

DESIGN AND CONSTRUCTION OF A TERRESTRIAL TESTING RIG FOR EXPERIMENTAL CHARACTERIZATION OF MULTI-TERRAIN SCREW-PROPELLED VEHICLE DYNAMICS

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ABSTRACT

Helical drives (sometimes known as Archimedes' screws) are a class of propulsion mechanism with the potential for application in amphibious, multi-terrain robotic ground vehicles such as Arctic rovers. Despite their simplistic construction, consisting of a screw-like rotating drum with a helically wound blade, their propulsion dynamics are complex and not well understood. There is a need for an experimental testing environment capable of controlling and recording the variables that characterize the dynamics of this terrestrial propulsion mechanism in order to experimentally validate dynamic and energetic modelling. Such variables include displacement, velocity, and acceleration of the mechanism in question in the x , y and z directions, as well as terramechanical properties such as substrate moisture content, subsequent density, and particulate size. This environment would also ideally be designed with modularity in mind in order to easily adapt to multiple different test conditions and terrestrial propulsion mechanisms. This paper describes the design of the experimental testing rig created to serve the above-described purpose. The apparatus is tested with an example of a helical screw drive at three different rover weights. Results of an initial test are shown, and the trends shown in the x position

(longitudinal travel), z position (vertical travel), and effective pitch length are discussed. Keywords: Helical drive, terramechanics, experimental apparatus.

1. INTRODUCTION

Terrestrial propulsion mechanisms such as wheels and tank treads are commonly used in various land-based vehicles, but their dynamics can be difficult to characterize due to the complex interactions between the mechanism and the terrain. These interactions become more complicated with more unique propulsion mechanisms such as helical screw drives. Some previous studies have experimentally characterized helical drive dynamics^[1], others have performed computational studies^[2], and still others have performed both^[3]. These studies all agree that the dynamics of helical drives are influenced by many factors such as terrain roughness, mechanical design of the propulsion mechanism and vehicle, and the speed at which the mechanism is operating. These interactions can make it challenging to accurately model and control the motion of these vehicles, which can limit their performance and utility.

In this study, we consider an experimental screw propelled robotic vehicle intended for multi-terrain and amphibious operation. Two helical screw drives are

kinematically linked via a set of gears in order to ensure each drive is rotating at equal speeds in opposite directions, and are powered by a single motor. In future studies, each drive will be powered by its own motor, allowing for each drive to rotate at different speeds so that maneuvers such as turning can be studied. The design of this testing apparatus was largely inspired by the Multi-terrain Amphibious ARctic explORer (MAARCO) vehicle project.

The MAARCO vehicle is an example of a rover whose dynamics are difficult to model due to a few factors. First, the MAARCO vehicle is designed to explore the arctic. The diverse terrain found in the arctic consists of heterogeneous combinations of ice, snow, water, and permafrost with highly variable properties. These diverse terrains pose a challenge for the navigation of autonomous vehicles like MAARCO, as well as for the characterization of their dynamics. While autonomous arctic rovers have been proposed in the past^[4,5,6], their use of wheeled locomotion has largely restricted them to flat, uniform terrain, limiting their usefulness and the diversity of research missions they can be used for. It is for this reason MAARCO was designed to utilize two rotating helical drives, sometimes known as screw drives or Archimedes screws (which structurally are very similar to augers) as its method of propulsion. This unique propulsion mechanism is the second reason modeling MAARCO's dynamics are difficult.

Helical drives are capable of producing thrust on a wide range of different substrates as well as on the water and are considered a highly versatile means of propulsion for vehicles and other uniquely designed robots^[7,8]. Figure 1 shows four different scenarios where helical drives can be utilized. They primarily produce thrust by rotating about their longitudinal axis to displace a surrounding substrate or liquid and apply force opposing the desired direction of travel, though they can also be used similarly to wheels by rotating the drives in the same direction. Though helical drives have been used in many different kinds of manned and unmanned vehicles before, the complex means by which they produce thrust and the wide range of substrates they can encounter make it difficult to map the exact dynamics of a vehicle that utilizes helical drives. Past studies have only characterized portions of the dynamics, creating models that assume steady state operation or only model motion in a straight line^[2]. Without validating the dynamics, it is difficult to model a rover that utilizes helical drives and to predict said rover's performance on different terrains when planning missions.

