates), and even locomotion in fluids (shoes and flippers).

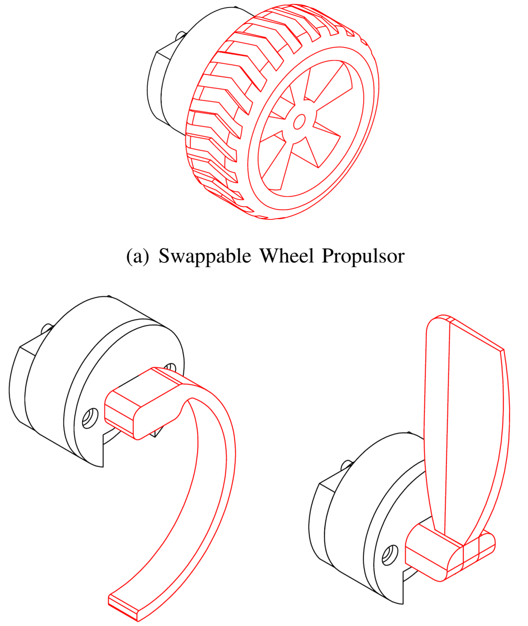
We begin by outlining a set of functional requirements for the swappable propulsor framework that can enable a range of adaptations. We then describe a specific design of swappable propulsors for legs and wheels which exploits directional magnetic forces for strong attachment and easy detachment. Finally, a unique prototype robot (shown in Fig. 1) is designed, fabricated, and experimentally evaluated. The experimental results illustrate the merits of this new approach.

II. Swappable Propulsor Framework

A. Functional Requirements

This section describes the functional requirements for the swappable propulsor framework. We envision that these requirements are applicable to many types of propulsors. Fig. 2 illustrates the concept of swappable propulsors. A mobile robot can carry around multiple sets of swappable propulsors, each assigned to its own unique terrain. These propulsors are all designed to mount into a single housing and can be easily attached or detached. The swappable wheel propulsor is an ideal choice for energy-efficient propulsion on flat surfaces, whereas the swappable leg propulsor is appropriate for rugged, off-road terrain. The swappable fin propulsor can enhance versatility by enabling the robot to move effectively in water.

1) ***High holding force***: When swapping propulsors, the system must have reliable attachment to keep its propulsors in place. Once swapped, the propulsor should enable the robot to traverse the propulsor-specific terrain without the risk of detaching or losing its functionality.
2) ***Low-force detachment using manipulator***: The propulsors must be easy for the manipulator to detach when the system is switching its mode of locomotion. The force needed to detach the propulsor should be small enough for the manipulator to execute reliably and repeatedly.
3) ***Electro-mechanically simple***: Swappable propulsors should not add substantial complexity or mass to the interface between the robot and the terrain.
4) ***Easily manipulated***: The swappable propulsors should be lightweight and have shapes or geometric features that can be exploited for reliable grasp and manipulation.



(a) Swappable Wheel Propulsor

(b) Swappable Leg Propulsor (c) Swappable Fin Propulsor

Fig. 2. This figure illustrates the framework of the swappable propulsor. Different types of swappable propulsors (red) can be incorporated into a single housing (black).

Since the principle of swappable propulsors is new, our search of existing works did not provide an existing system that meets all four functional requirements. Therefore, we developed our own system based on permanent magnets and geometric features.

B. Magnet Embedded Propulsors

Permanent magnets enable large force capacity with zero power consumption. However, this high force also makes permanent magnets difficult to detach. If the manipulator is used to simply pull the propulsor perpendicular to the steel surface (y-direction), Fig. 3 demonstrates that the detachment force F_B would have to be greater than or equal to the magnetic force F_{mag}. This method would require a powerful manipulator that would add considerable mass and complexity to the robot.

Geometry can be exploited to enhance manipulation-based detachment [24]. Consider a swappable leg propulsor that has an extrusion with an angled edge so that it can rotate about point A (as shown in Fig. 3). In this case, r is the distance from the center of the magnet to the angled edge, and the resulting moment created by the magnetic force about point A is $F_{mag}r$.

