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A Study of Omnidirectional Quad-Screw-Drive Configurations for All-Terrain Locomotion

by

Jon T. Freeberg

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering
College of Engineering
University of South Florida

Major Professor: Stuart Wilkinson, Ph.D.
Craig Lusk, Ph.D.
Kyle Reed, Ph.D.

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NOMENCLATURE

Symbol	*Description*	*Units*
c	Center-to-center of screws	in
h	Blade-height	in
l	Drum-length	in
r	Turning radius	in
D	Drum-diameter	in
Dm	Screw's major-diameter	in
L	Screw's lead	in
N	Number of blade revolutions	non-dimensional
T	Travel distance	ft
θ	Hinge-angle	^{o}
Φ	Helix-angle	^{o}

Acronyms	*Description*
C.G.	Center of gravity
MSA	Marsh Screw Amphibian
RCI	Rating cone index
RUC	Riverine Utility Craft
VCI	Vehicle cone index

A STUDY OF OMNIDIRECTIONAL QUAD-SCREW-DRIVE CONFIGURATIONS FOR ALL-TERRAIN LOCOMOTION

JON T. FREEBERG

ABSTRACT

Double-screw vehicles have been developed to operate in soft, wet terrains such as marsh, snow, and water. Their exceptional performance in soft and wet terrains is at the expense of performance on rigid terrains such as pavement. Furthermore, turning can be difficult because the method of turning varies depending on the terrain. Therefore, in this study, several different quad-screw-configurations were proposed and tested to improve upon double-screw vehicles.

A test-bed was developed which could easily be converted into each quad-screw-configuration for testing on a variety of surfaces (grass, dirt, sand, clay, marsh, snow, gravel, pavement, and water). In addition, a force-vector analysis was performed for each screw-configuration to predict and understand performance in different terrains.

From the testing and analysis, the inline-screw configuration was the most versatile because it was omnidirectional on all surfaces but water and pavement. Regardless, it was fully capable of navigating water, both on the surface and submerged, and pavement by rotating about its center.

CHAPTER 1: BACKGROUND

1.1 Fundamentals

Wheeled and tracked vehicles are a proven and effective means of locomotion for a wide range of surfaces. Nonetheless, there are conditions in which both means of locomotion have shortcomings. For instance, both vehicles encounter difficulty with marshy environments in which the ground's bearing strength is minimal. In such extreme off-road environments, it can be nearly impossible to prevent the vehicle from sinking and becoming immobilized.

In order to understand the degree of effectiveness a wheeled or tracked vehicle will display on a given surface, it is important to understand how it works. Note that while they may have dissimilar performance on a given surface, the underlying principle they use to provide locomotion is the same. "Conventional wheeled and tracked vehicles depend upon soil bearing strength for support, and on frictional and cohesive soil shear strength for propulsion." [1]

Clearly, most wheels and tracks provide negligible buoyancy to a vehicle, as is evident in a vehicle sinking in water or a soil of high moisture content. Furthermore, spinning tires on a slippery road demonstrate a wheel

or track's frictional requirement. Finally, wheels that are digging a hole in loose sand underscore the need for cohesive soil shear strength.

A novel locomotion concept, which may resolve the shortcomings of wheeled and tracked vehicles, consists of two counter-rotating, buoyant screws. The buoyant screw relies on completely different principles for locomotion as compared to a wheeled or tracked vehicle.

> *"[…] the support function is fulfilled by buoyant flotation, rather than by intrinsic soil strength. Propulsion is accomplished by viscous shear and reaction to mass movement of the medium, rather than by friction and cohesion in the soil mass." [1]*

Since the screw provides buoyant flotation, its application extends beyond surfaces of great moisture content to the surface of water itself. However, since the locomotion is generated by mass movement of a medium, it is restricted to non-rigid surfaces. On a solid and rigid surface, such as pavement, the blades rest on the surface and, in turn, operate on the same principle of locomotion as a wheel or track; an exception is ice in which a metal screw is able to carve into it. Though no specific studies were available regarding the mechanism for how a screw-vehicle works on ice, it has been shown to work. It can be surmised that screw-vehicles operate much like an ice skater digging into the ice.

Considering the nature of each locomotion system, it is understandable that the performances of screw-vehicles are nearly the opposite of wheeled and tracked vehicles for different surfaces [1]. Figure 1 shows the speed of the Riverine Utility Craft screw-vehicle. The Riverine Utility Craft, or RUC, is a full-scale double-screw military test-bed vehicle. It shows screw-vehicles

operate in water and on soil, but are optimal where conventional vehicles are not.

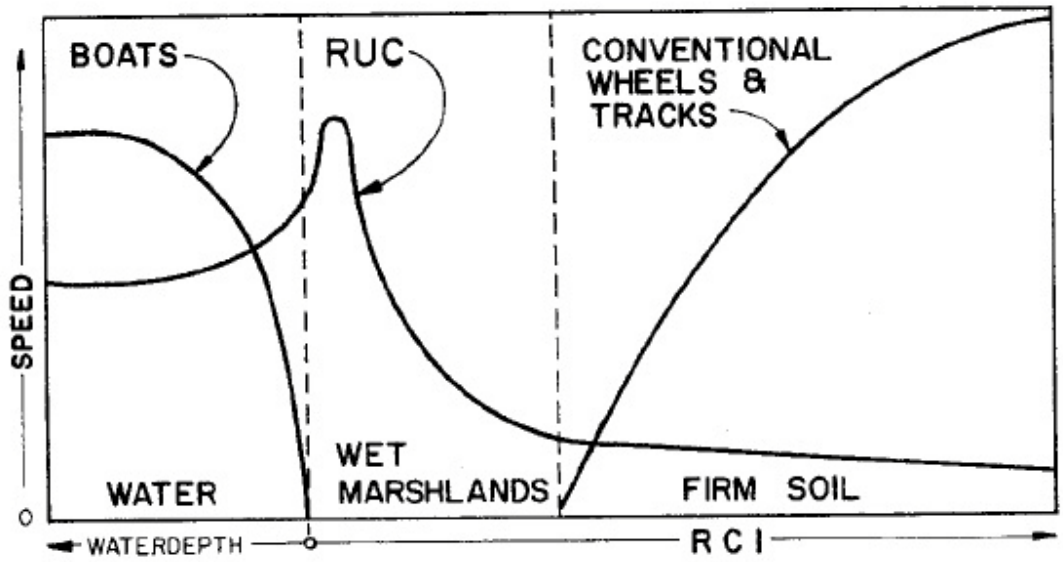


Figure 1: Riverine Utility Craft's (RUC) speed versus terrain firmness [2]. Note: all values are in generic units.

1.2 History of Screw-Vehicles

- 1804: A screw-steamboat is driven by Colonel John Stevens on New York's North River [3].
- 1841: Thomas J Wells patents the "buoyant spiral propeller" in which the screw provides buoyancy to the vessel [1].
- Late 1920's: The Fordson snowmobile is built; demonstrating snow and ice performance [3].



Figure 2: The Fordson Snowmobile [4].

- 1948: An amphibious screw-tractor is proposed in England by Lt. Col. H.O. Nelson [3].
- Early 1950's: A M29C Weasel tank is outfitted with screws to replace treads and is tested in Greenland by the US army [3].
- 1957: A German firm demonstrates a screw-amphibian at the Hanover exhibition [3].
- 1960's: The Russians develop a screw-tank to pick up and drop off cosmonauts in heavy snow [5].
- 1966: A patent for a marsh screw-vehicle is awarded to R.G. Schrader [3].
- 2001: The Snowbird 5 fails to cross the Bering Strait due to damage to its pontoon [5].
- 2002: The Snowbird 6 is developed and successfully crosses the Bering Strait [5].
- 2005: The Tyco® Terrain Twister toy is patented [6].
- 2007: A snake-like, screw-robot is researched [7].

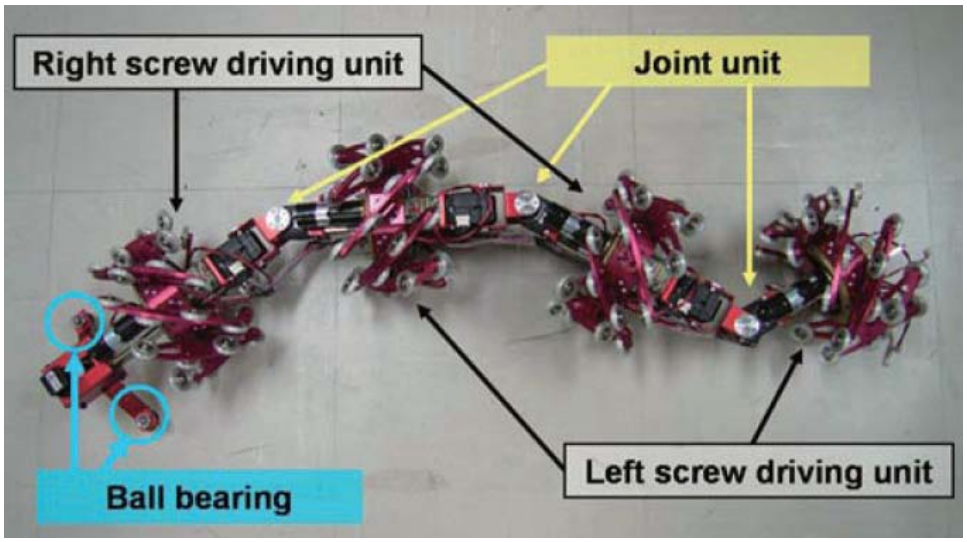


Figure 3: A snake-like screw-robot [7].

1.3 Applications

As discussed in section 1.1, screw-vehicles fill an important gap in vehicle performance between the terrain-navigating capabilities of boats and standard wheeled and tracked vehicles. Specifically, in shallow, marshy environments, boats risk damaging the propeller or becoming grounded, while wheeled and tracked vehicles perform poorly in saturated ground. Conversely, a screw-vehicle performs best in marshy environments [7, 8].

Another terrain condition not discussed is snowy ground. Screw-vehicles perform well in deep, powdery snow. On the contrary, a boat will not operate in snow, while wheeled and tracked vehicles must be specialized for snow in order to perform well. Therefore, a vehicle that must cross marshy or snowy surfaces would benefit from screw locomotion.

An important advantage of a screw-vehicle is its capability of traversing a wide range of environments without altering the vehicle. Amphibious cars and tanks have been developed, but they typically require a

transformation of their locomotion method or vehicle body to go from land to water. In contrast, a buoyant screw can provide flotation and it propels the vehicle aground and afloat. All in all, a screw-vehicle can operate on the ocean floor, on top of water, submerged and above the ocean floor, in marshes, snow, sand, dirt, grass, ice, and, to a limited extent, pavement.

Some examples of screw-vehicles that have been built in the past include:

- MudMaster (2009): The MudMaster was used for bauxite residue production in the alumina refining industry. It was useful for the alumina industry due to the screw-vehicle's effectiveness in mud and wet clay [10].
- Basin cleaning vehicle (BCV) (1999): The BCV was developed to crawl along lakebeds to remove sediment. Lakebed sediment impedes the percolation process that provides natural filtration to water supplies [11].
- Icy-water, oil-recovery vehicle (1996): An oil-recovery vehicle concept was considered by Sintef. The concept used screws to deflect ice and help collect spilled oil. The device was proposed to operate similar to a drum skimmer [12].
- Snowbird 6 (2002): The Snowbird 6 vehicle crossed snowy, Alaskan terrain and the Bering Strait using two counter-rotating screws [5].

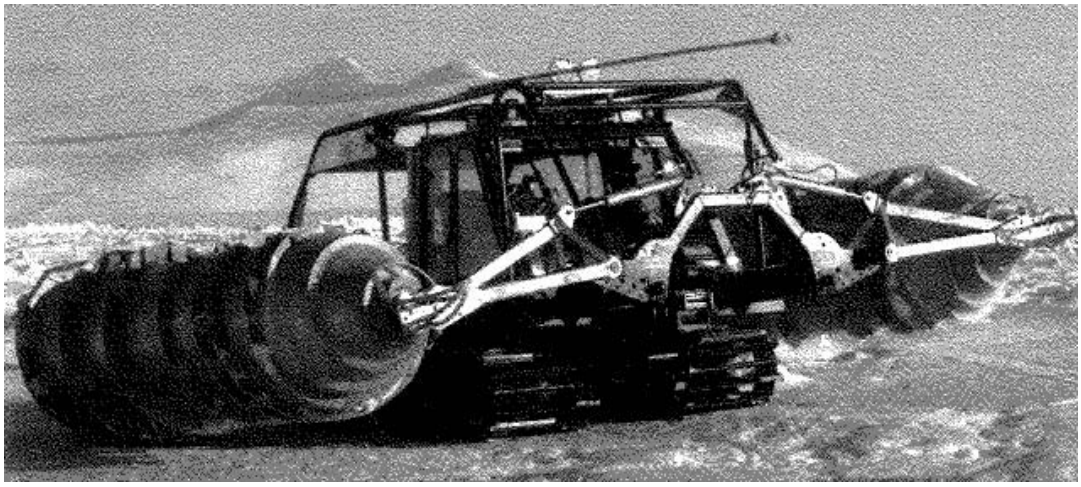


Figure 4: The Snowbird 6 [5].

