

DESIGN, PROTOTYPING, AND EXPERIMENTS USING SMALL-SCALE HELICAL DRIVE ROVER FOR MULTI-TERRAIN EXPLORATION

Ashwin Vadlamannati
North Carolina State
University
Raleigh, NC

Sumedh Bknalkar
North Carolina State
University
Raleigh, NC

Dustin Best
North Carolina State
University
Raleigh, NC

Matthew Bryant
North Carolina State
University
Raleigh, NC

Andre Mazzoleni
North Carolina State
University
Raleigh, NC

ABSTRACT

Rovers designed for polar exploration primarily operate in flat and arid central plateau of the Antarctic and are unsuitable for multi-terrain operation such as slushy snow, wet soil, open ice and open ocean. The Multi-terrain Amphibious ARctic explorer or MAARCO rover is a design concept that employs a pair of helical drives in order to traverse the diverse landscape of the Arctic for autonomous research missions. A small-scale prototype (3:10 scale) of the MAARCO rover was developed to test terrestrial motion. The prototype is a screw-propelled vehicle that has two helical drives (similar to Archimedes' screw) actuated by two independent motors to employ a differential steering system.

The prototype performed several different maneuvers on a dry and wet sand – moving in a straight line, turning left, and turning right, and moving sideways by controlling the rotational speeds of the two drives. The sensors on the prototype collect data on angular orientation, linear acceleration and motor rotations.

Through the tests the rover provided critical insight into the dynamics of the MAARCO rover; particularly, the effect of substrate failure or non-failure on the linear displacement of the rover. Further testing on different substrates and of the rover design on inclines surfaces will provide the MAARCO team valuable insight into designing a full-scale rover design.

1. INTRODUCTION

Global warming has caused melting polar ice and changing weather patterns. To study its effects in the inaccessible and hazardous polar regions, autonomous robots have been developed for data collection and experimentation. However, most robots have been deployed in areas of flat and mostly uniform terrain like the central plateau of Antarctica [1]-[5]. The focus on design simplicity and energy efficiency for long range missions limit the adaptability of these robots to varying terrains in the Arctic, which include snow, permafrost, ice-covered lakes,

sea ice, and open ocean. Current rover technology cannot meet the challenges of locomotion and autonomous navigation in such diverse and heterogeneous terrains, making it necessary for a robot deployed in the Arctic to be highly adaptable and capable of traversing both land and water.

The Multi-terrain Amphibious ARctic explorer, (MAARCO), is an innovative and proposed rover designed to traverse the diverse terrains of the Arctic. Its propulsion system employs a pair of helical drives or Archimedes' screws. The helical drives are screw-like rotating central cylinders with helical blades, which enable the vehicle to move across various surfaces. In soft/fluid substrate such as snow, mud, and melting ice, the helical blades push the surface medium backward and produce propulsion. The helical drives enable MAARCO to move both on water and under it. The hollow central cylinders of the helical drives provide buoyancy, allowing the rover to stay afloat while the rotating blades produce thrust, which enables it to move on the water surface. Conversely, the central cylinders can be flooded with water to make the rover neutrally buoyant, which enables it to operate underwater. While underwater, the rotating helical drives rotate to produce thrust. The variable buoyancy of the MAARCO rover, combined with its ability to move across different surfaces, makes it highly adaptable to the heterogeneous landscape of the Arctic.

Helical drives have been demonstrated as propulsion mechanisms in manned vehicles for over a century (Fig. 1). In the 20th century, SPVs were used for purposes of transporting cut logs in complicated mountain terrain [6],[7], on battlefields during the Second World War by both the United States and Russia [8]. However, due to limited understanding of the dynamics of helical drives or screw on different types of terrains, at the time, resulted in heavy and inefficient designs with low speeds and high-power requirements. Additionally, such vehicles were inefficient and prone to rapid wear on hard ground. While these characteristics make helical drives less practical and economical than conventional wheels or tracks for a typical

human-transport vehicle that operates primarily on roadways and firm ground substrates, their unique combination of snow, soft-ground, and water propulsion capabilities in a simple and compact mechanism may be ideally suited for a robotic Arctic rover.

In this paper, we present the design, fabrication, and experiments using a small-scale prototype of the proposed MAARCO rover. The prototype was built as a cost-efficient alternative to a full-scale prototype with the aim to develop a deeper understanding of the complicated dynamics of helical drives on different types of substrates. It is important to note that the tests were conducted on substrates and in test environments that are similar only in type and not in severity to the conditions in the Arctic. The prototype has also served to validate the terrestrial locomotion dynamics model developed by the group [9]-[10]. The results from this prototype along with the efforts of the group to model underwater propulsion of a rover with two helical drives [11]-[12] serve to inform in the creation of the full-scale prototype. Additionally, it has helped guide the effort in designing, and fabricating a full-scale prototype by avoiding pitfalls recognized during its design, fabrication, and assembly process. This paper discusses the tests performed using the small-scale prototype on dry and wet sand. However, work is in progress to test on different substrates such as snow, melting ice, and gravel under different loading conditions.