If a force F_C is applied at the tip of the propulsor (point C) in the positive y-direction, it will produce a moment $F_C h$ about point A. If this moment is greater than $F_{mag}r$, the propulsor will begin to tilt.

$$F_C > \frac{r}{h} F_{mag} \tag{1}$$

F_C becomes significantly smaller than the magnetic force F_{mag} as the propulsor length h becomes longer than r. As

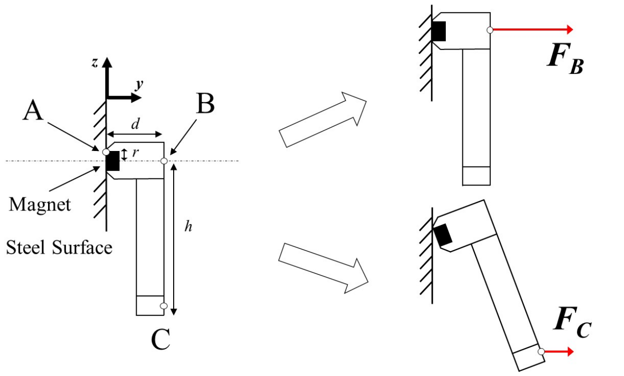


Fig. 3. A schematic illustration of the propulsor dimensions and the tilting propulsor concept. Tilting the propulsor requires significantly less force than pulling it off the steel surface. Once the propulsor is tilted, it can be detached easily.

a result, tilting should become much easier as the propulsor rotates. This methodology can enable a much lighter and simpler manipulator.

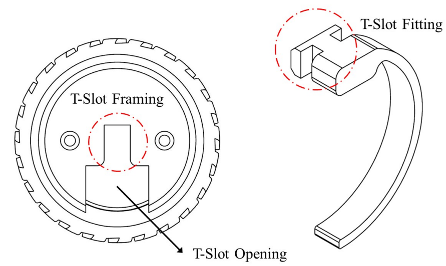
C. Mechanically Constraining Steel Surface Mounts

When used for locomotion, the swappable propulsors must be mechanically constrained to avoid undesired detachment. This consideration must be balanced with the need to detach the swappable propulsors with low forces and a simple grasp strategy.

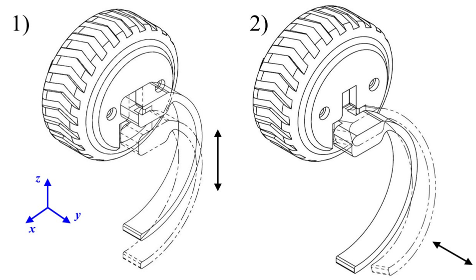
To constrain the propulsors on the robot, a steel surface mount with mechanical frames can be utilized. As shown in Figure 4(a), the steel surface mount consists of a t-slot opening, framing, and fitting. The t-slot opening provides room for attachment and detachment of the propulsors while the t-slot framing constrains the magnet embedded propulsor in every direction but the z-direction. Different types of propulsors can be placed on the steel surface mount, but the t-slot must be oriented to ensure that the propulsor does not detach during locomotion. For instance, the swappable leg-wheel propulsor design shown in Fig. 4, must be mounted such that the semicircular appendage is pointing in the negative z-direction. The t-slot framing would react to any forces applied during motion.

The attachment process of the propulsor must be simple enough for the manipulator to execute reliably and repeatedly. The t-slot fitting, which has an embedded magnet, is easily attached to the t-slot opening, that consists of a ferrous stainless steel surface (illustrated in Fig. 4-a). This minimizes the need for precise positioning of the end-effector when attaching the magnet embedded propulsor. If the manipulator approaches the t-slot opening within the magnetic attraction force threshold, the embedded magnet will attach itself. Once attached, the propulsor can be slid across the steel surface to the end of the t-slot framing to be constrained. With fixed positions of the steel surface mount on the robot, the end-effector and the mount can be coordinated to attach the propulsors.

The swappable propulsor framework combines two sequential linear motions to detach the propulsor from the surface mount. The first motion consists of a linear drag in the negative z-direction (illustrated in Fig. 4-b). The second motion consists of a linear pull in the positive y-direction. Once detached, the propulsors can be stored in the mobile robot.



(a) T-Slot Design.



(b) Detaching motion of the propulsor.

Fig. 4. A sliding motion is required to release the magnet embedded propulsor from constraint. Figure 4(a) illustrates the T-slot couplers on the swappable leg-wheel propulsor design. Figure 4(b) illustrates the sequential motion of the propulsor detachment. The sliding linear motion is followed by a lifting linear motion.