- Spiral Track Autonomous Robot (STAR) (1996): The STAR was a screw-robot designed for hostile terrain. Specifically, it was designed for American police and military personnel [13].
- Terrain Twister (2005): The Terrain Twister was a toy which used screws to go over terrains that most toys would not; including snow and water.

CHAPTER 2: PREVIOUS RESEARCH

2.1 Important Studies

The concept of a screw-vehicle dates back as early as the 1800's [3] with the screw-steamboat, and in the 1920's it was first used on land with the Fordson snow tractor [9]. More recently, screw-vehicles have seen niche applications, including the Snowbird 6 used to cross the Bering Strait. [5]. However, the 1960's was the period in which much of the rigorous research regarding screw-vehicles was performed. Specifically, in the 1960's screw design parameters were developed and screw-vehicle trafficability studies were performed.

In 1961, a pilot study on screw design was published in England by Dr. B.N Cole [14] and it serves to be an important technical report concerning amphibious screw-vehicles. Within Dr. Cole's report is a theoretical investigation of screw design parameters such as the blade's helix-angle and the screw's overall length. His research was for operation in and out of water. In supplement to the theoretical modeling, a scale model was built to compare six sets of left- and right-handed screws. These screws were used to reveal how actual data compared with his theoretical calculations. The sets of screws consisted of three 13-inch short screws and three 22.3-inch

long screws. Each group of long and short screws consisted of one set of 20^{o}-, 30^{o}- and 40^{o}- helix-angles.

The study performed by Dr. Cole was an important starting point for the investigation of screw-vehicles, but was only a pilot study of a scale model. Furthermore, Dr. Cole's research on soil trafficability was limited to highly frictional soils [3]. Around the same time as Dr. Cole's research, Chrysler Corporation Defense Engineering under contract with the Advanced Research Projects Agency developed the Marsh Screw Amphibian (MSA) test-bed prototype. The MSA was designed to be capable of carrying a payload of half of a ton [3].



Figure 5: Dr. B.N. Cole working with a model screw-vehicle [14].

In the fall of 1961, Chrysler built a 1/8 scale demonstration model of the MSA. The proof of concept was successful and in June of 1962, the Navy's Bureau of Ships, or BuShips, directed Chrysler to build a 1/5 scale model to determine screw design parameters. The screw design parameters

considered were the optimum length-to-diameter ratio, the height of the screw blade, the blade's helix-angle, and if 1-, 2- or 4-starts should be used. In addition, horsepower requirements and the screw's slip were investigated on land and water [15].

On December 31, 1962 the first full-scale model of the MSA was built. From the preliminary testing, 26-inch diameter drums, 32^{o} helix-angle blades, and double-start blades were used for the screws. The screw's drum is the portion of the screw that the blade wraps around. It was tested at the Detroit River, Chelsea, Michigan, and Michoud, Louisiana for 100 hours. After the initial tests, BuShips requested Chrysler perform a study on screw parameters in order to optimize water performance. From August to October 1963, the US Army Engineer Waterways Experiment Station, or WES, performed 124 trafficability tests in Louisiana. In the meantime, a second MSA was built for snow tests. In February 1964, the second MSA was tested in snow conditions at Houghton, Michigan [15].

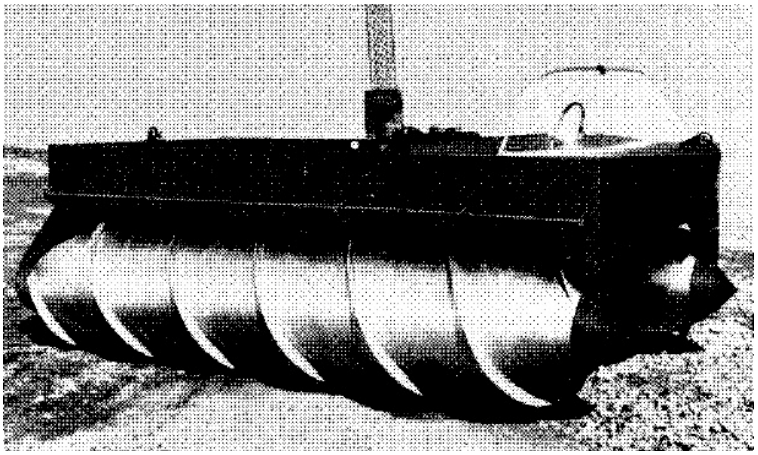


Figure 6: The Marsh Screw Amphibian [1].

The studies on the MSA provided much of the information regarding screw parameters and terrain trafficability used in this thesis. In addition, its success led to the development of another screw-vehicle program aimed at developing a finalized and practical vehicle. On July 25 1969, the Naval Ship Systems Command requested the US Army Engineer Waterways Experiment Station, or WES, to test Riverine Utility Crafts, or RUCs [9]. Similar to the MSAs, the studies on the RUCs were useful in this thesis.

2.2 Screw Design Parameters

There are several parameters to consider for a screw design. Some considerations for the screw's blade are its helix-angle, height, and number of starts. Furthermore, considerations for the screw-drum include its length and diameter. Each of the above parameters have been previously researched in the studies outlined in section 2.1 and are documented in this section.

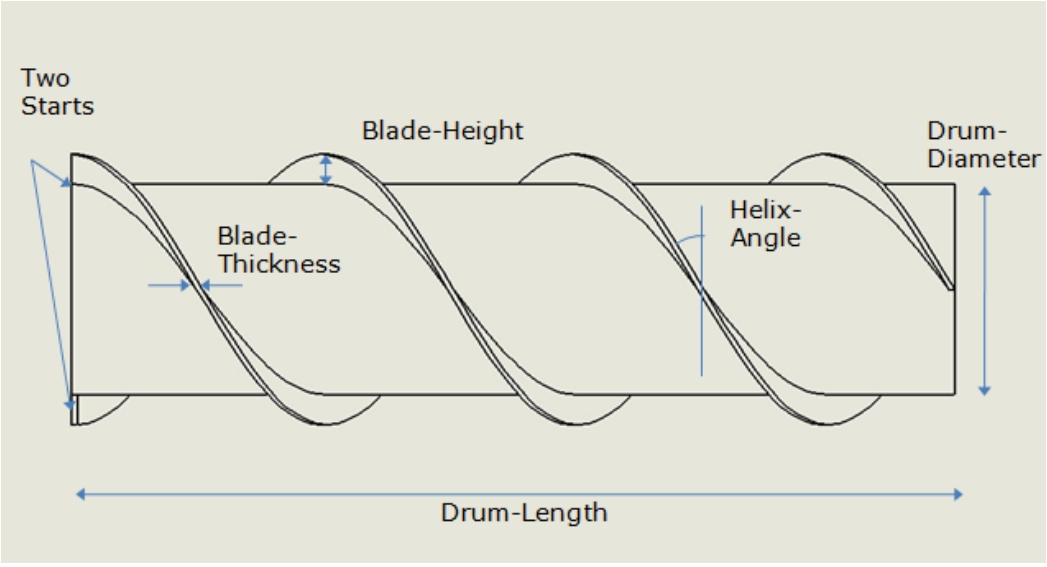


Figure 7: An illustration of important screw parameters.

2.2.1 Helix-Angle. Dr. Cole performed tests on screws comparing helix-angles. The helix-angles tested were 20^o, 30^o and 40^o and tests were conducted aground and afloat. Chrysler also compared the helix-angle of the blades; including, 30^o, 40^o and 50^o. From Dr. Cole's ground experiments, 20^o drew the most power from the screw's motors and created the greatest amount of ground deformation [14]. One benefit of the 20^o screw was that it had the best drawbar-pull capability. Drawbar-pull is a test used to determine the ratio of weight an off-road vehicle can tow in comparison to its own weight. In contrast to the 20^o screws, the 40^o screws required the least power but had the greatest amount of slippage [14].

The results of Dr. Cole's hydrodynamic experiments show that the greater the helix-angle, the greater the axial thrust and driving torque developed [14]. They also show that the propulsive efficiency is maximized at 30^o. Furthermore, referring back to the ground experiments, it is shown that the vehicle performance gap, as determined by the screw's slippage and power usage, is less between 30^o to 40^o than it is between 20^o to 30^o[14]. In addition, the drawbar-pull is nearly maximized at 30^o, with minimal improvement as the helix-angle decreases [3]. Therefore, combining the results of the aground and afloat tests, the optimum helix-angle is 30^o or slightly larger. In fact, the helix-angle chosen for the RUC was 32^o [15].

2.2.2 Blade-Height-to-Drum-Diameter Ratio. In all of Dr. Cole's tests, a blade-height-to-drum-diameter ratio of 0.375 was used. He concluded that, from the perspective of propulsive surface area and structural strength of the blades, a ratio of 0.375 was adequate [14]. The

tests performed by Chrysler included ratios of 0.125, 0.167 and 0.208 [3]. The experiments show that increasing the blade's height increases the weight of the failure surface in sand. The increased weight of the failure surface increases the drawbar-pull, but the effect is minimal [3]. Chrysler tested blade-height in muddy conditions and found that increasing the height reduced effectiveness of the vehicle. In particular, the increased blade-height captured more mud and resulted in greater motion resistance [3]. Overall, based off of the blade-height-to-drum-diameter ratios tested, 0.125 is the ideal ratio.

2.2.3 Number of Starts. Not much information is available regarding the impact of the number of starts for a screw-vehicle. Nonetheless, Chrysler did perform a study to determine the ideal number of starts. Though the study details were not available, it is apparent that two starts is optimal. The RUC and MSA vehicles each have a design in which there are two starts per screw [8, 14]. Furthermore, Dr. Cole mentions in his research that two starts would be more dynamically balanced than one [14].

2.2.4 Length-to-Drum-Diameter Ratio. The length-to-drum-diameter ratio is an important parameter because it has the greatest influence on the drawbar-pull capacity compared to the helix-angle or blade-height [3]. Unlike the other parameters, the length-to-diameter ratio does not have a monotonic trend of just increasing or decreasing performance as the ratio increases or decreases [3]. Fortunately, when tests were

performed in mud and sand, it was determined the optimum ratio was 6 for both mediums [3].

Another consideration is that increasing the length also increases the number of revolutions of the blade. Dr. Cole theorized that increasing the number of revolutions would have an impact on hydrodynamic driving torque and thrust [14]. From his tests, Dr. Cole concluded that longer screws with more rotations produce much larger driving torque and thrust [14].

2.2.5 Blade-Thickness. The performance due to the thickness of the blades is not explicitly discussed in any available studies. The blades were likely made thick enough to withstand the stresses imparted by the weight of the vehicle and terrain interaction. Also, the material used plays an important role in determining the required structural thickness. It is not entirely evident if there is any importance from the standpoint of performance, but there may be potential impact when on ice.

During shock testing of the RUC, the 0.5-inch blades, on a 39-inch diameter drum, did not fail. However, the screws cracked from loads imparted by the blades [2]. In order to reduce stresses, the blade-height was reduced and a support was added [2]. The support brace was added to the side of the blade opposite of the pushed ground when the vehicle was moving forward.

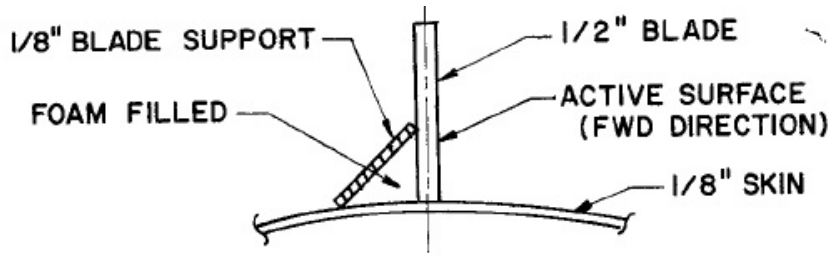


Figure 8: The RUC's blade support [2].

2.2.6 Center of Gravity. Although the location of the longitudinal center of gravity, abbreviated as C.G., is not inherently a characteristic of the screw, it is still worth mentioning for screw-vehicle design. Tests were performed by Chrysler to determine the effects of the location of the C.G. by placing the C.G. at four locations. The locations selected for the testing were 25% forward of the midpoint, at the midpoint, 12.5% aft of the midpoint, and 25% aft of the midpoint [3].

Effectiveness of the C.G. location was determined by monitoring the drawbar-pull capacity as the slip percentage increased. Typically, as slippage increases, the drawbar-pull capacity increases [3]. However, in sand it was shown that when the C.G. was at the front of the vehicle it began to plow into the sand as slippage increased [3]. The final results show that the vehicle operates best in sand with the C.G. at the midpoint or a little aft, and when in mud it works best when the C.G. is at the midpoint [3]. Figure 9 shows that the C.G. is near the midpoint for the RUC.