The paper is organized as follows:

Section 2 covers the rover design by separating the different components: the chassis, the drive electronics, and the sensor electronics. The section also delves into the motivation behind the different choices made in materials and components, which include size minimization, weight reduction and cost-effectiveness. In Section 3, preliminary results from the rover are discussed which will eventually assist in characterizing the dynamics of the MAARCO rover.

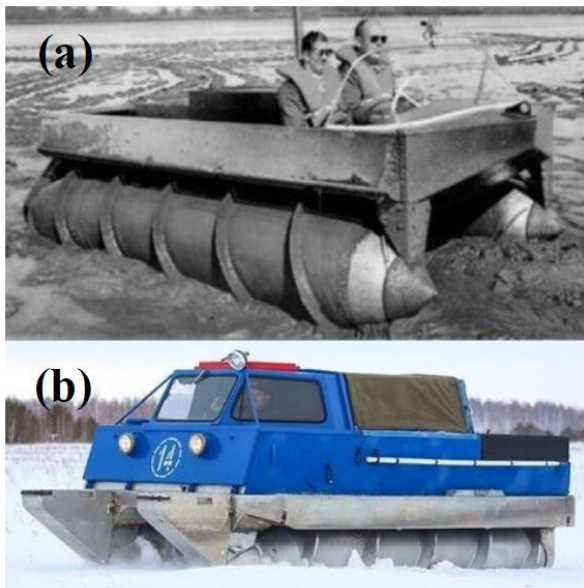


FIGURE 1: Screw Propelled Vehicles (SPV): (a) Marsh Screw Amphibian, and (b) ZiL 2906

2. DESIGN

The design of the small-scale prototype can be divided into four main components: chassis, helical drives, drive electronics, and sensor electronics. Each helical drive weighs 1kg while the chassis (including the drive electronics and sensors) weighs 3.95 kg. The total weight of the prototype is 5.95 kg. The overall dimensions of the prototype are 13.5'x8'x8.5' (LxWxH). Each component is described in detail in the following sections.

2.1 Chassis

The rover's chassis was designed with cost-effectiveness, modularity, and ease of manufacturing in mind. After several design iterations using off-the-shelf components, a 3/10 scale rover built from aluminum extrusion and plate was found to offer the best balance of these factors. The chassis' main plates are waterjet cut from 6061 1/4-inch-thick aluminum plate, which is relatively cheap compared to alternatives such as carbon fiber without sacrificing too much weight. The motor mounts were made from 1/8-inch 6061 aluminum plates for the same reason. The two main assembly plates are spaced apart using 1 x 2-inch aluminum extrusions, allowing for plenty of possible mounting points for sensors or additional components if needed in the future. The power from the motors is transmitted through pulleys and timing belts. The upper pulley is attached directly to the motor, and the lower pulley is attached to a drive shaft connected to the helical drive. The motor mount plate is designed to swing around one of the mounting holes as a means of tightening the drive belt. The driveshafts are supported by flange-mounted ball bearings, which were chosen for their good radial and axial load ratings.

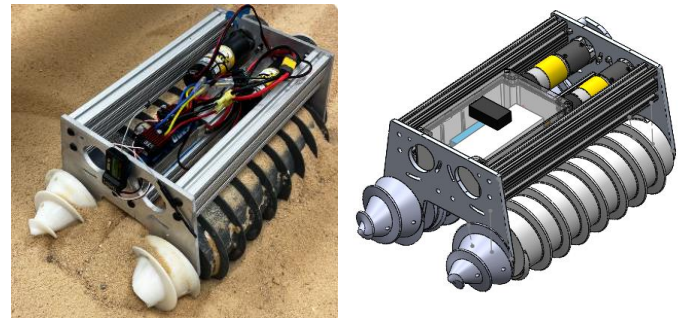


FIGURE 2: Rover in Action (left) and Model of Rover (right)

The rover is designed to be modular and can be easily disassembled by removing either the front or rear chassis plate allowing for easy and quick helical drive and drivetrain component swaps. The motor mounts are also easily removable and interchangeable so that different motors can be swapped out if needed. These features allow the rover to not only be easily repaired but also for the testing of various motor, drivetrain, and helical drive combinations with relative ease.