III. Manipulator: Static Analysis

To make full use of the swappable propulsor, the manipulator must be able to achieve the kinematics and kinetics of attaching and detaching the swappable propulsors. For this study, a five degree of freedom (5 DOF) serial robotic manipulator was considered for a swappable leg-wheel propulsor. The 5 DOF was chosen to ensure that the manipulator can reach objects in proximity and in distance. The wrist joint was integrated to exploit the geometric features of the propulsors. With Eq. 2, Jacobian static analysis can be used to predict the manipulator joint torques required to detach a swappable propulsor. This analysis can then be used to either design the manipulator or the swappable propulsor. Using the two linear motions discussed in the previous section, Fig. 5 illustrates these motions as static forces on the end-effector frame.

$$\tau = J^T f \tag{2}$$

$$f_{slide} = \begin{bmatrix} -F_{x_6} & 0 & F_{z_6} & 0 & 0 \end{bmatrix}^T \tag{3}$$

$$f_{pull} = \begin{bmatrix} 0 & F_{y_6} & 0 & 0 & 0 \end{bmatrix}^T \tag{4}$$

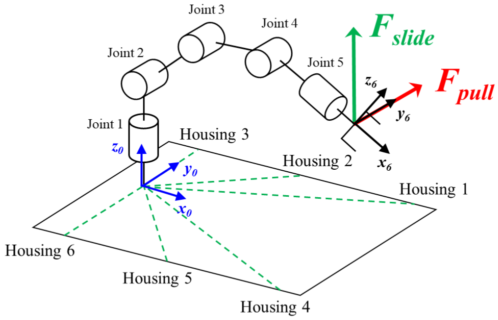


Fig. 5. An illustration of the manipulator configuration and layout with static forces for propulsor detachment.

Since the kinematics of serial manipulators are well known, we do not repeat them here. Equations (3) and (4) represent the static forces for the detachment. The analysis outlined here can be used to determine the joint torques when detaching a swappable propulsor and then moving it. These results can be used to design the swappable propulsor based on a known manipulator, or design the manipulator based on the known swappable propulsor.

IV. Implementation

A. Chassis Design

The swappable propulsor prototype was designed, fabricated, and experimentally evaluated. The motor mounts and the body cover were 3D printed on a Lulzbot TAZ 6 printer with Polylite PLA material. The storing base of the swappable legs were 3D printed and embedded with 3.175 mm neodymium magnets. The prototype is approximately 363 mm long, 230 mm wide, and weighs approximately 1.6 kg including the battery and all electronic components.

B. Swappable Leg-Wheel Propulsor

To ensure simplicity, the leg propulsor was designed to be swappable while the common housing was designed as a wheel propulsor. This allows the system to revert to wheel propulsors once the swappable leg propulsor is removed. The wheel propulsors consist of 3D printed wheel housings and rubber tires. A 3D printed t-slot framing is mounted on top of the wheel propulsor. 0.635 mm thick 430 stainless steel sheet was used to create the steel surface mount. The leg propulsors were 3D printed and embedded with 6.4mm nickel plated neodymium magnets each rated at a maximum of 5.39 N.

The amount of force to slide the propulsor was approximately 0.88 N for this prototype. The amount of force to pull the propulsor by exploiting directional forces was no more than 0.1 N.

C. Actuator Selection

Since the swappable propulsors are relatively lightweight, the manipulator joint torques are primarily dependent on the detachment forces. Using Eq. 2 and substituting the forces defined above into Eq. 3 and 4, the maximum joint torques for each joint in N-m were computed to be:

$$\tau_{max} = \begin{bmatrix} 0.042 & 0.176 & 0.132 & 0.0968 & 0.0968 \end{bmatrix}^T \quad (5)$$

D. Modes of Locomotion

The robot employs six Dynamixel XL-320 position-controlled servos during its leg mode and wheel mode. A Pololu 7.5V, 2.6A step-down voltage regulator was used to power the XL-320 servos.

$Wheel\ Mode$: Proportional + Derivative (PD) control was implemented for the robot's wheel mode. The robot disables torque on the two middle wheels and the manipulator during its wheel mode.

$Leg\ Mode$: The MiniRHex open source software is used to operate in leg mode [25]. A tripod gait pattern was used for legged locomotion.

(a) Wheel mode.

(b) Leg mode.