In cases like these, where the dynamics of a specific propulsion mechanism are highly complex, there is a clear need for an experimental testing environment capable of controlling and recording the variables that characterize the dynamics of terrestrial propulsion in order to experimentally validate the dynamic model in question. Similar testing apparatuses have been successfully utilized to validate dynamic models of complex systems in the past^[9,10], however, the novel

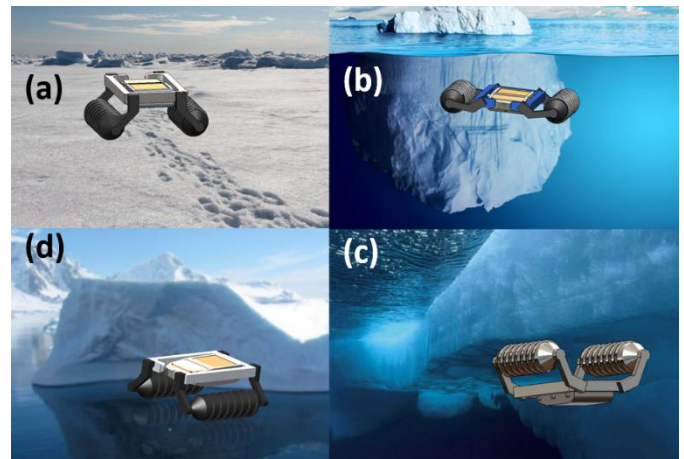


FIGURE 1. MAARCO ROVER CONCEPT ILLUSTRATING DIFFERENT MODES OF HELICAL DRIVE-BASED LOCOMOTION: (A) ON GROUND, (B) UNDERWATER, (C) ON THE UNDERSIDE OF AN ICE SHEET, AND (D) ON WATER.

contribution this paper makes to the larger body of literature is (1) detailing a design made to experimentally study the effect normal force has on the helical drive dynamics via a weight-offloading system, and (2) showcase early results of said system being tested on a single substrate to determine the aforementioned design's efficacy. This paper discusses the experimental setup designed to validate the progressing terrestrial dynamic model for the MAARCO rover and to provide intuition necessary for determining optimal rover design. The experimental setup is designed with modularity in mind so that dynamic models for other complex propulsion mechanisms can also be validated in the future.

For a dynamic model to be successfully validated, the following variables would need to be recordable by the experimental testing setup: position, velocity, and acceleration of the test article in the x , y , and z , the forces acting on the test article in the x , y , and z , the moments acting about the test article in the x , y , and z , the torque being applied to the propulsion mechanism, substrate characteristics including moisture content, density, and particulate size. The following sections break down the testing apparatus and explain how the above variables are recorded.

2. MATERIALS AND METHODS

a) System Design: The platform's first test subject was a helically driven rover chassis designed to (within this testing environment) travel in a straight line forward and backward over a chosen substrate or combinations of substrates (see section 2.c) via two kinematically linked helical drives driven by a single DC motor. All the subsystems, electronic communications, and means by which they interface that make up this platform will be described in detail. A simplified diagram showing the major important components and their organization is shown in Figure 2. This platform was designed to be modular in order to test