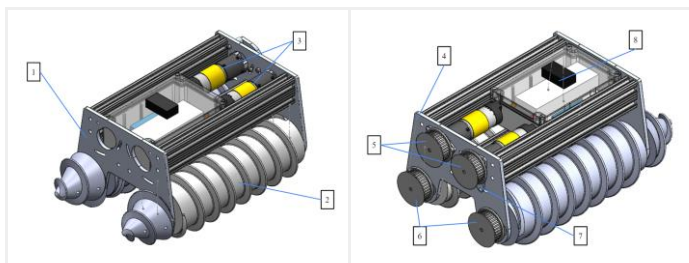


FIGURE 3: Components of the rover chassis: front chassis plate (1), helical drive (2), motors (3), rear chassis plate (4), upper pulleys (5), lower pulleys (6), motor mount plate (7), and electronics enclosure (8)



FIGURE 4: Helical Drives

TABLE 1: Helical drive dimensions

Helical Drive Property	Dimensions (inches)
Length	11.5
Cylinder diameter	3.5
Blade height	0.525
Pitch	1.44

2.3 Helical Drives

The dimensions of the helical drives have been listed in Table 1. This design of the helical drives was chosen based on the those used in the experimental setup described in [10]. For the prototype helical drives had a smaller ballast diameter compared to the experimental setup helical drives, however, the ballast diameter-to-blade height ratio and the pitch length was kept constant. Similarly, the length of the prototype helical drives was

shorter than that of the experimental setup helical drives. The helical drives were 3D printed using ABS filament. The helical drives were mounted to the chassis using custom made aluminum joints.

2.2 Drive Electronics

The rover's drive electronics consist of two brushed 12 VDC motors, one 11.1 V 3s LiPo battery, and two electronic speed controllers (ESCs) which can be controlled by either a radio-controlled (RC) receiver and transmitter or an Arduino microcontroller. A schematic for the drive electronics can be seen in Figure 5.

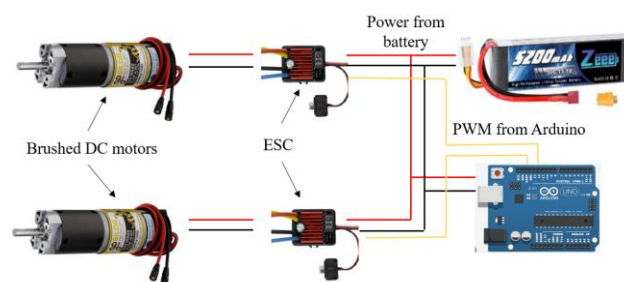


FIGURE 5: Drive electronics wiring diagram

2.2.1 Motors

The motor chosen for the rover is a brushed 12 VDC motor with an attached gearbox and a built-in rotary encoder. The gearbox is a 99.5:1 8-stage planetary gearbox, allowing the motor to deliver a stall torque of 133.2 kg.m [13]. However, that limits the maximum rotational speed to 60 RPM. The built-in rotary encoder is a dual-channel sensor so both RPM and direction of the motor can be determined. The maximum current drawn from the motor is 9.2 A, and the no-load current is 0.25 A.

The torque requirements for the small-scale prototype were estimated based on the steady-state operation of the bot in the experimental setup [10]. The weight and dimensions of the two systems were compared. After including a factor safety (higher amounts of torque are required to get from a state of rest to steady state motion), the motor torques were determined. Because the proposed MAARCO rover is a high-torque and low-speed system while moving on land, a relatively low speed of 60 RPM was deemed acceptable.

2.2.2 Electronic Speed Controllers (ESCs)

The ESC for the rover is a Hobbywing Quicrun 1060 brushed motor ESC. It receives a standard PWM signal and can accept power from 2s-3s LiPo batteries [14]. The maximum continuous current draw through it is 60 A, and it is rated to take a pulse current draw of up to 360 A. These ESCs are also water-resistant as they are intended to be used in 1:10 scale RC dirt racing cars. The ESCs are connected to the RC receiver and battery through a wiring harness and connectors, making them easy to replace or upgrade if necessary.

2.2.3 ESC Control

The control of a rover's motors is achieved through the use of Electronic Speed Controllers (ESCs) [15], which require only a Pulse Width Modulation (PWM) signal for operation. An Arduino microcontroller is used to send the PWM signals to the two ESCs which control the motors that actuate the left and right helical drives. A prescribed voltage is supplied to the ESC's which dictates the rotational speed of the motors and thereby the helical drives. By using an Arduino microcontroller, the rover can be programmed to follow a set path or perform specific tasks, thereby increasing the accuracy and reliability of the experiment results.