Fig. 6. The swappable propulsor prototype has two different modes of locomotion. Figure 6(a) shows the robot in wheel mode. Figure 6(b) shows the robot in leg mode.

E. Manipulator

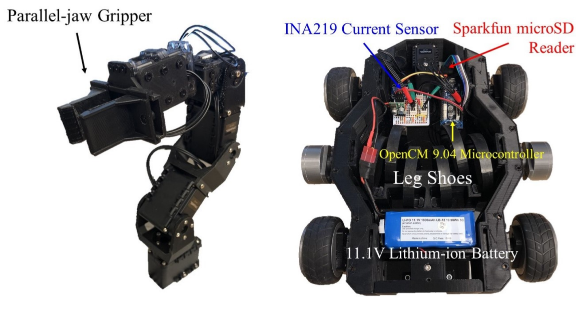
Based on the maximum torques calculated (Eq. 5), joints 4 and 5 were assigned with smaller actuators to reduce the size and weight of the manipulator. For consistency, the gripper was also reduced in size. The manipulator consists of three Dynamixel AX-12A servos and three Dynamixel XL-320 servos (shown in Fig. 7-a). The sixth XL-320 servo is used as a gripper. A parallel-jaw gripper was custom designed and 3D printed. The manipulator is mounted on the rear of the robot for maximum workspace. As with other mobile manipulators, this system can be used for a range of purposes, including sampling the environment, manipulating objects, and positioning sensors. The maximum payload of the manipulator when fully extended is: 350 g.

F. Control

The OpenCM9.04 microcontroller board was used in tandem with custom written Arduino IDE and OpenCM IDE software for the locomotion and manipulation of the robotic device. An 11.1 V, 1800 mAh lithium-ion battery was used to power the robot.

G. Measurement

An INA219 high side DC current sensor breakout board was used to measure the power consumption of the robot. SparkFun microSD transflash breakout board was used to record the data collected during experiments.



(a) (b)

Fig. 7. Figure 7(a) represents the 5 DOF prototype manipulator. The manipulator consists of five revolute joints and a parallel gripper to attach/detach the leg propulsor. Figure 7(b) illustrates the internal components of the robot.

V. Results

A. Overview

Experiments utilizing the prototype robot were carried out on a range of terrain. Energy consumption, distance traveled, and travel time were measured. These were used to determine cost of transport, which is a common metric for the energetic performance of mobile systems. The experiments are illustrated in the accompanying video. The swappable leg-wheel propulsor prototype was tested on four different terrains (concrete, grass, forest, and gravel). During the experiment, the robot was allowed to traverse through the given terrains at maximum actuator speed (114 rpm) over a straight 18 m course. Voltage and current of the battery were measured throughout the experiment. Using the measurements obtained, battery power, energy consumption, and cost of transport (COT) were calculated using Eq. (6), (7), and (8).

$$\text{Battery Power} = V_{battery} \times I_{battery} \tag{6}$$

$$\text{Energy} = \int_0^t BatteryPower(t)\ dt \tag{7}$$

$$\text{Cost of Transport} = \frac{Energy}{mass \times gravity \times distance} \tag{8}$$

B. Legged vs. Wheeled Locomotion

To provide a baseline illustration of the trade-offs between wheeled and legged locomotion, we performed a series of experiments with wheels and legs. These did not include the manipulator. The wheels performed well on concrete (flat ground), but eventually failed to advance on grass, forest, and gravel. The legs utilized a tripod gait [6], and were able to traverse all terrain. These experiments are shown in the accompanying video.

These results illustrate the widely known versatility of legs [26]. Consequently, there is a tendency to only use legs to traverse a broad range of terrain. However, as Fig. 8 illustrates, wheels were more energy efficient than legs on flat concrete surface. The robot in legged locomotion drew an average power consumption of 6.5 W, whereas the wheeled locomotion drew an average power consumption of 4.287 W. The COT of legged locomotion was 3.087, while the COT of wheeled locomotion was 1.106. Since flat ground is very common, this illustrates the need to swap propulsors.

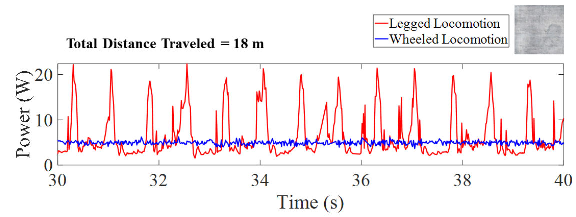


Fig. 8. Power consumption measurements on flat concrete surface over 18 meters. Average power consumption for legged locomotion was 6.5 W. Average power consumption for wheeled locomotion was 4.287 W.