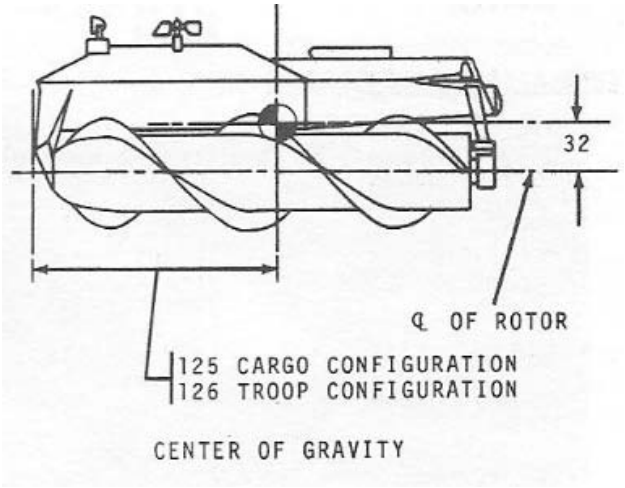


Figure 9: The RUC's center of gravity [9].

2.3 Trafficability Tests

In order to understand the performance of off-road vehicles, it is important to perform trafficability tests. Trafficability tests are tests performed in a uniform terrain that reveal vehicle-to-terrain behavior [9]. Tests may include maximum straight-line speed-tests, maximum maneuver speed-tests, drawbar-pull tests, and repetitive pass, or vehicle cone index, tests [9]. The tests performed on screw-vehicles were meant to determine worst-case operating conditions. As a result, many of the tests resulted in vehicle immobilization.

Maximum straight-line speed-tests and maximum maneuver-speed-tests are exactly what their names imply. They test the fastest a vehicle can possibly travel in a straight line or maneuver through an obstacle course. Drawbar-pull tests are used to determine the ratio of weight an off-road vehicle can tow in comparison to its own weight, and are among the best tests for determining off-road vehicle performance [3]. Vehicle cone index, or VCI, is a measure of the minimum rating cone index, or RCI, required for a terrain to support a vehicle for a specified number of passes [9]. Typically, 50 passes are specified for the VCI test. The number of passes a VCI is tested at is indicated with a subscript showing the number of passes. Therefore, a 50 pass test is VCI_{50}. The RCI is a measure of soil strength, where a low RCI is a soft soil [9]. The value of RCI is found with a tool called a penetrometer.

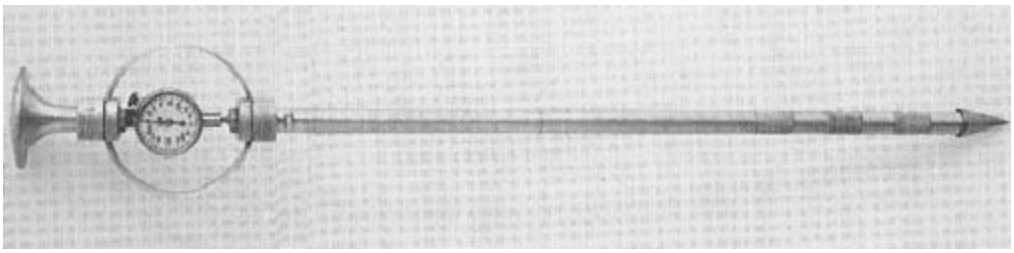


Figure 10: A cone penetrometer [9].

2.3.1 Sand. Sand is characterized by a high coefficient of friction and minimal particle cohesion when dry [8]. From trafficability tests performed on the MSA, it is evident that characteristics of sand work against screw-vehicle performance. The RCI of the sand averaged at 95 and ranged from 46-159 during the testing, but it was determined that the impact of the RCI was minimal in sand [8].

During repetitive pass tests, the MSA displayed difficulty driving straight when unloaded. Furthermore, when it was loaded, it could only make 2 to 3 passes at full throttle [8]. An explanation is when the MSA was unloaded the blades may not have dug in as much and skipped. Alternatively, while loaded the screws may have needed more power to rotate. When driving slower, the MSA was able to complete 50 passes. The MSA was unique to conventional vehicles because it encountered increased difficulty on successive passes after the first pass [8]. Conventional vehicles, on the other hand, can make an indefinite number of passes on loose dry sand if they can make the first pass [8].

The maximum speed tests showed the MSA travelled slowly in sand with 2.3 mph at the fastest and 1.0 mph at the slowest in full throttle [8]. Also, the MSA could not pass any maneuver tests without becoming

immobilized. In addition, the drawbar-pull of the MSA was much less than an equivalently powerful tracked vehicle, the M29C Weasel. The M29C Weasel was considered to display trafficability results that were standard for tracked vehicles [8].

Dr. Cole's testing in sand was more optimistic than the MSA trafficability tests. During Dr. Cole's testing of screw performance, he noted that the screws deformed the ground the most over loose, dry sand [14]. However, he added that the ground deformation was not as bad for screws as for conventional wheels [14]. He further noted that drawbar-pull capacity increased for greater sand compaction and moisture content [14].

Tests showed the MSA travelled laterally with ease. Therefore, the difficulty of the MSA in sand was due to its screws. More specifically, the poor performance of a screw-vehicle in sand was attributed to the frictional resistance of sand meeting or exceeding the tractive-force of the screws [8].

2.3.2 Fine-Grained Soil. Trafficability tests were performed on the MSA in fine-grained soils of varying moisture content and RCI values. The MSA was able to operate in softer terrain with a VCI_{50} of 5 compared to the M29C Weasel with a VCI_{50} of 15 [8]. The tests showed that the moisture content of the soil played a larger role in performance than the RCI. More importantly, the less friction, the better the MSA performed [8]. An example of the importance of reducing friction was the MSA showed improved performance when there was slick grass on the soil [8].

The MSA performed better than the M29C Weasel in many of the fine-grained soil tests. Nonetheless, due to the demanding nature of trafficability

studies, there were several conditions that immobilized the MSA. In soil that was too soft to support the MSA, the carriage bulldozed into the soil. When the carriage bulldozed into the soil, the tractive-force of the screws was less than the motion resistance from the bulldozing [8]. The researchers noted that if the soil was wetter, the soil could have been marshy enough to minimize the bulldozing from the carriage and permit locomotion [8]. Another condition that immobilized the MSA was when the soil was sticky, soft, and dry. In sticky, soft and dry soil, the soil adhered to the screws and prevented the screws from turning [8]. When the same soil was moistened with water, the MSA was able to pass the terrain [8].

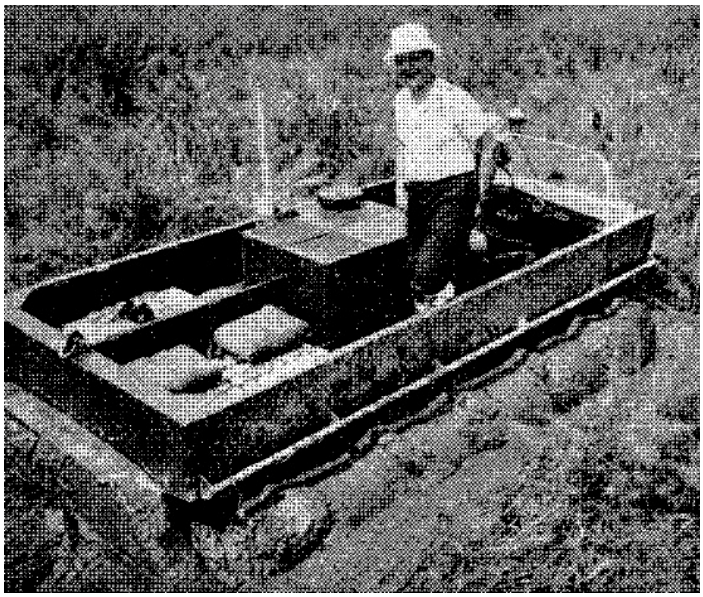


Figure 11: The MSA buried on pass 36 [8].

Maximum speed tests showed that the MSA went as fast as 5 mph on the softest soil tested with an RCI of 10. When the RCI was as firm as 20, the speed dropped to 2 mph. The MSA was also tested on soil with 3- to 6-inches of water on the surface of the soil, and the vehicle reached speeds of nearly 20 mph [8].

The overall performance of the MSA can be simplified to less friction is better, and although soft soil is typically ideal it cannot be generalized as being optimum. For example, soft soil can allow the vehicle to sink and bulldoze. In addition, drawbar-pull tests showed maximum pull test values at an RCI of 40, because the soil was firm enough to limit rutting but soft enough to allow blade penetration [8]. A potential solution to the first issue is to design a vehicle in which the screws provide sufficient flotation to keep the hull out of the soil.

2.3.3 Snow. The MSA was also tested in deep snow. Based on the results of the fine-grain soil testing, snow has ideal characteristics for locomotion. The actual report concerning the snow tests could not be obtained, but a paper summarizing the various MSA trafficability tests mentions that the MSA reached speeds of 20 to 25 mph in deep snow [1]. In comparison to the speeds of 2 to 5 mph in dry soil, it is evident that the MSA performs well in snow. The MSA travelled at approximately 20 mph in mud with a large layer of water, slightly slower than snow, further emphasizing the importance of low friction on the performance of the MSA.

2.3.4 Water. Dr. Cole performed a variety of tests on screws in water. He placed the screws in four different water depths to observe the differences in torque and thrust. Specifically, he experimented with the screw-axis 12-inches below the surface and 3-inches below the surface, the blade-tip slightly breaking the surface, and with the screw-axis directly at the surface [14]. When the depth of immersion was less, the torque and thrust decreased [14]. Specifically, when the screw was exposed to air, the torque

and thrust significantly dropped [14]. Clearly, the torque and thrust reached a maximum at the deep immersion condition. With the screw-axis submerged 12-inches, the torque and thrust were nearly proportional to the square of the rotational speed of the screw [14]. Dr. Cole ran the screws at speeds of up to 2300 RPM with no cavitation [14].

Tests were also performed in water on the MSA. The primary observations made from tests in water were that it was stable in water and responded readily to steering [8]. In addition, the maximum speed the MSA travelled at in water was 5 to 6 mph [8]. The speed the MSA travelled at in water was similar to the soft, dry terrain but not as fast as the soft and wet terrain.

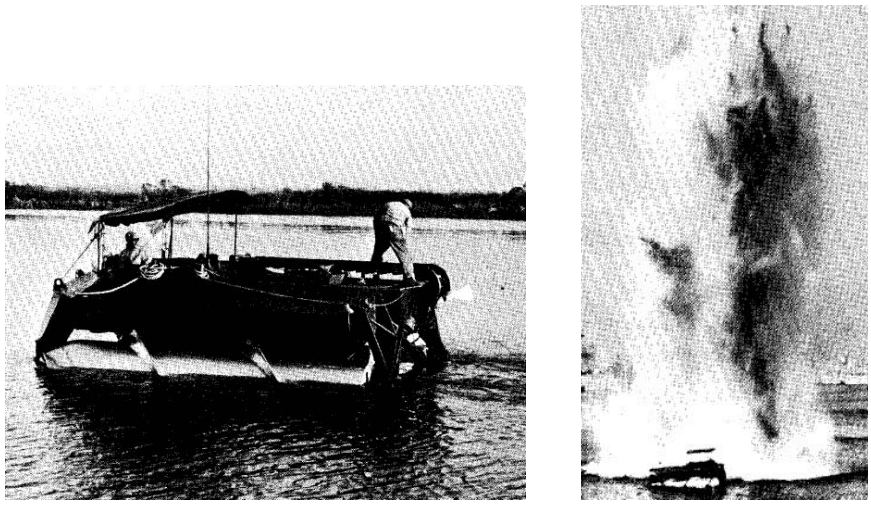


Figure 12: The RUC performing a mine sweep test [2].

2.3.5 Trafficability Tests Summary. From the testing on the MSA, it was concluded that its performance spectrum was the opposite of wheeled and tracked vehicles. Specifically, the MSA performed better in wet and soft soils of low friction in comparison to dry, firm, frictional soils [1]. They also concluded that it was largely unaffected by vegetation, it worked well in

water and worked best in mud, excluding sticky mud, of low water content, that is firm enough to walk on. Sticky, dry and firm mud had a tendency to stick to the screws enough to seize them up [1]. Also, it was shown that the screw vehicle should be heavy enough for blade penetration, but not so heavy that the power required to rotate is too large.

The trafficability tests discussed provide a detailed account of a screw-vehicle's performance. However, all of the testing reviewed has been limited to double-screw-vehicles. Furthermore, after Chrysler's MSA testing, they concluded that future tests were desirable for hard-ground maneuverability and for improvements in sand [15].

CHAPTER 3: THE DOUBLE-SCREW

3.1 Capabilities

All of the studies discussed thus far were about vehicles with a single pair of opposite-handed screws. In this thesis, the screw configuration just described is called the double-screw, and applies to any vehicle or robot that employs this mode of locomotion. As will be discussed, many more configurations of screws can exist for a screw-vehicle, so the names must be kept simple.

In this study, three basic motions are necessary for a screw-vehicle to be considered omnidirectional.