2.3 Sensor Electronics

The sensor electronics are what allow us to measure the pertinent metrics in order to construct and validate a dynamic model for the rover. These metrics include the current supplied going to each motor, the direction and RPM of each motor, and the orientation and acceleration of the rover. The sensor electronics wiring is completely independent of the drive electronics wiring except for the power source. This allows each of the wiring harnesses to be worked on separately and allows for components in each to be changed with ease. The data from all sensors is read using an Arduino and then recorded to an SD card also located on the rover that is retrieved after testing. The following sections provide additional information regarding the sensor electronics.

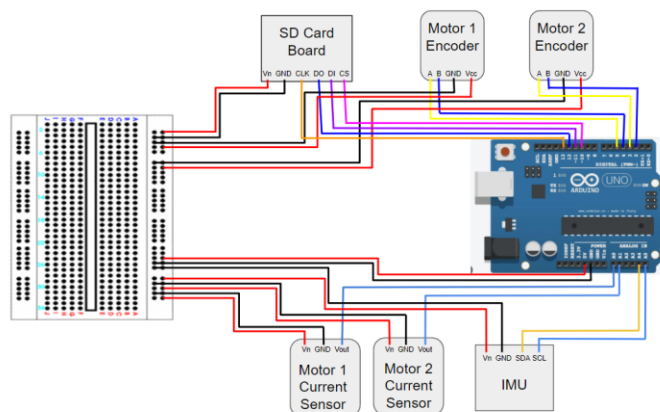


FIGURE 6: Sensor electronics wiring diagram

2.3.1 IMU

The IMU, or Inertial Measurement Unit, has an accelerometer, magnetometer, and gyroscope that allow the measurement of the unit's orientation as well as the applied rotational and transnational forces. The BNO055 Adafruit IMU [17] utilized here can measure absolute orientation (Euler Vector or Quaternion Output), angular velocity vector, acceleration vector, magnetic field strength, linear acceleration vector (acceleration not including gravity), gravity vector, and temperature. For this rover only the linear acceleration vector, absolute orientation, and gravity vector data will be collected.

2.3.2 Current Sensors

The current sensor is a bidirectional hall ACHS-7121 effect-based current sensor that has a range of -10 A to +10 A sensor and can measure current flow in either direction [17]. A. The sensor outputs a proportional analog voltage of 185 mV/A that is centered at 2.5 V. The analog voltage is measured directly by the Arduino through.

2.3.3 Rotary Encoders

Each of the drive motors has two rotary encoders built in that have a 90-degree phase shift between them [15]. This allows for the number of rotations to be measured simply from the encoder count and the direction of the rotation to be found by comparing the two encoder states.

2.3.4 SD Card Breakout Board

The SD card breakout board simply allows the microcontroller to interface with and save data to a micro-SD card as a text file [18]. This allows the rover to operate completely wirelessly. The text file is then post-processed in MATLAB.

3. TERRESTRIAL LOCOMOTION DYNAMIC MODEL

Terrestrial locomotion of the MAARCO rover (discussed in [9]) involves complex interaction between the surrounding substrate and helical drives. The motion of helical drives depends on the reaction of the surrounding substrate to the stresses exerted by the rotating helical drives. Whether the substrate fails or stays intact under the stresses exerted by the helical drive determines the locomotion of helical drives and therefore the MAARCO rover. The velocity of the point of contact of the blade with the surface medium in a direction perpendicular to the face of the blade is either non-zero or zero depending on the whether substrate between the blades failing or not. When the rover motion is along a straight line (achieved through counter-rotating helical drives acted upon by the equal amounts of torque) without failing the substrate, the velocity constraint can be simplified to $x = P \cdot n$ or $x = P \cdot \theta / 2\pi$, where x is the linear displacement of the center of mass of the rover, and P , n , and θ are the pitch length, number of rotations, and angular displacement of the helical drives, respectively. In this case, the motion of the rover resembles that of a "bolt through a threaded hole". The holonomic constraint $x = P \cdot n$ if valid can then be applied to be used to calculate the lateral displacement of the rover as a function of the number of rotations thereby simplifying the problem considerably. However, when the substrate fails, the linear displacement of helical drive is less than $P \cdot n$, i.e., $x < P \cdot n$. The prototype described in this paper is used to validate the dynamics of the locomotion model while moving in a straight on substrates that fail and substrates that stay intact under the stresses exerted by the rover.

4. RESULTS AND DISCUSSION

Preliminary testing was conducted with the small-scale prototype on multiple substrates, namely wet sand and dry sand.

4.1 Motion on Wet Sand

Two types of motion were conducted on wet sand: i) straight line motion by prescribing the equal and opposite speeds to both motors and ii) turning motion by providing a difference in the magnitude of speeds to both motors.