C. Adding the Manipulator

Since wheels provide substantial energetic improvements on flat ground, manipulation can be used to transition to wheels for long stretches of flat ground. However, if the added mass from the manipulator increases power dramatically, then such a strategy is not viable. Therefore, we conducted additional experiments with the manipulator added. For this comparison, power is a better metric than cost of transport because the manipulator does not participate in active locomotion. The results, shown in Table I, illustrate that the added mass of the arm only increases the wheeled and legged power consumption slightly. Therefore, the use of the arm to switch to wheeled mode is a viable strategy for increasing energetic performance.

TABLE I
Swappable Leg-Wheel Propulsor Robot Power Consumption Values

Mode	Power (W)	Energy (J)	Mass (kg)	Distance (m)	Time (s)	COT
WHL[a]	4.287	263	1.346	18	50	1.106
WHL-A[b]	4.440	268	1.566	18	50	0.970
LEG[c]	6.500	762	1.4	18	110	3.087
LEG-A[d]	6.558	930	1.62	18	136	3.253

[a] WHL: Wheeled Locomotion.
[b] WHL-A: Wheeled Locomotion Manipulator Attached.
[c] LEG: Legged Locomotion.
[d] LEG-A: Legged Locomotion Manipulator Attached.

D. Performance of Fully-Integrated System

With the benefits of manipulation clearly demonstrated, we performed a number of experiments to illustrate the performance of a fully functional prototype. The manipulator was incorporated into the vehicle and the vehicle used the optimal mode of locomotion on four surfaces. Flat concrete featured wheeled locomotion, and the COT was 0.97. This represents a roughly three-fold decrease when compared to the legged results on concrete. For grass, gravel, and forest, the optimal mode was legged (COT was infinite for wheeled due to getting stuck). The COT was 3.3 for grass, 5.3 for forest, and 6.7 for gravel. The time histories are shown in Fig. 9.

Fig. 9 shows how the swappable leg-wheel propulsor robot in leg mode was successful on terrains the wheel mode failed to traverse. The leg mode consumed least amount of energy on grass with average battery power draw of 5.23 W and COT of 3.312. The leg mode had the highest power draw on gravel which had the most uneven surface.

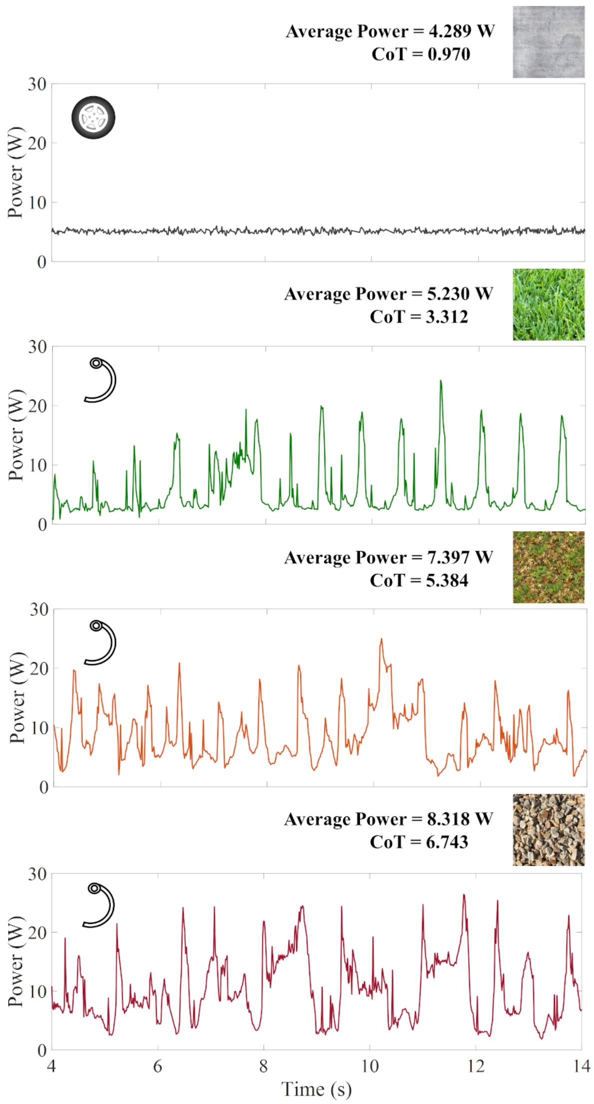


Fig. 9. Power consumption of the swappable leg-wheel propulsor robot on various terrains at maximum actuator speed (114 rpm) over 18 meters.