- Longitudinal: Forward and backward locomotion.
- Lateral: Transverse locomotion similar to a crab's locomotion.
- Rotational: Locomotion that is ideally about the vehicle's center.

Figure 13 shows the forces imparted on left- and right-handed screws by a compliant surface. Specifically, figure 13 shows what is termed tractive- and rolling-force in this study. The tractive-force is along the screw's axis while the rolling-force is directed perpendicular to the screw's axis. Clearly, tractive- and rolling-forces depend on the direction of rotation and the handedness of the screw's blade.

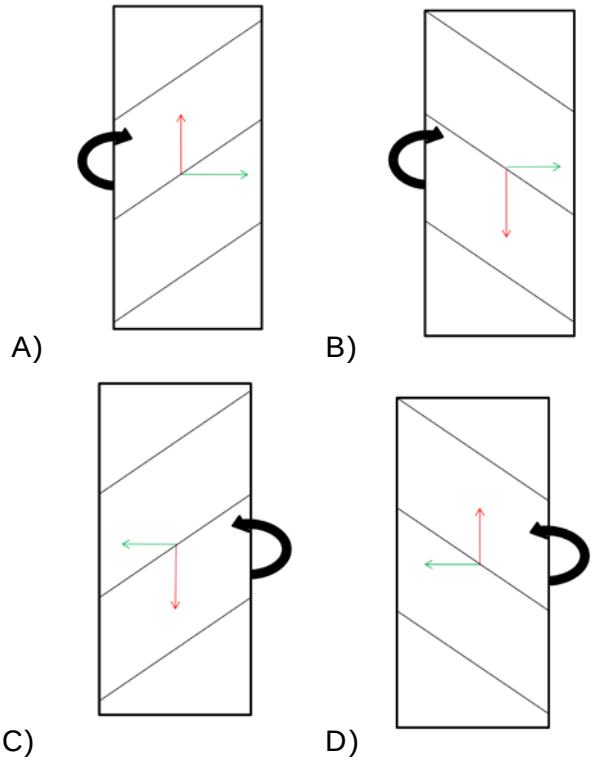


Figure 13: Rolling- and tractive-forces imparted on screws by a soft terrain. A) Right-hand, clockwise B) Left-hand, clockwise C) Right-hand, counter-clockwise D) Left-hand, counter-clockwise

The tractive- and rolling-forces are what cause locomotion. Therefore, the tractive-force pushes a screw longitudinally forward or backward. Alternatively, the rolling-force produces lateral, left and right, locomotion. Through different orientations of screws and different directions of screw rotation, a variety of directions of net locomotion are possible.

In this study, all of the screws were assumed to rotate at the same speed. Therefore, all tractive-forces were considered equal, and all rolling-forces were considered equal. However, the tractive- and rolling-forces were not necessarily the same. The tractive- and rolling-forces weren't always considered the same because the magnitude of each force would vary depending on the helix-angle, the friction between the screw and terrain, the

depth of penetration of the screw's blade, the cohesion of particles within the terrain, and the terrain's softness.

3.1.1 Counter-Rotating Screws. With the double-screw, longitudinal locomotion is achieved in water and soft terrain by simply counter-rotating the screws at the same speed. On rigid surfaces, excluding ice, the screws cannot easily dig into the ground, and so the tractive-forces that produce forward or backward locomotion are negligible. On the contrary, friction and, as a result, rolling-forces are sufficient for locomotion on pavement. Since rolling-forces are friction dependent, on low-friction water the rolling-forces are negligible compared to the tractive-forces. Figure 14 shows the forces imposed on a pair of screws and the resulting locomotion. It should be noted that by reversing the directions of the counter-rotating screws the system moves in the opposite direction.

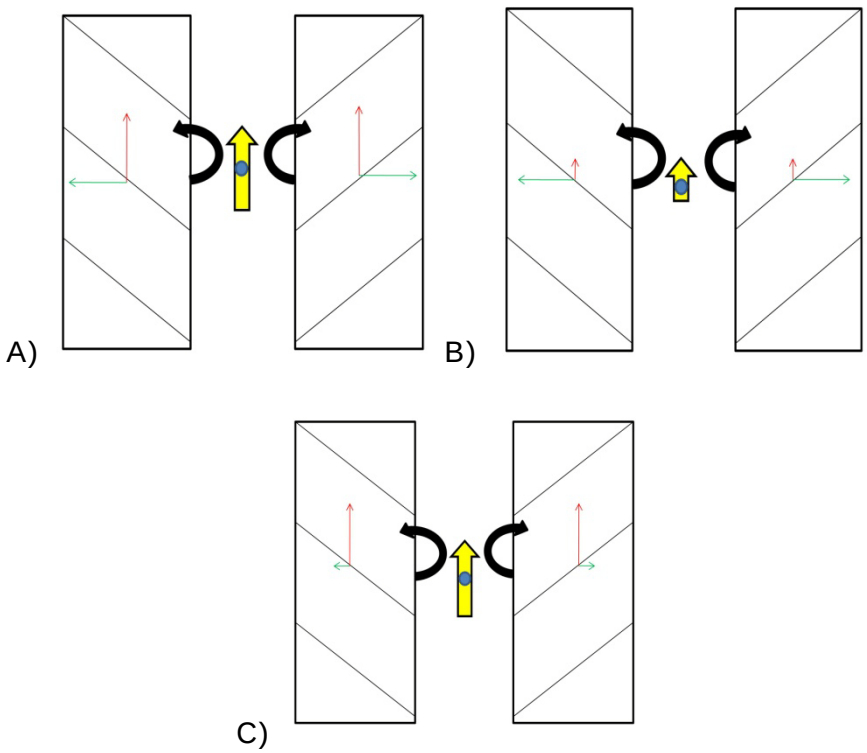


Figure 14: Screws counter-rotating on different surfaces.
A) Compliant surface B) Rigid surface (small force) C) Water

3.1.2 Co-Rotating Screws. On paved ground, if both screws are rotated in the same direction and speed, a crab-like, lateral locomotion is produced. In contrast to longitudinal locomotion, pure lateral locomotion is only possible on paved or other rigid surfaces. The fact that a double-screw cannot move longitudinally but can move laterally on pavement is similar to why the opposite is true of a bicycle. When the wheels on a bicycle are counter-rotated, no meaningful locomotion is produced. However, forward and backward locomotion is viable when rotated in the same direction. In both cases the vehicles cannot travel along the axis of rotation and locomotion is only produced when the wheels are moved in the same direction.

In soft ground, a double-screw vehicle with co-rotating screws will travel in a curved path. The path is more curved in softer soil because the blades interact with the soil more. Therefore, pure lateral locomotion does not occur on soil for a double-screw. Similarly, lateral locomotion is not possible on water with a double-screw. On water, the rolling-force of the screw is negligible, and the screws produce a net rotational locomotion. Figure 15 illustrates how a double-screw moves on different surfaces when the screws are turned in the same direction. Again, reversing the direction of the screws will move the double-screw in the opposite direction.

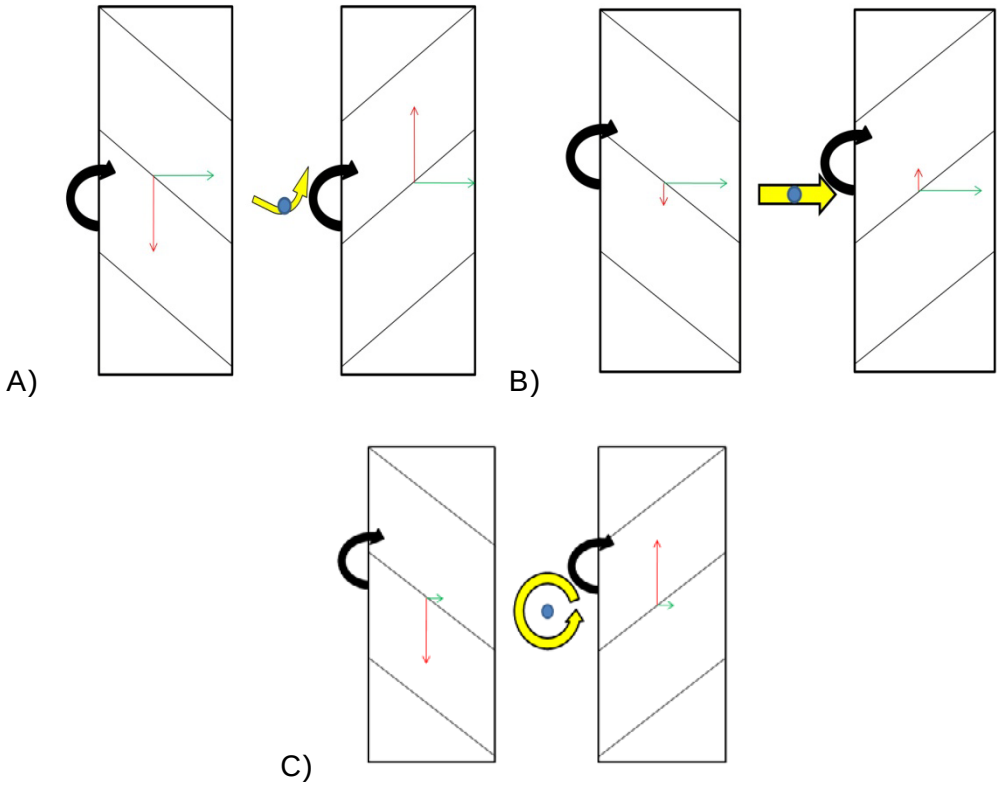


Figure 15: Screws co-rotating in different terrains.
A) Compliant surface B) Rigid surface C) Water

3.1.3 Turning. The method and capability of turning depends on the type of ground a double-screw is on. When aground, one method of turning

relies upon either not rotating one of the screws or by varying the revolutions per minute (RPMs) between both screws; this method of turning is termed skid-turning [9]. Skid-turning works best on soft, cohesive ground and is nearly impossible in RCI's firmer than 6 [9]. Figure 16 shows skid-turning by rotating the left screw.

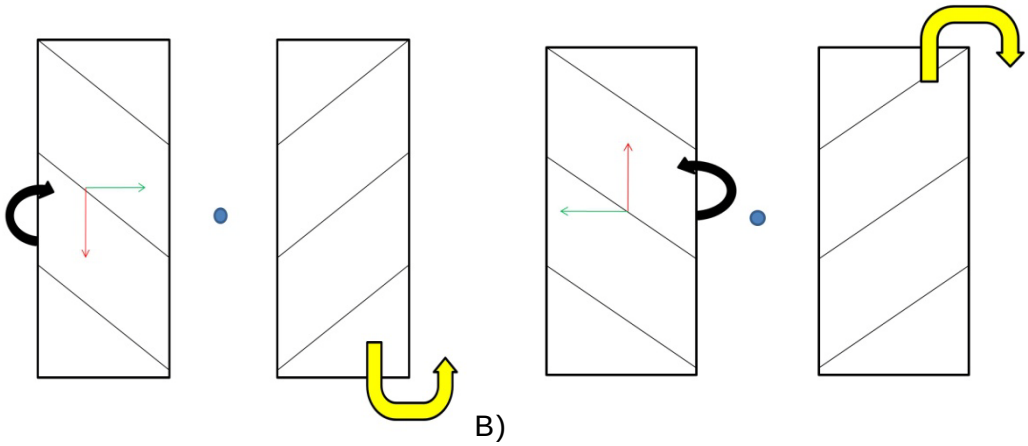


Figure 16: Screws skid-turning on soft ground.
A) Left screw rotating clockwise B) Left screw rotating counter-clockwise

The turning radius for skid-turning relies on the resistance to the stationary screw and the amount of tractive-force generated by the rotating screw. Therefore, the turning radius for skid-turning on a compliant surface is tighter than in water because the stationary screw has less resistance to hold it in place in water. In addition, skid turning does not work on pavement because it either results in no net locomotion or straight, lateral locomotion; the result depends on whether the stationary screw is locked or free to rotate.

As discussed in the lateral locomotion section, another method of turning is rotating both screws in the same direction and at the same speed. In firm soil, turning the screws in the same direction causes the vehicle to

travel in a wide arc, and this turning is called arc-turning [9]. In soft cohesive ground, such as marsh, turning the screws in the same direction causes the vehicle to turn in a much tighter circle and is termed pivot-turning [9]. During pivot-turning, the blades dominate the direction in which the vehicle travels and produce a tight pivot [9]. Similarly, in water, any lateral locomotion produced by the rotation of the drums is negligible and the effect of the blade is dominant. Therefore, a double-screw will turn approximately about its center on water when the screws are rotated in the same direction. Figure 15 in the co-rotation section shows pivot-turning, arc-turning, and turning in water.