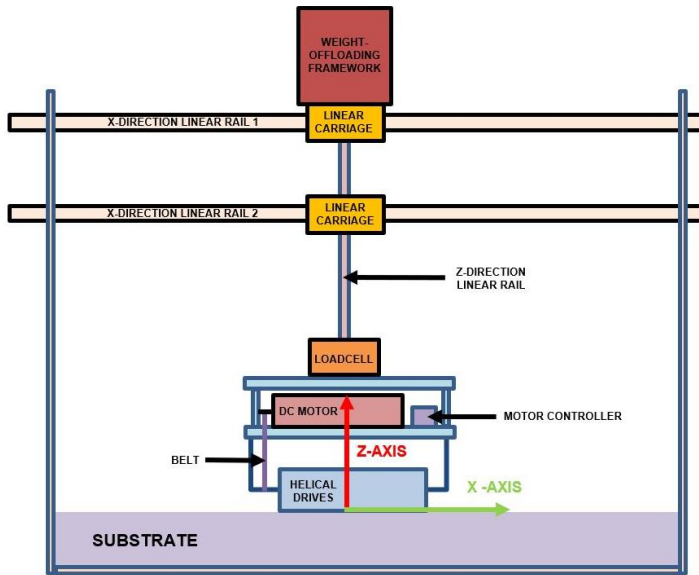


FIGURE 2: MAARCO TERRESTRIAL TESTING RIG DIAGRAM SHOWING BASICS OF IMPORTANT COMPONENTS AND COORDINATE SYSTEM

multiple different propulsion mechanisms, on different substrates, at different effective gravitational loads and different inclines. With modularity having been in mind throughout the design process, the system is capable of having the propulsion mechanisms replaced quickly and easily by one or two researchers. The system has been designed to collect data on the torques and forces experienced by the dual-helical drive mock rover as it traverses the substrate in the rig. The electrical system (discussed in more detail in later sections) allows for the control of the helical drive's angular positions, speeds, and accelerations, as well as serves as the data acquisition system's foundation for all data collected from the various sensors and encoders.

b) Mechanical Setup:

b.1) Extruded Aluminum Frame: The main body of the testing rig is constructed from a repurposed stock tank that measures approximately 2438.4mm by 914.4mm by 609.6mm (8ft by 3ft by 2ft) and has curved edges. The watertight rolled aluminum construction allowed for an economic environment to house the wide variety of planned testing substrates ranging from dry sand, mulch and gravel, to mud, and even water. A frame of extruded aluminum channels was constructed around the stock tank to serve as a rigid mounting point for the testing rig's low friction linear rails, as well as to provide a structure for mounting sensing equipment and other electronics. The low friction linear rails chosen were PBC Linear Redi-Rails with low profile linear carriages. The manufacturer, PBC Linear, lists the average coefficient of friction for their low friction linear railings as 0.01 for dynamic friction, and 0.02 for static breakaway^[1]. This friction opposes the motion of the two x and z direction carriages, and in steady-state locomotion, creates a force in the longitudinal and vertical directions respectively. Since the railings for the low-profile, low-friction linear carriages used are thin and prone

to bending, each of the two custom length 2,500mm linear railing used to control x-axis movement were mounted to an eight-foot-long aluminum c-channel measuring two in wide and two in tall to provide a stiff flat surface for the low friction railings to secure to. The low-profile carriages used with the low friction railings are capable of carrying a substantial amount of weight if that load is applied normal to the surface of the carriage, however, it was discovered during testing that they are prone to seizing if a moment is applied about the longitudinal axis. For this reason, two x-axis railings were used, with their carriages connected by a single z-axis railing to mitigate any moments applied to either carriage by the y-axis forces experience by the helical drive carriage. The combination of these x and z axis railings fix the movement of the electronics carriage in the y direction, however, the load cell used to collect data on the forces and moments the carriage experiences allows for forces acting in the y direction on the carriage to still be measured. Additionally, two magnetic linear encoders are attached to the rig's bottom x-axis c-channel, and the z-axis sting in order to measure the displacement in the x and z directions during testing. The sensors and data acquisition systems will be further discussed in the Electrical Setup section.

b.2) Weight Offloading System: The weight offloading mechanism is a pulley-based system that effectively removes weight from the helical drive electronics carriage by applying an upward force via a set of modular weights attached to the end of a cable. Figure 3 shows how the system is mounted to the top x-axis low-profile rolling carriage and implemented in the experimental testing rig, and Figure 4 shows a simplified diagram of the construction of the weight offloading system. This cable is attached through a series of pulleys to the top of the z-axis sting. The modular weights sit on the opposite side of the x-axis rail as the z-axis, and when a downward force is applied to the cable via said weights, it applies an equal upward force on the z-axis, effectively reducing the weight of the carriage and the normal force exerted by the substrate on the carriage. This system was developed in order to simulate different gravitational loads during testing, however it is important to note that while it does change the normal force the propulsion mechanisms experience, it also affects the system's moment of inertia. Even when no weight is being offloaded from the rover, the weight-offloading mechanism itself adds mass to the system. The weight offloading system can be considered a part of the upper x-direction carriage, and with no weights attached has a mass of 4.13 kg (9.1 lbs). This added weight does not affect the normal force applied by the substrate onto the helical drives because it is supported by the uppermost x-axis linear railing and c-channel, and serves only as a constant addition to the system's overall mass when not being used to "remove" weight from the rover.