E. Using Manipulation to Enable Adaptive Mobility

To evaluate the adaptive mobility aspect of the swappable leg-wheel propulsor design, the manipulator was given forward kinematic control commands to attach the leg propulsors to its wheel propulsors. Using known coordinates of each t-slot openings, the 5 DOF manipulator and the wheels were coordinated to place the legs. The robot switching its mode from wheel mode to leg mode has been illustrated in Fig. 10. The process to swap a single propulsor took 13 seconds. Future studies will look to optimize the speed and robustness of swapping propulsors.

VI. Conclusion

In this paper, we presented a new approach to adaptive terrain locomotion. We formulated a unique manipulation-based framework for adaptation that exploits a combination of the powerful adhesion forces of permanent magnets with geometric features for easy detachment. We analyzed how the swappable propulsors can be manipulated in simple linear motions and used these results to create a functional prototype robot. We specifically focused on the leg-wheel propulsors to demonstrate that changing modes for a specific terrain can be energy efficient. We also showed how adding a multi-purpose manipulator does not signficantly change the power consumption of the robot during locomotion.

Our system was designed to be simple with minimal integration of sensors. Many methods including manipulation and terrain transition are currently open-loop or human-in-the-loop. Therefore, future work will focus on creating robust and rapid manipulation strategies. In addition, we are excited to examine how perception and mapping can be used to plan paths for these vehicles that minimize energy consumption. Such techniques would identify which terrain would require an adaptation and would use the adaptations to reduce overall energy expenditure. Lastly, there are other propulsors that merit further exploration, such as ones that enable transition between water and land.

Acknowledgment

The authors would like to thank David Booker-Earley, Eric Dong, Varun Madabushi, Avi Balakirsky, and all the DART Lab members for supporting this project.

(a) Grasp leg propulsor inside chassis.

(b) Detach from storing base.

(c) Attach to wheel propulsor.

(d) Slide propulsor to constrain.

Fig. 10. A photographic illustration of the swappable leg-wheel propulsor robot attaching a leg propulsor is shown.

REFERENCES

[1] D. F. Hougen, S. Benjaafar, J. C. Bonney, J. R. Budenske, M. Dvorak, M. Gini, H. French, D. G. Krantz, P. Y. Li, F. Malver, *et al.*, "A miniature robotic system for reconnaissance and surveillance," in *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065)*, vol. 1. IEEE, 2000, pp. 501–507.

[2] F. Matsuno and S. Tadokoro, "Rescue robots and systems in japan," in *2004 IEEE International Conference on Robotics and Biomimetics*. IEEE, 2004, pp. 12–20.

[3] B. M. Yamauchi, "Packbot: a versatile platform for military robotics," in *Unmanned ground vehicle technology VI*, vol. 5422. International Society for Optics and Photonics, 2004, pp. 228–237.

[4] R. D. Quinn, J. T. Offi, D. A. Kingsley, and R. E. Ritzmann, "Improved mobility through abstracted biological principles," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3. IEEE, 2002, pp. 2652–2657.

[5] J. M. Morrey, B. Lambrecht, A. D. Horchler, R. E. Ritzmann, and R. D. Quinn, "Highly mobile and robust small quadruped robots," in *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)(Cat. No. 03CH37453)*, vol. 1. IEEE, 2003, pp. 82–87.

[6] U. Saranli, M. Buehler, and D. E. Koditschek, "Rhex: A simple and highly mobile hexapod robot," *The International Journal of Robotics Research*, vol. 20, no. 7, pp. 616–631, 2001.

[7] D.-Y. Lee, G.-P. Jung, M.-K. Sin, S.-H. Ahn, and K.-J. Cho, "Deformable wheel robot based on origami structure," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 5612–5617.

[8] T. Aoki, H. Yamato, M. Shimaoka, and S. Mitsumori, "Study of omnidirectional all terrain mobile robot with globular metal spring wheel," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 5606–5611.