4.1.1 Straight Line Motion

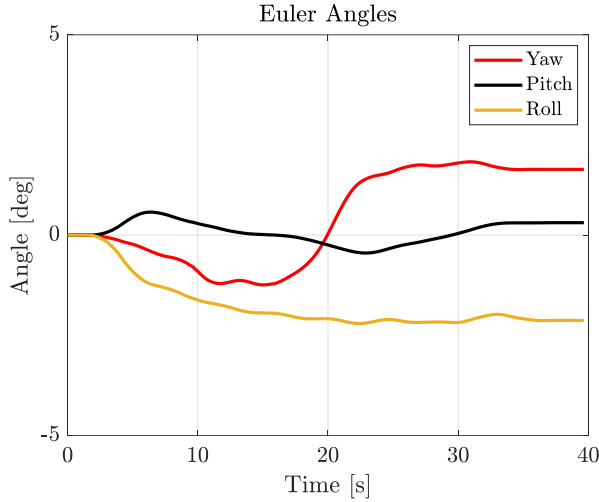


FIGURE 7: Euler angles during straight line motion on wet sand.

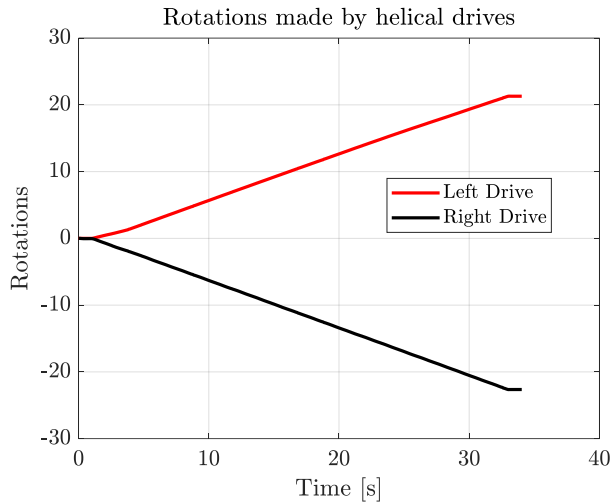


FIGURE 8: Revolutions completed by helical drives during straight line motion on wet sand

The rover exhibits minimal rotation about any its body axes while traveling in a straight line and hence the yaw, pitch and roll stay between -3 degrees and 3 degrees as depicted in Figure 7. The perturbations in roll, pitch, and yaw angles maybe sensor noise or to the fact that the sand surface was not flattened down before testing. The helical drives on both sides completed the same number of rotations but in opposite directions (Figure 8). The test began at $t = 5$ seconds and stopped at $t = 35$ seconds, which explains why the Euler angles and number of rotations abruptly flatline.

Comparison between experimental and predicted positions

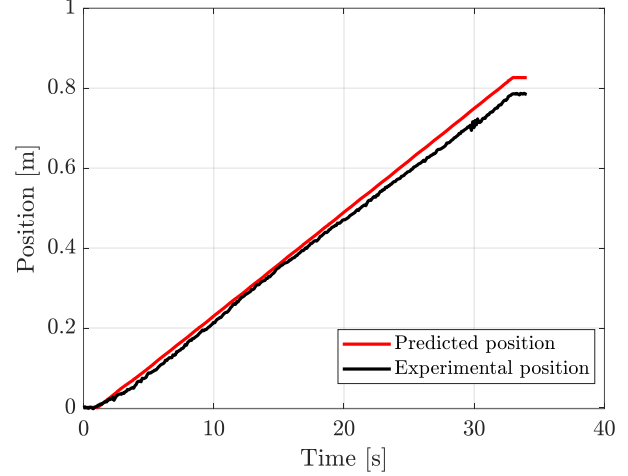


FIGURE 9: Comparison between experimental position and predicted position assuming no surrounding substrate failure during straight line motion on wet sand