c) Substrate Setup:

c.1) Substrate types: The project has collected several substrates for use in the testing rig to help create a variety of testing environments on which to characterize the helical drive's performance characteristics. These substrates include: dried

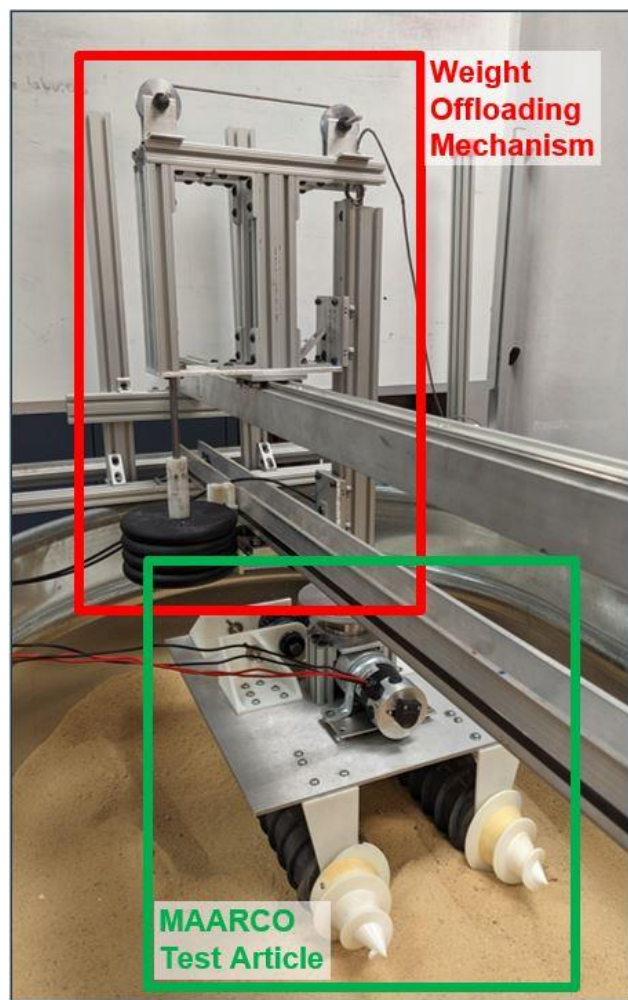


FIGURE 3: STOCK TANK AND MOUNTING FRAME WITH THE WEIGHT-OFFLOADING MECHANISM HIGHLIGHTED IN RED, AND MAARCO TEST ARTICLE HIGHLIGHTED IN GREEN.

sand, gardener's topsoil, gravel, and soil collected from a local construction site heretofore referred to as "ground soil." These substrates were chosen for their widespread availability and their broad coverage of different terramechanic properties such as shear strength, average particle size, and material density. Additionally, the moisture content of these substrates can be monitored and manipulated to change their terramechanic properties to further diversify the range of possible testing environments. For example, the dry sand can be mixed with water to create wet sand with varying levels of moisture content from dampened to fully-saturated. The amount of water added to a completely dry substrate is tracked in order to estimate the overall moisture content based on mass, and is recorded during testing. To empirically characterize the substrates, a process (discussed in the next section) was developed for preparing the substrates and recording their important characteristics before they are implemented in testing.

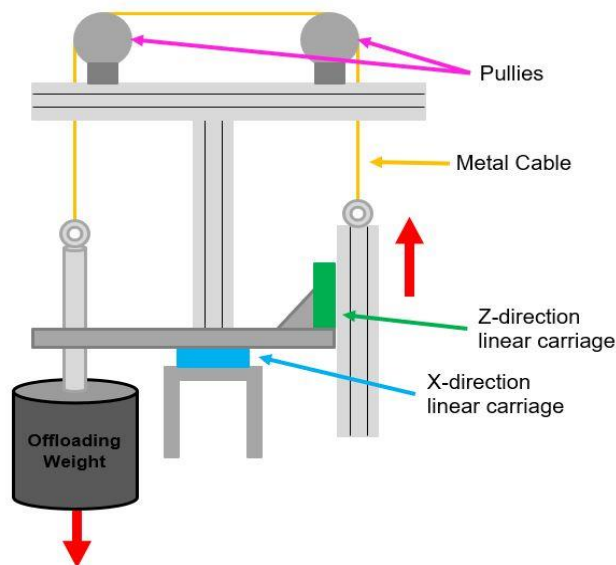


FIGURE 4: SIMPLIFIED DIAGRAM OF WEIGHT-OFFLOADING MECHANISM MOUNTED ON TOP OF THE UPPER X-DIRECTION LINEAR CARRIAGE.