Finally, on pavement, no combination of screw motions can allow a double-screw to turn, except potentially on ice. There were no resources describing turning capability on ice found. Nonetheless, an exception to the lack of turning capability of a double-screw on rigid surfaces is the patented Tyco® Terrain Twister, a plastic radio-controlled toy. The Terrain Twister has the ability to hinge its screws several degrees about the vertical axis of their center points. The turning radius of a hinging, double-screw on pavement is given by formula 1 and is shown in figure 17.

$$r = \frac{c}{2\sin(\theta)} + \frac{l}{2} \qquad (1)$$

Where:

r= Turning radius

c= Center-to-center of screws

θ= Hinge-angle

l= Drum-length

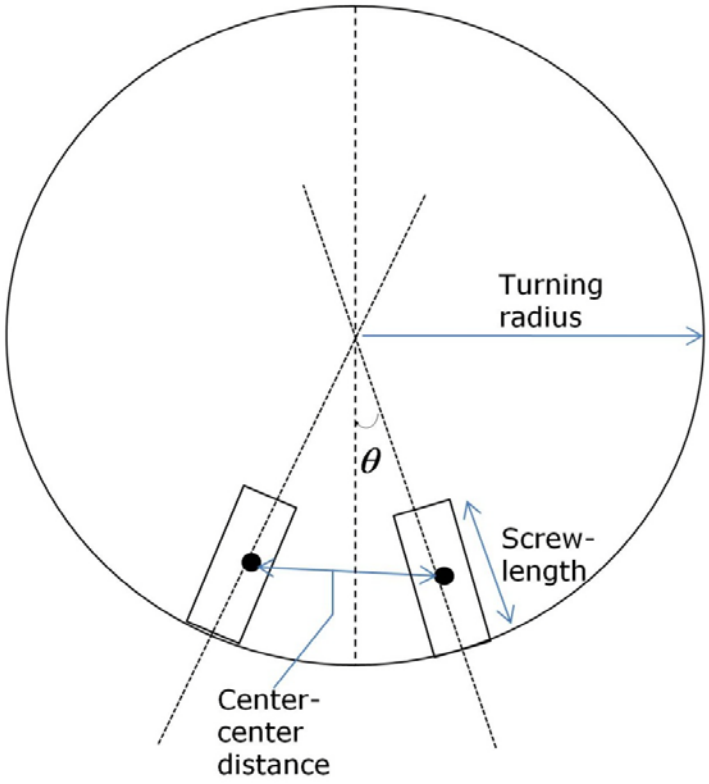


Figure 17: The turning radius of hinged-screws.

The turning radius is smallest when θ=90°, as shown in formula 2 and figure 18.

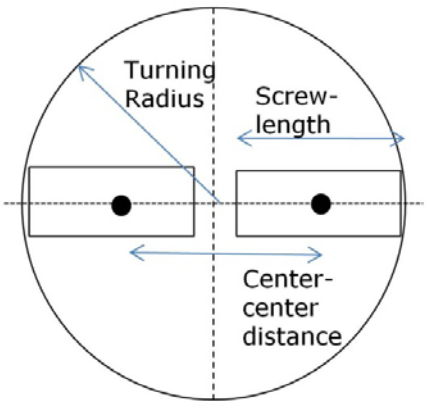


Figure 18: The minimum turning radius for hinged-screws.

$$r = \frac{c}{2} + \frac{l}{2} \qquad (2)$$

3.2 Limitations

The double-screw is capable of moving in many directions and over a wide range of terrains. However, they are not fully omnidirectional and their locomotion capabilities vary depending on the terrain. This section discusses, in detail, the limitations of the double-screw from the perspective of omnidirectional locomotion. A discussion for each limitation is given regarding if it can be remedied with a different configuration of screws.

The first limitation of a double-screw to consider is its inability to move longitudinally on a rigid surface. Unfortunately, due to the nature of screw locomotion, there may be little that can be done to improve longitudinal locomotion on pavement. As will be discussed, a solution is to employ a combination of lateral locomotion and rotation to overcome rigid obstacles such as pavement.

Another limitation of the double-screw is the impure lateral movement on all but the most rigid surfaces. Clearly, controlling a vehicle can be cumbersome if it tends to follow an arced path. Furthermore, control issues are exacerbated by the variable nature of the arc. Specifically, a double-screw makes a wide arc on firmer ground but nearly turns about its center on soft soil. As will be discussed, this issue can also be overcome with another configuration of screws.

The final limitation of the double-screw is rotation. Although turning is possible on all surfaces, the efficacy and method of turning is not consistent for each surface. An ideal system would employ the same method of turning on any surface and always be capable of turning about its center.

One of the turning methods discussed was skid-turning. Skid-turning is incapable of turning the vehicle directly about its center point. As a result, skid-turning requires more space for maneuvering than an ideal turning method. Furthermore, the stationary screw is forced to skid or plow across the surface of the ground, thereby reducing turning time and possibly damaging the screw thread. Tests performed on the RUC show that pivot-turning is quicker than skid-turning on soils in which both are possible [9].

Turning is possible on hard surfaces by utilizing hinged-screws. In the case of the Terrain Twister, its unique hinged-screws allow for steering on hard surfaces, but since the screws do not hinge 90^{o}, the turning radius is not about its center. Furthermore, the action of hinging the screws takes time and may damage the screws or pavement by scraping the blades along the surface. In all, the benefit of hinged-screws may be further reduced due to complicated design. In particular, hinged-screws require more joints than a non-hinging double-screw and require a mechanism, such as an actuator, to perform the hinging motion.



Figure 19: An example of hinged-screws.

Finally, when rotating the screws in the same direction on increasingly soft soils, arc- and pivot-turning is possible. The degree of arc in the path depends on the helix-angle, the weight of the vehicle and the softness of the soil. The issue of firm soil, in which the blades cannot fully dig into the soil, is clear because the turning radius is wide. However, even when the double-screw is pivot-turning on very soft soil, it does not turn about its center.

CHAPTER 4: ALTERNATIVE SCREW CONFIGURATIONS

4.1 Overview

Chapters 2 and 3 discussed the issues that the double-screw has regarding locomotion on different terrains. Nonetheless, a screw-vehicle, in general, likely has the potential to overcome many of the limitations of a double-screw. Several new screw configurations have been considered prior to building a test-bed. This chapter outlines the assumptions and analysis made about each configuration of screws considered.

This chapter includes vector analysis for screw configurations of interest. Additional vector analyses are provided in appendices A through C. In vector analyses in this chapter and appendices A through C, tractive-forces are red arrows, as are the moments resulting from those tractive-forces; while the rolling-forces are green arrows, as are the moments resulting from the rolling-forces. Lastly, yellow arrows indicate the net direction of locomotion.

4.2 Bendable-Screw

Among the first solutions considered to resolve the limitations of the double-screw was the adoption of a bendable-screw. The concept of the bendable-screw was that it could be bent to steer the vehicle. By bending

the ends of the screws toward the vehicle's hull, rotation about the center of the vehicle may be possible. Furthermore, by bending the front of both screws either left or right, the vehicle may be able to travel in the direction the screws point to.

In theory, bendable-screws may be promising from the perspective of turning. However, two bendable-screws alone would not resolve the issue of arced locomotion. Furthermore, there were many complications that could have arisen when developing a bendable-screw.

A known issue was that bending a screw places tension on one side of the screw and compression on the other side. When the screw begins rotating, the tension and compression alternates, resulting in cyclical stress. The cyclical tension- and compression-stresses imposed on the blades could have resulted in failure.

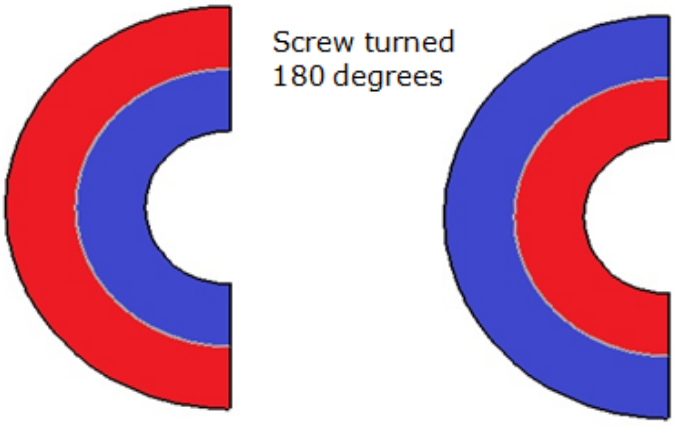


Figure 20: Red and blue halves experiencing alternating tension.

If a material was used that could withstand the alternating stresses imposed by bending a rotating screw, another complication would have still existed. In order for a bendable-screw to work, it was important that the

screw remain flat on the ground while it rotated about its center axis. A likely problem was that the screw may rotate about the axis projected through its two endpoints. The result would have been a screw that rotates similar to a jump-rope and with no effect from the blades. In summary, since the best design is the simplest design, the bendable-screw was not pursued.

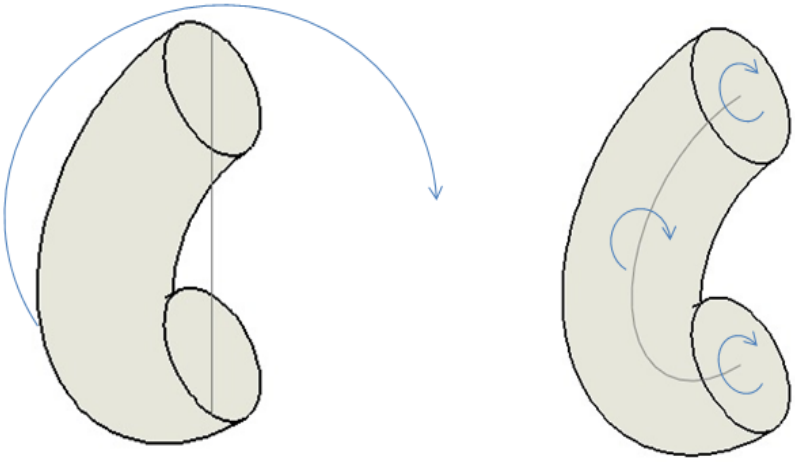


Figure 21: Modes of rotation for a bendable-screw.

4.3 Split-Screw

Another configuration considered for a screw-vehicle was one with four screws. Specifically, the screws would be oriented in a box formation in which the front- and rear-screws would be axially aligned and the screws on the left and right side would be fixed parallel to each other. The parallel screws would have opposite blade handedness, similar to the double-screw, while the screws directly behind the front-screws would have the same blade handedness as those directly in front of them. The configuration described is essentially the same as the double-screw with the freedom to rotate the

front- and rear-screws independently. Therefore, the screw configuration described is called the “split-screw” throughout this thesis.

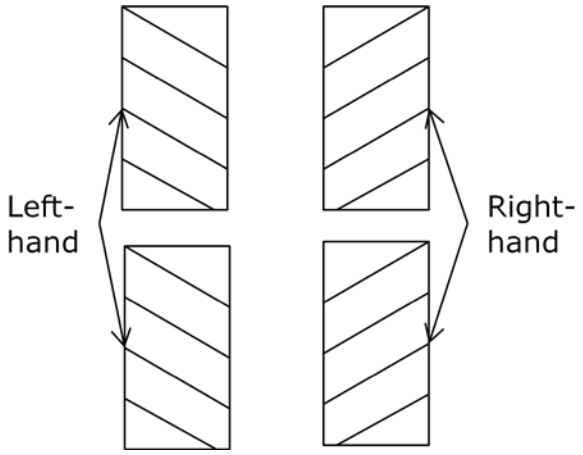


Figure 22: Top view of the split-screw layout.

From the perspective of skid-turning, moving forward, backward, and laterally, the split-screw was presumed to act the same as a vehicle with two screws. In order to behave exactly like a double-screw, the screws in the rear must turn in the same direction and speed as the screws directly in front. As shown in figure 23-B, straight lateral locomotion was not considered possible in soft soils.

The assumed advantage of the split-screw over the double-screw was turning could become possible on solid surfaces and improve on soft surfaces. Turning was thought to be similar to a tank. When the screws in the front are rotating in the same direction and the screws in the rear are rotating in the other direction, the vehicle could possibly turn about its center on hard and soft surfaces. Figure 23-C shows a vector analysis of a rotating split-screw. Clearly, the tractive- and rolling-forces cancel and the moment due to tractive-forces cancel, leaving the moment due to rolling-forces to generate clockwise rotation.

In summary, full experimental testing was not carried out on the split-screw because it showed minimal improvement over the double-screw, except that it could rotate about its center. Since it was critical that a screw-configuration be developed that could move in a straight, lateral direction on any surface, more configurations were investigated.