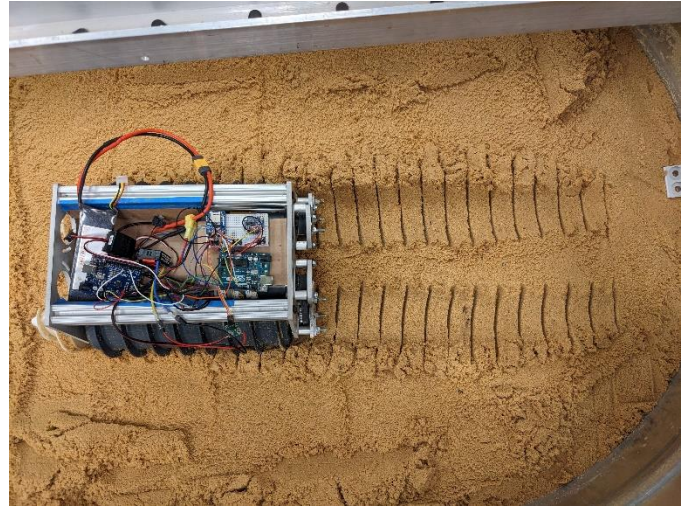


FIGURE 10: Tracks made on wet sand after straight line motion

From Figure 10, it is visible that the surrounding substrate does not fail and stays intact under the stresses exerted by the rover. The grooves in the sand are the exact distance as the pitch of the helical drives. This means that the rover must follow the holonomic constraint $x = P \cdot n$. Figure 9 shows agreement between the experimental forward position of the rover during straight line motion on wet sand and the position predicted by the previously mentioned holonomic constraint.

4.1.2 Left and Right Turns

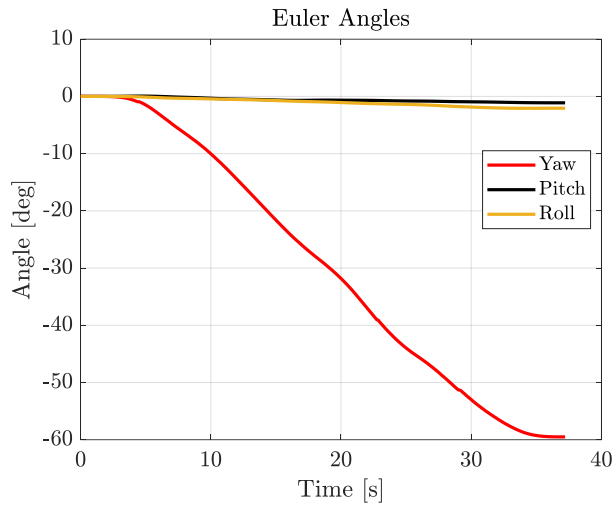


FIGURE 11: Euler angles for left turn motion on wet sand

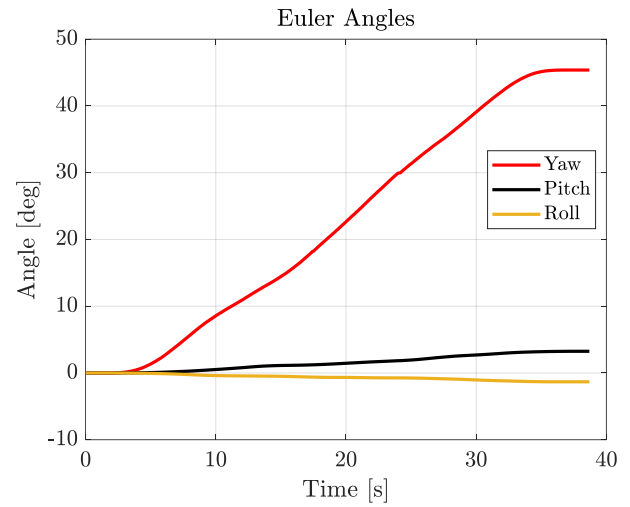


FIGURE 14: Euler angles for right turn motion on wet sand

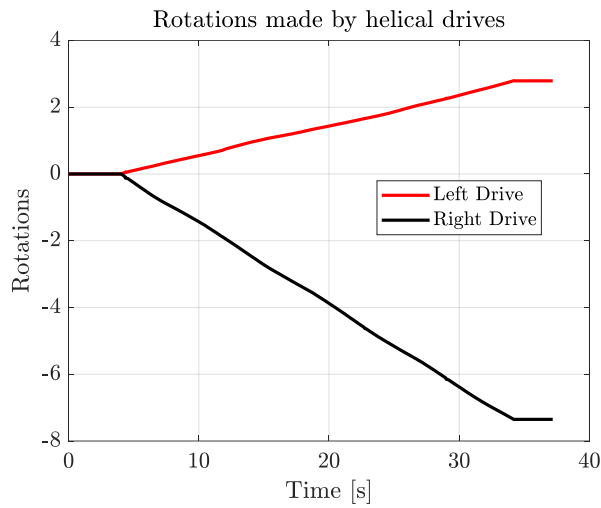


FIGURE 12: Revolutions completed by helical drives during left turn motion on wet sand