c.2) Substrate preparation: The process for preparing the substrates is different for each substrate type. Inorganic substrates tested such as sand are passed through a set of industrial soil sieves to determine the substrate's average particle size. Afterwards, the substrates are baked in an industrial soil oven at $230^{\circ}\text{F} \pm 9^{\circ}\text{F}$ for 30 minutes or until completely dry in order to ensure the substrates do not have any moisture content. Once the substrate is dry, water can optionally be added in order to change the moisture content. When testing, in order to ensure accurate repeatability, the substrates are first weighed in their dry state, and then again as water is added. This allows for researchers to ensure approximately the same water per substrate mass ratio can be reached before each test.

A similar process is followed when processing the organic substrates like mulch. The substrate would be first passed through industrial soil sieves in order to determine and assure a maximum particle size. The substrate can either be dehydrated at a low temperature in an oven, or alternatively, allowed to dry out in the open air of the lab, being mixed and tilled in order to ensure it fully dries out over time. Weight and volume measurements are taken in order to determine density of the substrate when dry, and water can be added by mass as mentioned previously in order to control the mass ratio of substrate to water to ensure repeatability.

In both cases, detailed notes are taken on the substrate's condition, location of origin, etc. to characterize it in as much detail as possible in order to create a record to be used when repeating tests with the more unique substrates.

d) Electrical Setup:

d.1) Helical Drive Carriage: The helical drive "electronics carriage" (sometimes referred to as "test article" or

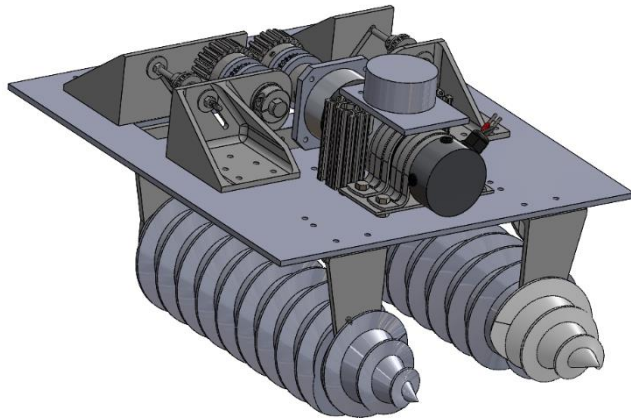


FIGURE 5: CAD ASSEMBLY OF THE ISOLATED MAARCO DUAL-HELICAL DRIVE CARRIAGE

“rover”) is the collection of electronics, sensors, and mechanical components that make up the modular assembly that attaches to the testing rig’s z-axis redi-rail and sting (shown in Figure 5). Specifically, the carriage is composed of (from the top down) 1) a 6 degree of freedom (DoF) load cell to measure the forces and torques the helical drive carriage experiences, 2) a DC motor to power the rotation of the helical drives, 3) an Arduino UNO, motor controller, and other electronics to control the DC motor, 4) a toothed belt and pulley system to transfer the torque from the motor to the helical drives, 5) and the helical drives themselves, all mounted to 6) a piece of sheet metal machined with mounting holes for each component. The ways these components interface is outlined in the electrical system schematic found in Figure 6. The testing rig was purpose-built such that the helical drive carriage could be swapped out with different propulsion mechanisms such as wheels or treads, or with the same propulsion mechanisms in different orientations, such as a single helical drive, a single wheel, or a single tread instead of pairs of each. For the tests explored in this paper, the carriage setup used a single Midwestern Motion Products 24 volt brushless DC motor (model number MMP S27-411D-24V GP81-035 EU-100 FL34)¹ with a rated continuous current of 22.4 amperes to power two separate helical drives. These two helical drives were attached to the motor via two belt and pulley systems, and one pair of gears. One helical drive received its torque from a belt and pulley system mounted directly to the DC motor, and the other received its torque from a belt and pulley system that was mounted to a separate axle that was connected via a pair of gears to the DC motor. This pair of gears had a one-to-one ratio and reversed the direction of the rotation of the motor so that the two helical drives would rotate opposite of each other as they would for standard forward propulsion operation. The carriage is attached to the bottom of the z-axis low friction Redi-Rail. The top of the z-axis rail is attached to the weight offloading pulley system.