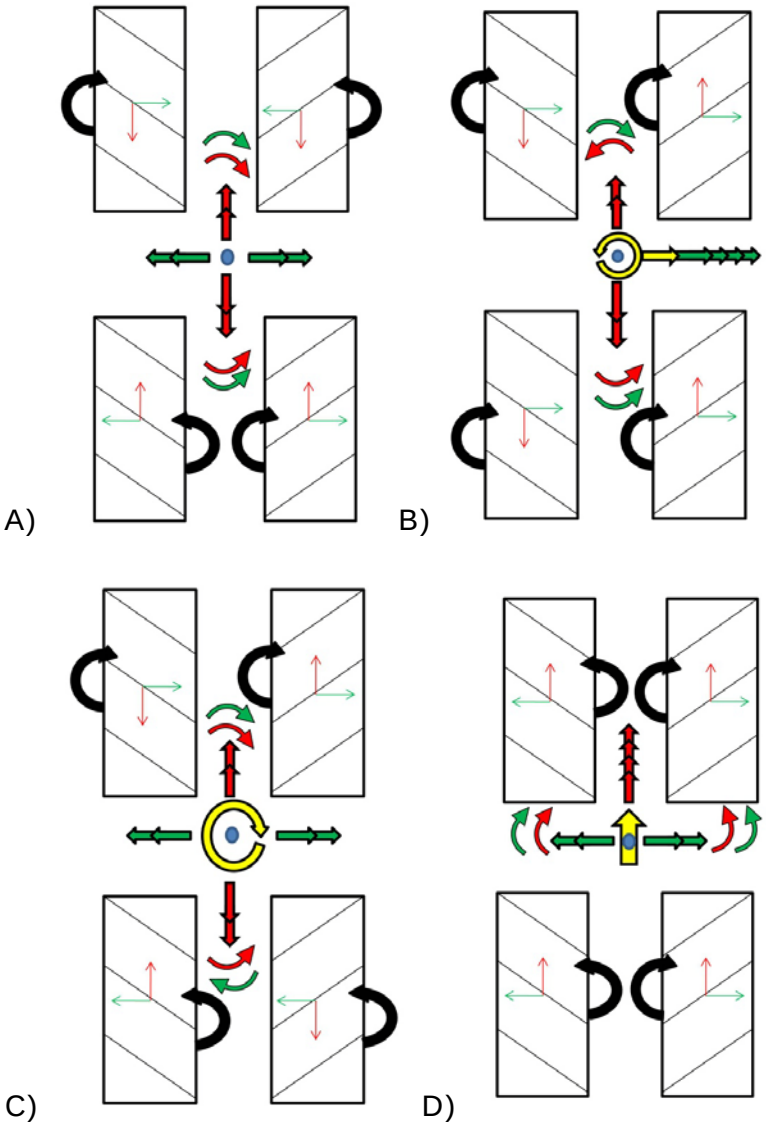


Figure 23: Four symmetric screw rotations for the split-screw. A) No locomotion B) Lateral (impure skew motion) C) Rotational D) Longitudinal

4.4 Inline-Screw

Another configuration utilizing four screws which was considered was one in which the screws are similar to the split-screw. However, each screw's handedness alternates. As a result, the described screw configuration is unique to the double-screw. Therefore, the screw configuration described is termed "inline-quad-screw", or simply inline-screw, in this thesis.

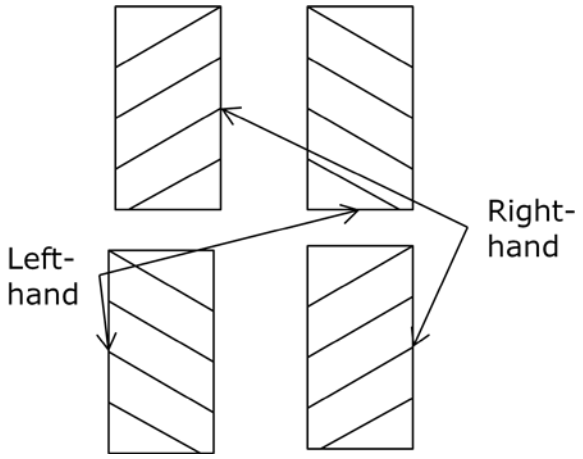


Figure 24: A top view of the inline-screw.

Figure 24 illustrates the inline-screw configuration specifically used for the test-bed. An alternative inline-screw configuration has each left- and right-handed screw switched; this screw-pattern is termed the mirrored-inline-screw in this study. Appendix C shows the vector analyses for the mirrored-inline-screw.

For the inline-screw, longitudinal locomotion is not achieved in the same manner as the double-screw or the split-screw. Instead, in order to go forward and backward, the front must be counter-rotated and the back must be counter-rotated in the opposite direction of the front. To get rotation

about the vehicle's center, the front-screws are rotated in one direction while the rear-screws are rotated in the opposite direction.

Similar to the split-screw, the inline-screw can rotate about its center. Furthermore, its turning radius is dictated by the size of the vehicle. The turning radius of the inline-screw is given by formula 3 and is shown in figure 25.

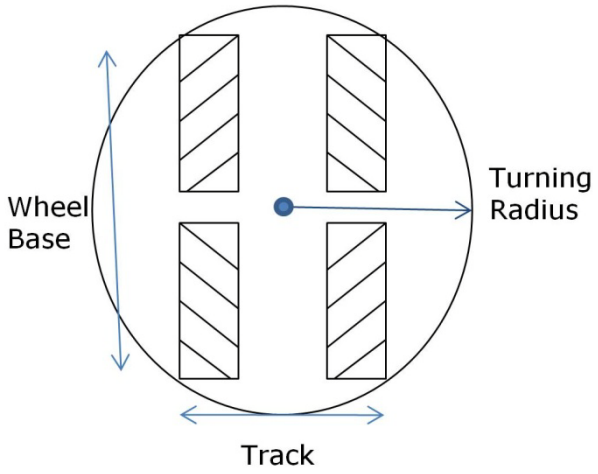


Figure 25: The turning radius of an inline-screw.

$$r = \sqrt{\left(\frac{Track}{2}\right)^2 + \left(\frac{Wheelbase}{2}\right)^2} \qquad (3)$$

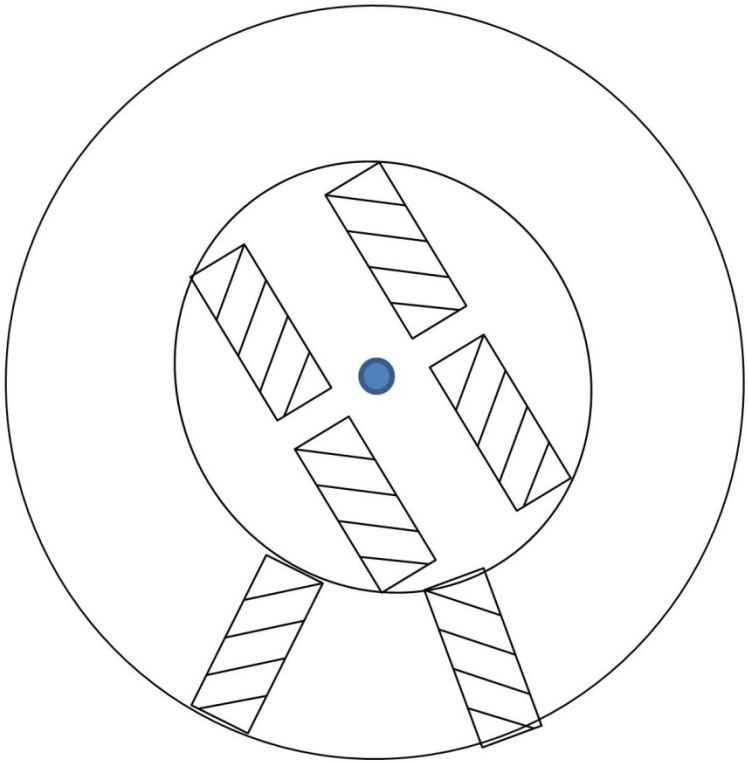


Figure 26: The turning radius of an inline-screw superimposed on a hinged screw's turning radius.

A major advantage of the inline-screw over the split-screw was determined to be when attempting lateral locomotion in soft, wet terrain. Since the screws are of opposite direction on the inline-screw, the front- and rear-screws were presumed to attempt to travel in opposing arced paths. The result would be cancelation of both arced paths and the creation of a straight, lateral path. More specifically, all of the moments created by the tractive-forces cancel out during lateral motion. Since the inline-screw shows promising directions of locomotion, it was chosen to undergo all of the tests in this study.

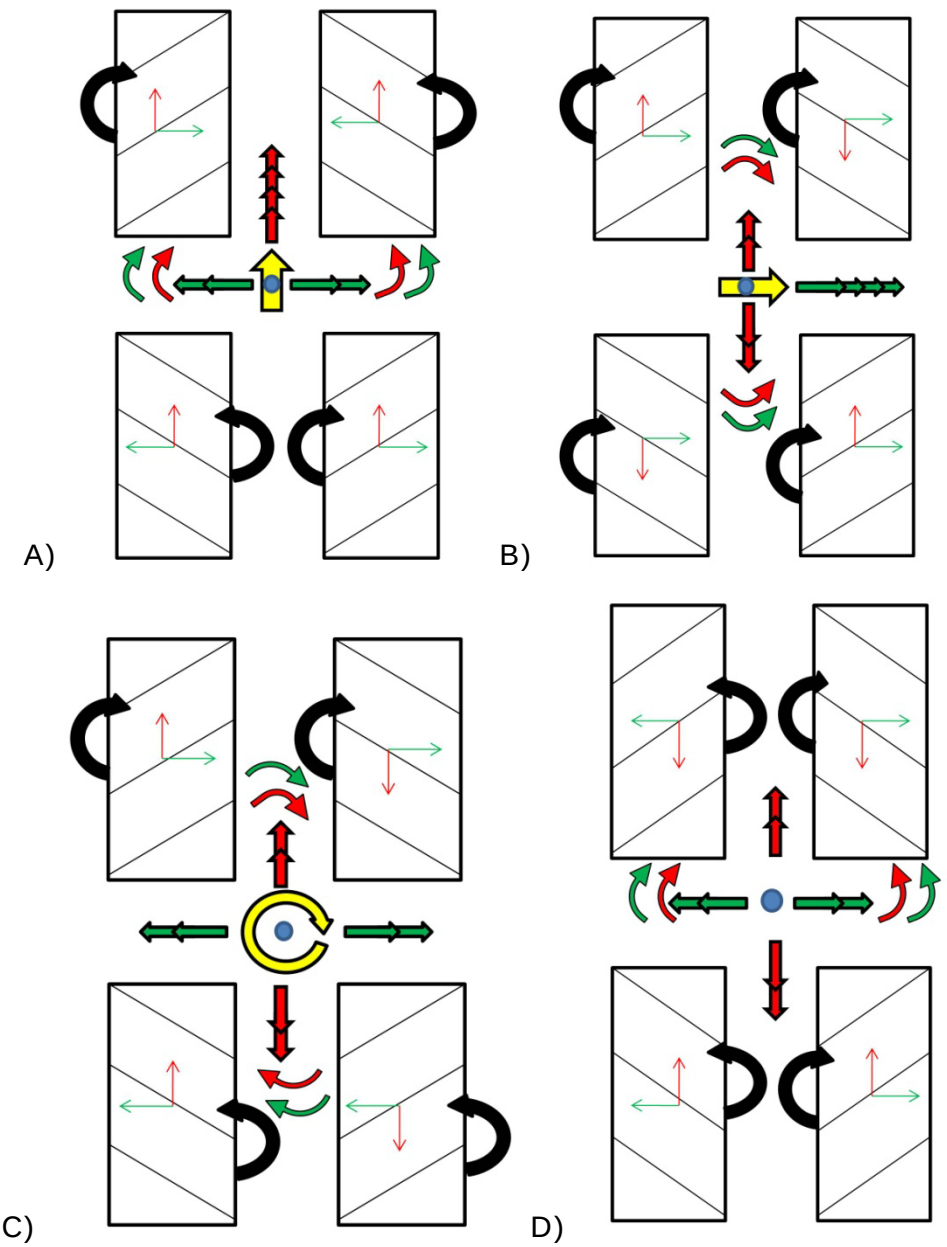


Figure 27: Four symmetric screw rotations for the inline-screw.
A) Longitudinal B) Lateral C) Rotational D) No locomotion

Comparing figure 27 to figure 28 shows that reversing the direction of each screw's rotation, for each symmetric switch pattern, results in the inline-screw moving in the opposite direction. This is true for all double- and quad-screw-configurations.