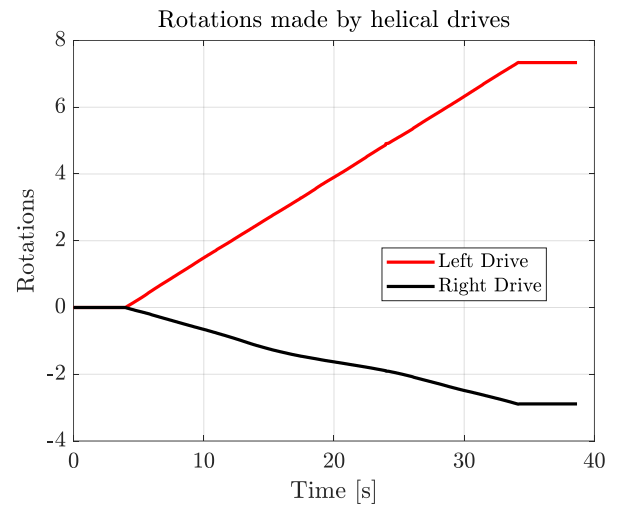


FIGURE 15: Revolutions completed by helical drives during right turn motion on wet sand



FIGURE 13: Tracks made on wet sand after a left turn

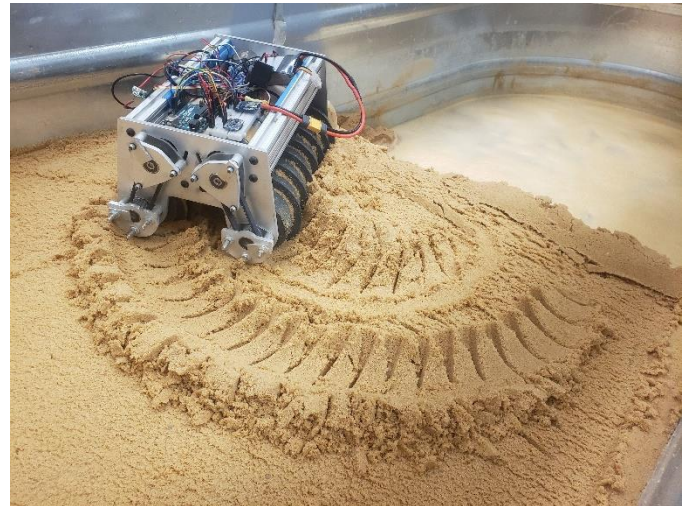


FIGURE 16: Tracks made on wet sand after a right turn

Left and right turn motion was prescribed by providing different RPMs to the two motors. Figures 11 and 14 depict the Euler angles after a turn. The roll and pitch stay close to zero while the yaw increases in the direction of motion. The motors are prescribed to go at different speeds to achieve the turns as depicted by the data picked up from the rotary encoders in Figures 12 and 15. In order to make a left turn, the helical drive on the right needs to be faster than the left and vice versa. Figures 11, 12, 14 and 15 depict data from 30-second-long test runs. Figures 13 and 16 depict tracks made in the sand after running the rover for over 90 seconds.

4.2 Motion on Dry Sand

The rover was tested out in dry sand in two modes: i) screw mode and ii) crab crawl. Screw mode is the operation also performed on wet sand in which the rover moves in the direction the nose cones are pointed and the two helical drives are rotated in opposite directions. The distinction has been drawn here because on dry sand, an alternate form of forward travel is faster. In this mode, referred to hereon as crab crawl, both helical drives are rotated in the same direction and the rover travels in a direction perpendicular to the direction the nose cones are facing.

4.2.1 Screw Mode

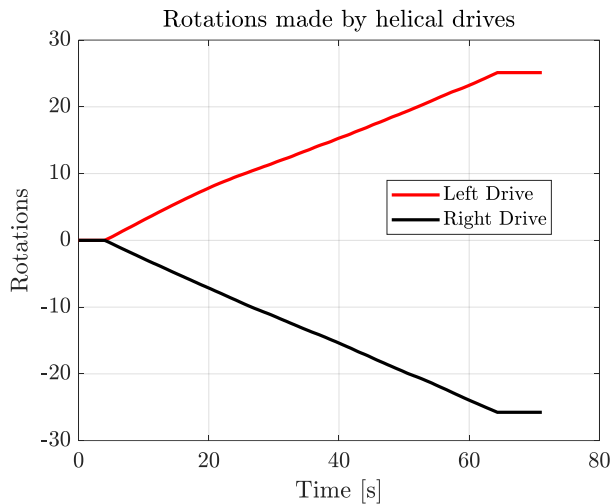


FIGURE 17: Revolutions completed by helical drives during straight line motion in screw mode on dry sand

In this test run, the rover was propelled forward by prescribing equal and opposite rotation to both helical drives (Figure 17). Figure 18 shows that the position is far below the predicted position when no substrate failure is assumed. The tracks on dry sand in Figure 19 show the substrate failure as well (demonstrated by the lack of clear grooves). Further tests with the rover will allow for the characterization of the substrates.