[9] Y.-S. Kim, G.-P. Jung, H. Kim, K.-J. Cho, and C.-N. Chu, "Wheel transformer: A miniaturized terrain adaptive robot with passively transformed wheels," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 5625–5630.

[10] Y. She, C. J. Hurd, and H.-J. Su, "A transformable wheel robot with a passive leg," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 4165–4170.

[11] J. Park, D. H. Kong, and H.-W. Park, "Design of anti-skid foot with passive slip detection mechanism for conditional utilization of heterogeneous foot pads," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 1170–1177, 2019.

[12] K. Nagatani, M. Kuze, and K. Yoshida, "Development of transformable mobile robot with mechanism of variable wheel diameter," *J. Robot. Mechatron*, vol. 19, pp. 252–253, 2007.

[13] K. Iagnemma, A. Rzepniewski, S. Dubowsky, and P. Schenker, "Control of robotic vehicles with actively articulated suspensions in rough terrain," *Autonomous Robots*, vol. 14, no. 1, pp. 5–16, 2003.

[14] Y.-J. Dai, E. Nakano, T. Takahashi, and H. Ookubo, "Motion control of leg-wheel robot for an unexplored outdoor environment," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS'96*, vol. 2. IEEE, 1996, pp. 402–409.

[15] F. Michaud, D. Letourneau, M. Arsenault, Y. Bergeron, R. Cadrin, F. Gagnon, M.-A. Legault, M. Millette, J.-F. Paré, M.-C. Tremblay, *et al.*, "Multi-modal locomotion robotic platform using leg-track-wheel articulations," *Autonomous Robots*, vol. 18, no. 2, pp. 137–156, 2005.

[16] J. B. Jeans and D. Hong, "Impass: Intelligent mobility platform with active spoke system," in *2009 IEEE International Conference on Robotics and Automation*. IEEE, 2009, pp. 1605–1606.

[17] J. A. Smith, I. Sharf, and M. Trentini, "Paw: a hybrid wheeled-leg robot," in *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.* IEEE, 2006, pp. 4043–4048.

[18] D. Zarrouk, A. Pullin, N. Kohut, and R. S. Fearing, "Star, a sprawl tuned autonomous robot," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 20–25.

[19] G. Endo and S. Hirose, "Study on roller-walker-energy efficiency of roller-walk," in *2011 IEEE International Conference on Robotics and Automation*. IEEE, 2011, pp. 5050–5055.

[20] T. Okada, W. T. Botelho, and T. Shimizu, "Motion analysis with experimental verification of the hybrid robot peopler-ii for reversible switch between walk and roll on demand," *The International Journal of Robotics Research*, vol. 29, no. 9, pp. 1199–1221, 2010.

[21] C. C. Phipps, B. E. Shores, and M. A. Minor, "Design and quasi-static locomotion analysis of the rolling disk biped hybrid robot," *IEEE transactions on robotics*, vol. 24, no. 6, pp. 1302–1314, 2008.

[22] K. Tadakuma, R. Tadakuma, A. Maruyama, E. Rohmer, K. Nagatani, K. Yoshida, A. Ming, M. Shimojo, M. Higashimori, and M. Kaneko, "Mechanical design of the wheel-leg hybrid mobile robot to realize a large wheel diameter," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2010, pp. 3358–3365.

[23] S.-C. Chen, K.-J. Huang, W.-H. Chen, S.-Y. Shen, C.-H. Li, and P.-C. Lin, "Quattroped: a leg–wheel transformable robot," *IEEE/ASME Transactions On Mechatronics*, vol. 19, no. 2, pp. 730–742, 2013.

[24] A. Mazumdar and H. H. Asada, "Mag-foot: A steel bridge inspection robot," in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2009, pp. 1691–1696.

[25] M. Barragan, N. Flowers, and A. M. Johnson, "MiniRHex: A small, open-source, fully programmable walking hexapod," in *Robotics: Science and Systems Workshop on "Design and Control of Small Legged Robots"*, Pittsburgh, PA, June 2018, workshop abstract.

[26] C. Ordonez, J. Shill, A. Johnson, J. Clark, and E. Collins, "Terrain identification for rhex-type robots," in *Unmanned Systems Technology XV*, vol. 8741. International Society for Optics and Photonics, 2013, p. 87410Q.