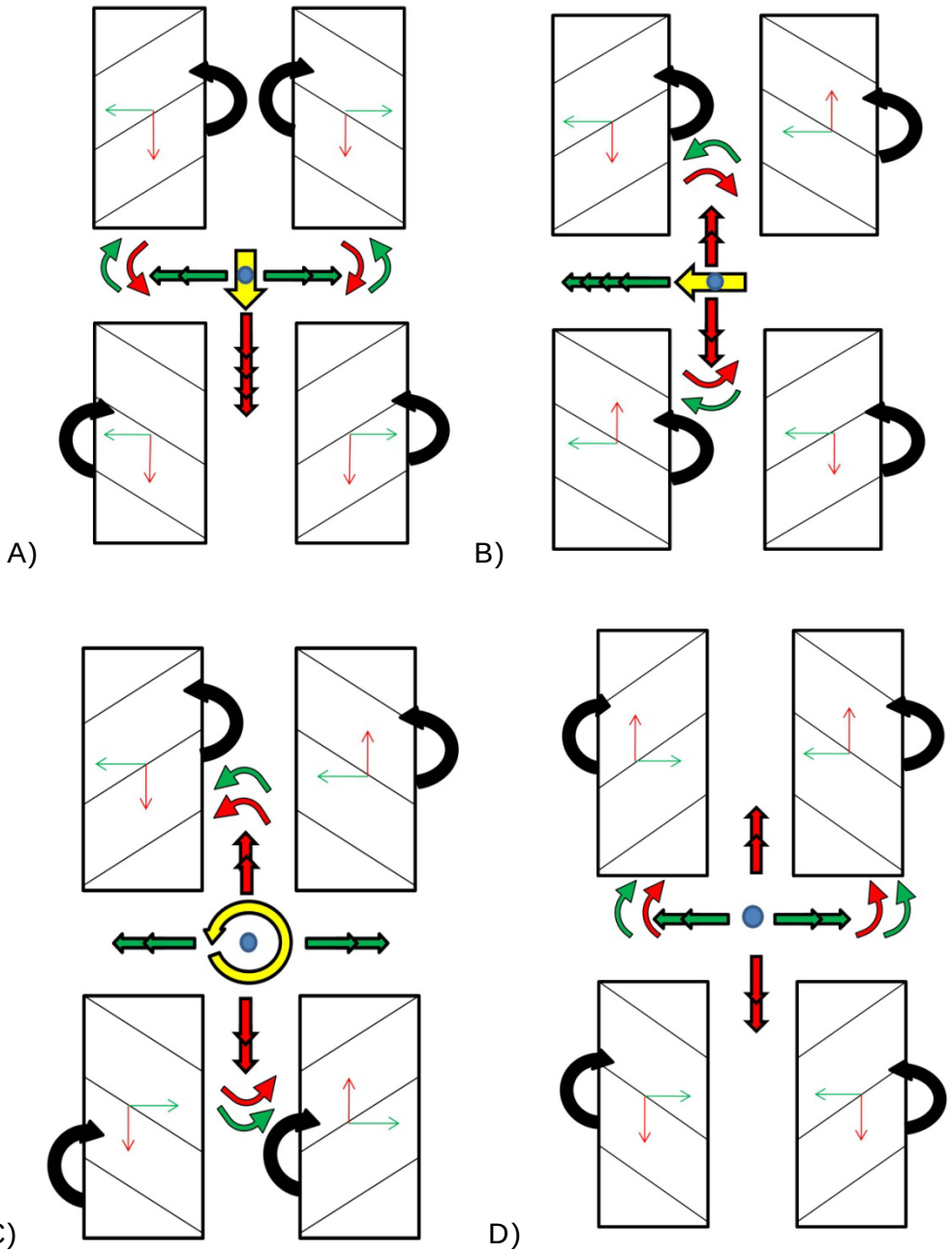


Figure 28: Reversing the direction of rotation for each symmetric switch pattern results in the opposite direction of locomotion.
A) Backward B) Left C) Counter-clockwise D) No locomotion

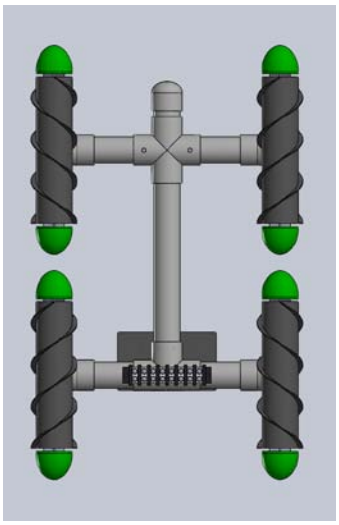


Figure 29: Model of the inline-screw.

4.5 Cross-Screw and Diamond-Screw

Other interesting screw-configurations consist of cross and diamond shapes. The screws are located in the same pattern as the inline-screw, except the screws are not inline. The cross-shaped configuration is oriented with all four screws pointing to the center of the vehicle, while the diamond-shaped configuration has each screw perpendicular to the cross orientation. The described configurations are termed the cross-screw and diamond-screw, respectively, and can be seen in figure 30.

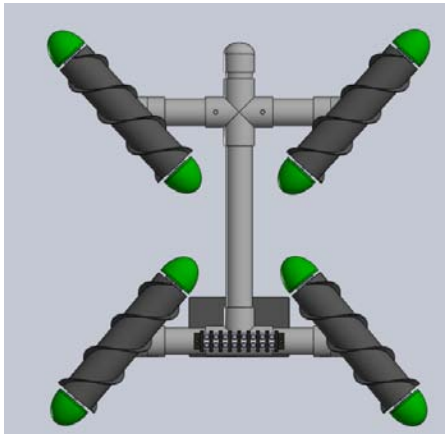
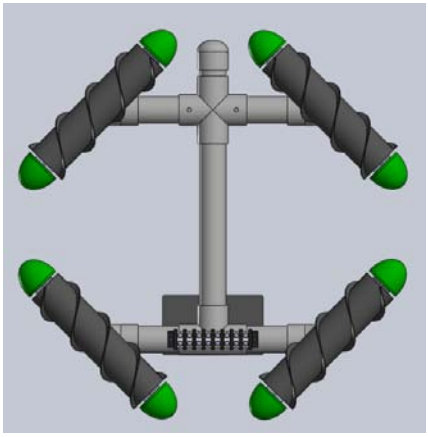
A)  B) 

Figure 30: Models of the cross-screw and diamond-screw.
A) Cross-screw B) Diamond-screw

Clearly, the diamond-screw and cross-screw can also exist for the split-screw configuration. Figures 32 and 33 show the vector analyses of the cross-screw and diamond-screw, while appendices A and B show the split-screw's cross- and diamond-shaped vector analysis. A review of each vector analysis reveals that the cross-screw and diamond-screw are superior to their split-screw counterparts. Therefore, the split-screw's cross- and diamond-shaped configurations are not tested in this study. Furthermore, for simplicity, the split-screw's cross- and diamond-shaped configurations are called the S-cross-screw and S-diamond-screw. Finally, just as there is a mirrored version of the inline-screw, there are mirrored versions of the diamond-screw and cross-screw. Only one version of the diamond-screw and cross-screw were tested. The diamond-screw and cross-screw had their screws in the same order as the inline-screw that was tested.

Unlike the inline-screw proposed here, the cross-screw and diamond-screw are not new, but were discovered during a patent search of screw-vehicles. The order of screws for the diamond-screw and cross-screw in the patent matched the order tested in this study. Since the diamond-screw and cross-screw were patented concepts with no evidence of a scientific study, they were tested in all of the same conditions as the inline-screw. Furthermore, by testing the cross-screw and diamond-screw, the roles of the tractive- and rolling-forces were better understood.

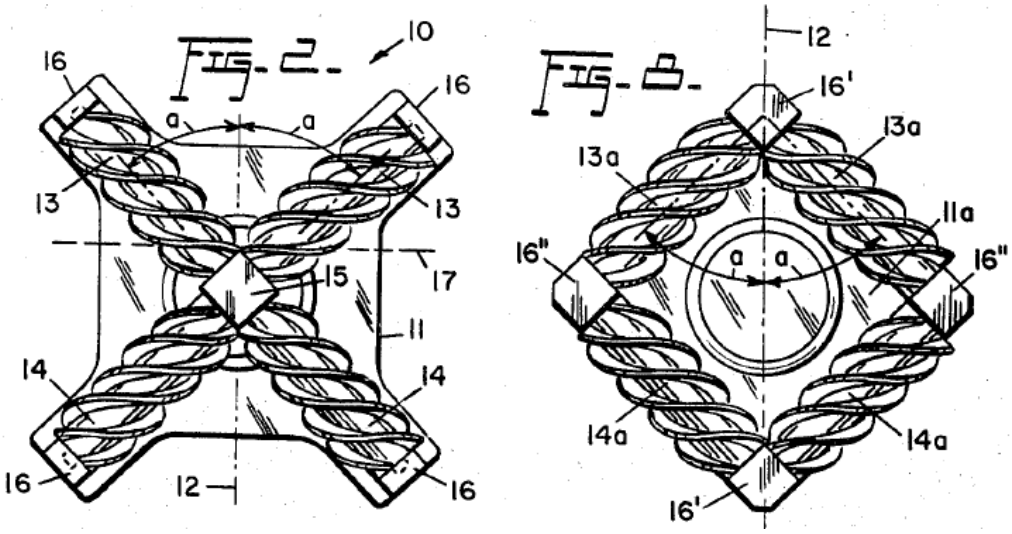


Figure 31: The patented cross-screw and diamond-screw configurations [16].

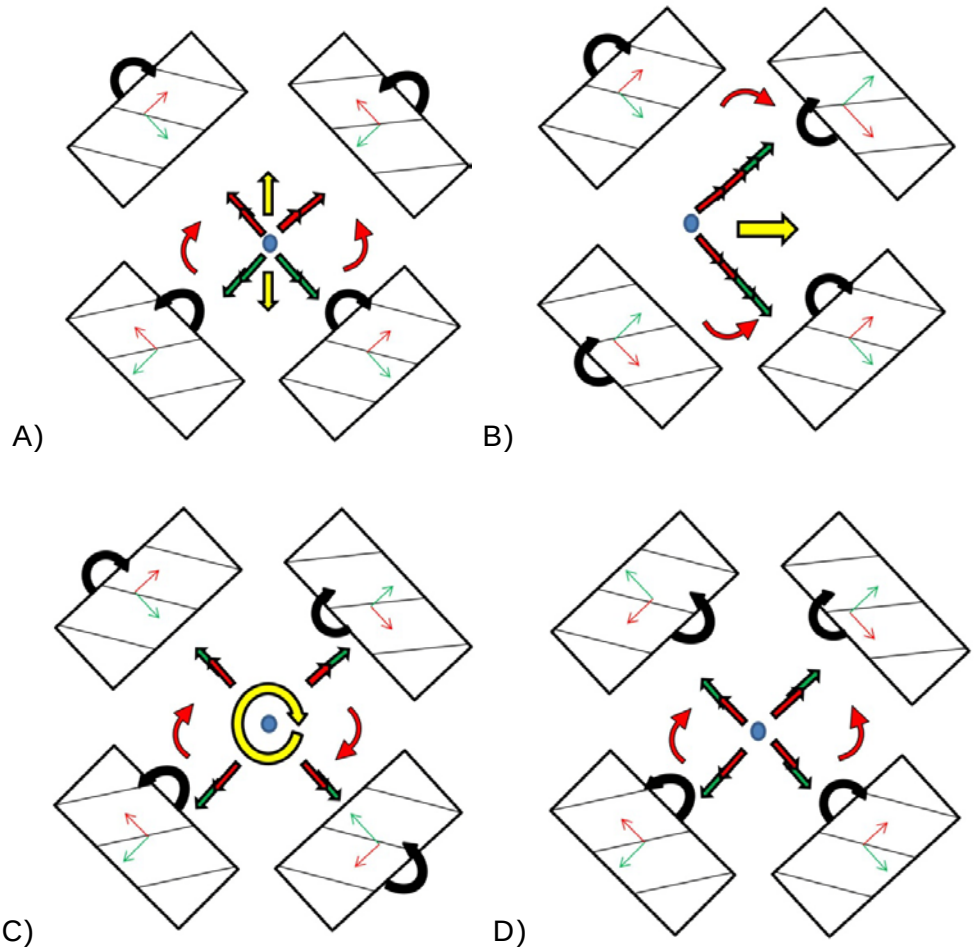


Figure 32: Four symmetric screw rotations for the diamond-screw.
A) Longitudinal (forward or reverse is indeterminate) B) Lateral C) Rotational
D) No locomotion

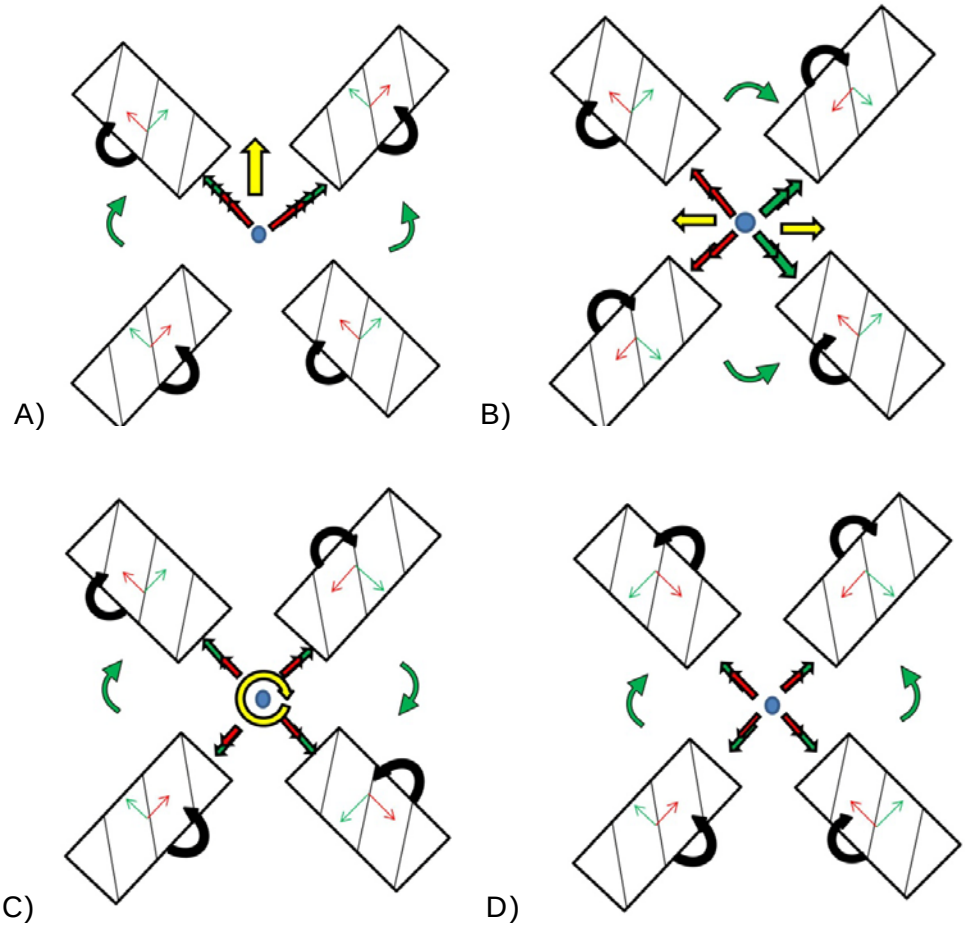


Figure 33: Four symmetric screw rotations for the cross-screw.
A) Longitudinal B) Lateral (left or right is indeterminate) C) Rotational D) No locomotion

CHAPTER 5: THE TERRAIN TWISTER

5.1 Description

The Tyco® Terrain Twister is a remote controlled toy that uses two screws to drive. It uses two DC motors to individually power the screws. These motors are housed in a watertight plastic shell and are located inside the screws. The motors turn a plastic tab, clipped to the inside of the screw, to turn the screw.