¹ Back EMF Constant (K_e) = 4.9 V/KRPM
Torque Constant (K_t) = 6.6 OZ-IN/AMP

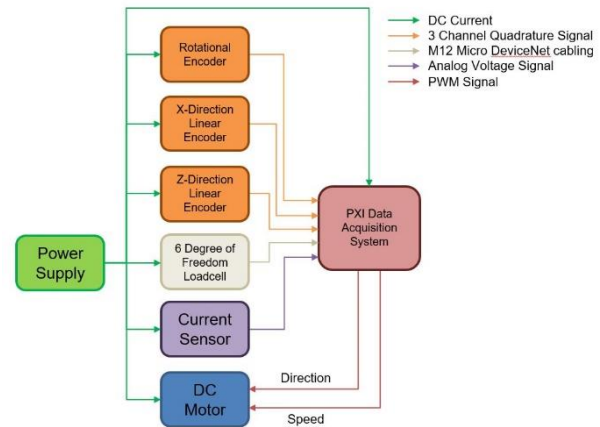


FIGURE 6: ELECTRICAL SYSTEM SCHEMATIC SHOWING THE PRIMARY POWER FLOWS AND DATA SIGNALS

d.2) Sensors and Data Acquisition Systems Summary:

The testing rig utilizes two magnetic linear encoders to measure displacement in the x and z axes, a rotational encoder attached to the motor to measure the rotational position, velocity, and acceleration of the motor (and thus of the helical drives due to their kinematic linkage), and a 6 degree of freedom load cell to measure the forces and moments acting in and about the x, y, and z directions.

3. RESULTS FROM EXAMPLE CASE STUDY

While this testing rig has been used to test the terrestrial and aquatic capabilities of various helical drive designs, preliminary tests in dry sand showed that a helical drive with larger ballasts, and smaller blade heights performed better than helical drives shaped more like augers, which had a tendency to tear up the substrate. As a result, this paper will focus on the findings from testing of a helical drive with the fixed design variables listed in Table 1, in dry sand.

Table 1: Fixed HD and Rover Design Variables

Variable	Value
HD Ballast Length	317.5mm
HD Ballast Diameter	95.25mm
HD Blade Height	6.985mm
HD Blade Thickness	4.826mm
HD Pitch Length	36.576mm
Electronics Carriage Weight	191.3N
Distance Between Centers of HDs	228.6mm
Substrate Type	Dry Sand