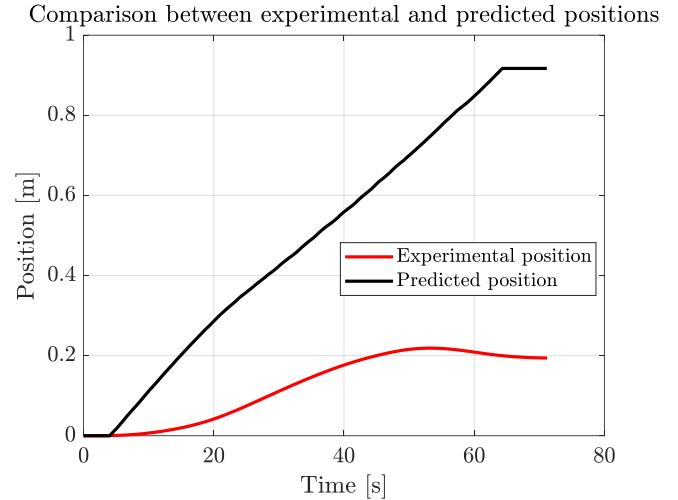


FIGURE 18: Comparison between experimental position and predicted position assuming no surrounding substrate failure during straight line motion on dry sand

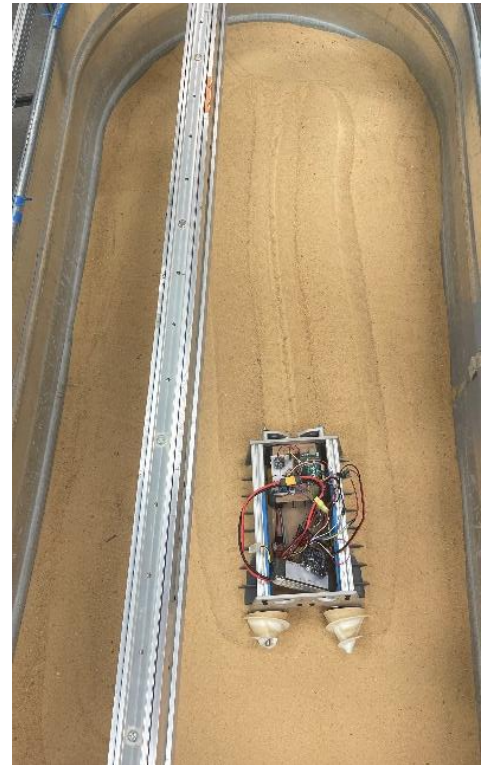


FIGURE 19: Tracks made on dry sand after straight line motion in screw mode

4.2.2 Crab Crawl

When provided the same rotation on both helical drives (depicted in Figure 20), the rover traversed dry sand by traveling over the surface without displacing as much sand as when it traveled in screw mode (Figure 21).

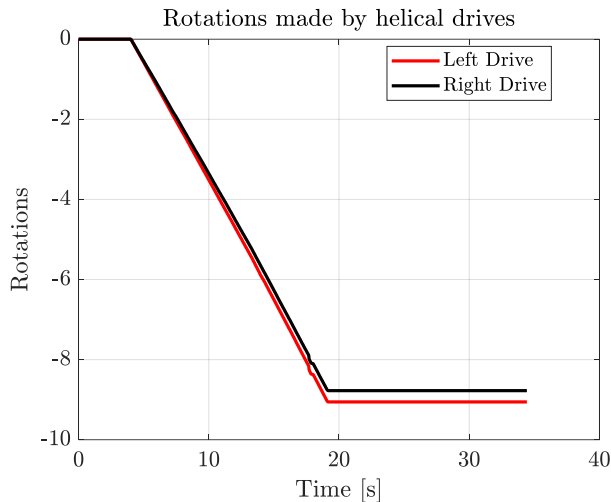


FIGURE 20: Revolutions completed by helical drives during straight line motion in crab crawl on dry sand



FIGURE 21: Tracks made on dry sand after straight line motion in crab crawl

5. CONCLUSION

This prototype has been used to get valuable insight to design the full-scale rover to further study the dynamics of helical drives. Preliminary testing has demonstrated the promise of this rover to perform turns on wet sand as well as execute multiple modes of locomotion on dry sand. Future modifications to the rover will also prioritize closed-loop control for which more sophisticated methods of state

estimation are necessary and the use of time of flight sensors is planned for position estimation to avoid dead reckoning errors.

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