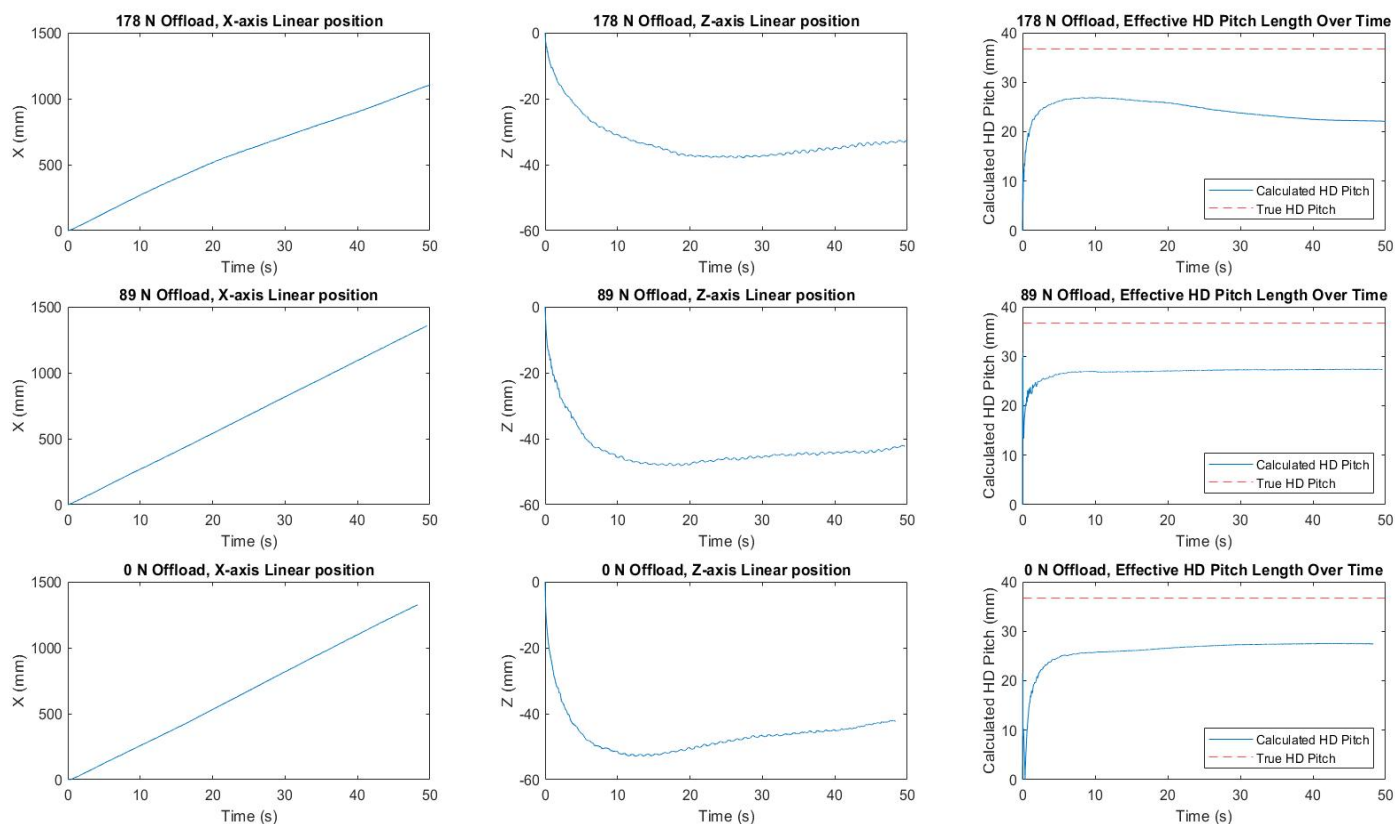


FIGURE 7. TESTING RESULTS WITH 3 DIFFERENT WEIGHT-OFFLOADING CASES. TOP ROW, CENTER ROW, AND BOTTOM ROW OF RESULTS SHOWN HAVE 178 N (40 LBS), 89N (20 LBS), AND 0 N (0 LBS) WEIGHT OFFLOADED RESPECTIVELY, WITH A RESULTANT EFFECTIVE ROVER WEIGHT OF 13.3 N (3 LBS), 102.3 N (23 LBS), AND 191.3 N (43 LBS). LEFT, CENTER, AND RIGHT COLUMNS SHOW X POSITION OF ROVER, Z POSITION OF ROVER, AND EFFECTIVE PITCH LENGTH COMPARED TO TRUE PITCH LENGTH OF HELICAL DRIVES

a) Results with 178 N (40 lbs) Offloaded:

The first series of tests was done with 178 N (40 lbs) offloaded from the rover, resulting in an effective weight of 13.3 N (3 lbs). During operation, the rover traveled 1104.2 mm in the x direction in 50 seconds, resulting in an average x direction velocity of 22.084 mm per second. The effective pitch length of the rover which was calculated by dividing the linear position in the x by the number of revolutions of the helical drive initially peaked above 1 inch, and then slowly began to drop off, leveling out at around 20.955 mm (0.825 in). This is considerably lower than the true helical drive pitch length of 36.576 mm (1.44 in). The helical drives sunk a maximum depth of 37.94 mm (1.5 in) into the substrate before slowly beginning to rise back up overtime.

b) Results with 89 N (20 lbs) Offloaded:

The second series of tests was done with 89 N (20 lbs) offloaded from the rover, resulting in an effective weight of 102.3 N (23 lbs). During operation, the rover traveled 1355.5 mm in 50 seconds, resulting in an average x direction velocity of

27.11 mm per second. The effective pitch length of the rover plateaued to approximately 1.07 in. This is considerably lower than the true helical drive pitch length of 36.576 mm (1.44 in), but also higher than the pitch length that the 178 N (40 lbs) offloading test results plateaued to. The helical drives sunk a maximum depth of -48.19 mm into the substrate before slowly beginning to rise back up overtime to just below 40 mm.

c) Results with 0 N (0 lbs) Offloaded:

The third and final round of tests that will be discussed in this paper was done with 0 N (0 lbs) of weight offloaded from the rover, resulting in an effective rover weight of 191.3 N (43 lbs). During operation, the rover traveled 1325.5 mm in 48 seconds, resulting in an average x direction velocity of 27.6 mm per second. The effective pitch length of the rover plateaued to approximately 1.08 in, lower than the true pitch length of the helical drive, but approximately the same as the effective pitch length calculated from the 89 N (20 lbs) offloading test. During the run, the helical drives sunk a maximum depth of -52.9 mm

into the substrate, and then began to rise ending the run at -42.37 mm.

d) Comparing Results:

The 178 N (40 lbs) offloading case had the slowest average velocity of the three runs, with the 20 and 0 N (0 lbs) offloading cases sharing similar, higher average velocities. Each case showed relatively linear trends for the x position over time, indicating that the average velocity for each run is a good estimate of the true velocity throughout the run. As expected, the 178 N (40 lbs) offloading case resulted in the shallowest maximum sinkage, with the 0 N (0 lbs) offloading case resulting in the deepest sinkage. Interestingly, the 89 N (20 lbs) and 0 N (0 lbs) offloading cases rose overtime to similar sinkage depths by the end of their perspective runs. From the trends shown in Figure 7, it appears that all three cases had yet to reach a steady state regarding the z direction sinkage, however they had traveled the majority of the length of the 8-foot stock tank that housed the testing environment, preventing the tests from continuing further. All three tests plateaued to effective pitch lengths shorter than the true helical drive pitch length, which is likely caused by the shearing of the substrate as the helical drives rotate. In a perfectly rigid environment, like a screw rotating through a tapped hole, the effective pitch length would be equal to the true pitch length of the helical drive because for every single rotation, the screw would move forward one pitch length. However, since our substrate during these tests was dry sand, a material with a low shear strength, the material sheared and gave way as the helical drive rotated through it, resulting in a forward displacement less than the true pitch length.

Future tests of the helical drives will include a higher resolution of weight offloading case studies for each substrate. It's been shown that the shear strength of sand increases with water content^[12], so to begin the studies of different substrates, three tests will be conducted after increasing the water content of the original sand: completely dry, 50% from saturation, and full saturation. Other substrates such as top soil, and gravel have been purchased and are planned for testing. Finally, changes will be made to the mechanical design of the helical drives. Ballast diameter, blade height, and pitch length will all be adjusted to determine the connection between these variables and performance.

4. CONCLUSIONS

Three tests were conducted using helical drives as a means of propulsion through dry sand. The effective weight of the rover being tested was changed via the weight-offloading system from 13.3 N (3 lbs), to 102.3 N (23 lbs), and then finally to 191.3 N (43 lbs). Results showed that at a constant rotation speed of the helical drives, an approximately constant linear velocity resulted no matter the weight of the rover. The constant linear displacement per rotation, however, was, in each case, less than the pitch length of the helical drives, suggesting the substrate was shearing beneath the rover. Finally, the heavier weight cases sunk deeper into the substrate, but no case's z displacement was ultimately able to reach steady state before reaching the

maximum length of the testing environment. These results showcase that the terrestrial testing rig described in this paper is an effective means of recording locomotion data such as displacement in the x and z directions, as well as the rotations in rad per second of the helical drives. Further, this rig has shown to be an effective tool for use when studying the effects varying normal forces have on helical drive propulsion characteristics and efficacy as a means of locomotion. Further work will include testing on more substrates, add the ability to record force and moment data, as well as precisely record the current and voltage being supplied to the rover over time.

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