Each of the Terrain Twister's screws is made of two hollow plastic shells that fit around a rod, motor, and Styrofoam. The rods are used to hold the screws and motors in position and they are held in place by forks that attach to both ends of the rods. The forks both mount to the body of the toy which contains all of the electrical and radio signal components. The toy also has gears that rotate the forks so the screws can hinge inward and outward allowing for turning on hard surfaces.

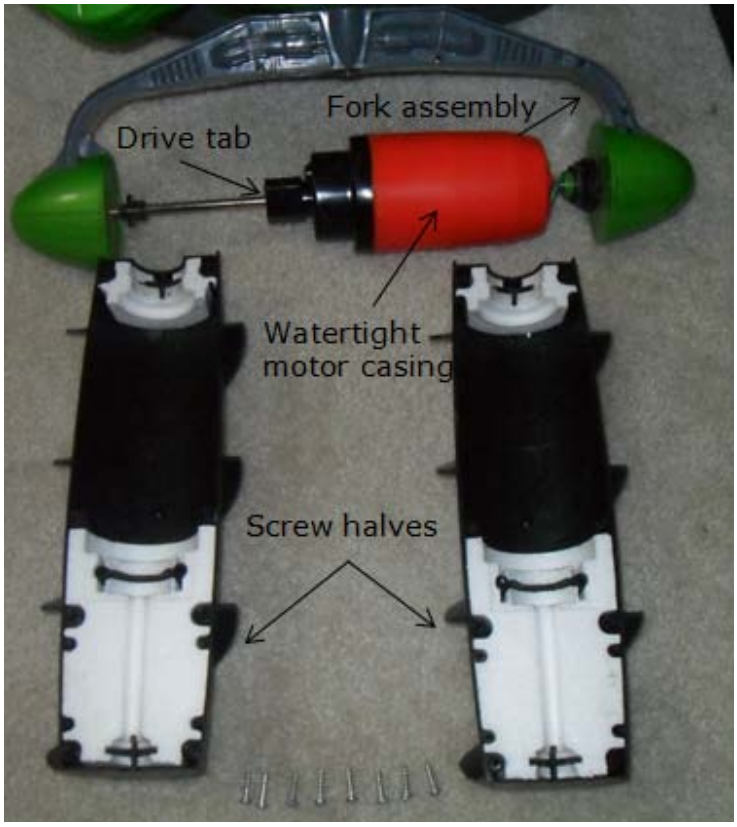


Figure 34: The Terrain Twister screw-assembly.

5.2 Test-Bed Construction

The Tyco® Terrain Twister was useful for the quad-screw test-bed because it already consisted of screws that work effectively on water, dirt, snow, sand, and to a limited extent, hard surfaces. From the studies reviewed in chapter 2, the screws that came with the Terrain Twister had a geometry that closely matched an ideal screw for most terrains. Table 1 compares the geometry of the Terrain Twister screws to an ideal geometry. The only parameter that did not closely match the ideal screw geometry was the length-to-drum-diameter ratio. Nonetheless, the geometry was acceptable. All of the geometric values for the Terrain Twister's screws are provided in appendix D with calculations for the values in Table 1.

Table 1: Terrain Twister screw geometry

Parameter	Terrain Twister	Ideal	Comments
Helix angle (^{o})	31.03	30 or slightly larger	[3,14]
Blade height to diameter ratio	0.125	0.125	center diameter measurement [3]
Number of helix blade starts	2	2	[3,14]
Length to diameter ratio	3.65	6	center diameter measurement [3]
Blade thickness (inches)	0.0625	-	no information on performance impact

The Terrain Twister screw was also convenient. The screw already had a motor housed inside it, allowing any combination of screw rotations to be performed. Specifically, the individual motors eliminated the need for complicated gearing, belts, or any other transmission system. Also, the screws were lightweight enough to easily float in water with additional buoyancy. Although the Terrain Twister was convenient, it was no longer marketed at the time of this study. Therefore, Terrain Twisters were purchased through Ebay, an online auctioning service.

The two fork-and-screw-assemblies were permanently removed from the body of the Terrain Twister to mount to the frame of the test-bed. Since the test-bed used four screws, two Terrain Twisters were utilized. The Terrain Twister was disassembled so that the forks and screws remained intact. The wires leading from the motors were also kept intact so that they could be used in the wiring of the test-bed.

5.3 Test Comparison

The testing which will be discussed in chapter 7 sought to understand the advantages and limitations of each quad-screw configuration by observing behavior on different terrains. However, in order to make sense of the observations, comparisons were made using a double-screw and the quad-screw configurations with identical screws. By testing the double-screw in each terrain, it was possible to note if the vehicle behaved in the manners described in previous research. When the double-screw operated as discussed in other papers, it demonstrated that the screw's geometry and scale were appropriate for testing the quad-screw configurations.

CHAPTER 6: QUAD-SCREW TEST-BED CONSTRUCTION

6.1 Test-Bed Frame

The frame of the test-bed served as a compartment for batteries and a mounting surface for the screw-assemblies, the switchbox and other electrical components. Therefore, the material selected for the frame was important. The entire frame of the test-bed was made of schedule 40 PVC because it was lightweight, sturdy, hollow, easy to assemble, and readily available.

A single piece of 1.25-inch diameter PVC was used for the body to house D-cell batteries, used to power the test-bed, and provide appropriate spacing between the screws. The total length of the body piece provided a 1-inch gap between the ends of each screw. The 1-inch gap existed between the front- and rear-screws when in the inline-screw configuration.

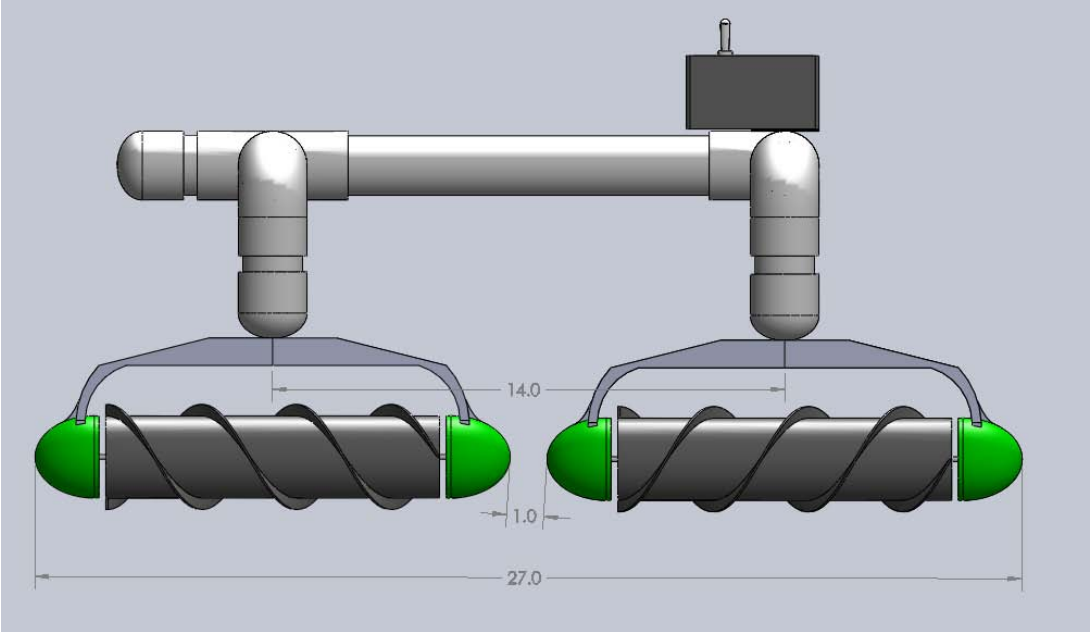


Figure 35: Right plane, test-bed model. The figure illustrates a 1-inch gap between the screws and 14-inch distance between the centers of the front and rear legs.

A PVC T-fitting at the back of the body formed the connections for the rear-legs and provided a mounting surface for an electrical barrier strip. The rear-legs served to hold the rear-screw-assemblies. At the front-end of the body piece was a cross-fitting made of PVC. The cross-fitting was used to hold the front-legs for the two front-screws. Also, a short length of PVC was fitted to the end of the cross-fitting so that a cap could be placed on it. The cap was used to add and remove D-cell batteries.



Figure 36: A PVC end-cap with the spring for battery contact.

The legs of the test-bed each consisted of a horizontal and vertical section. The horizontal sections of the legs were cut to a length that spaced the centers of the left and right screws 14 inches apart. The centers of each screw formed a square with 14-inch sides; which permitted the cross-screw and diamond-screw. The horizontal and vertical sections were connected using 90^{o} PVC fittings. Since the fork-assemblies on the screw-assemblies were already tall, the vertical sections of the legs were kept short. None of the literature reviewed mentioned the importance of the vertical C.G. in screw-vehicle performance. Finally, end-caps were attached to the end of the vertical sections of PVC to provide a mounting surface for the screw-assemblies.

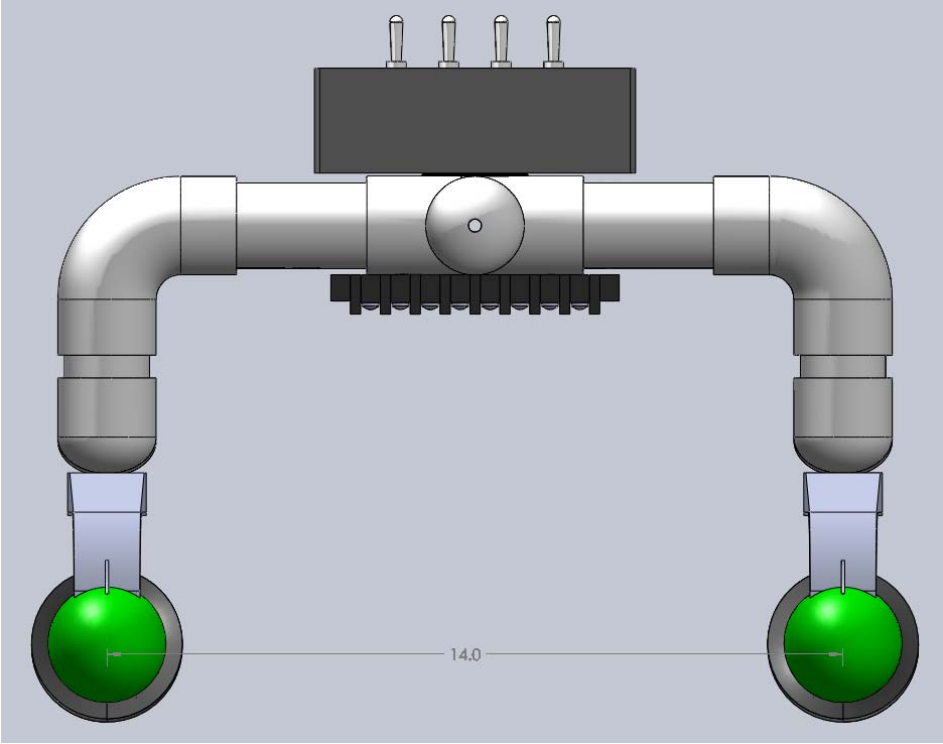


Figure 37: Front plane, test-bed model. This figure illustrates the 14-inch distance between the centers of the left and right legs.

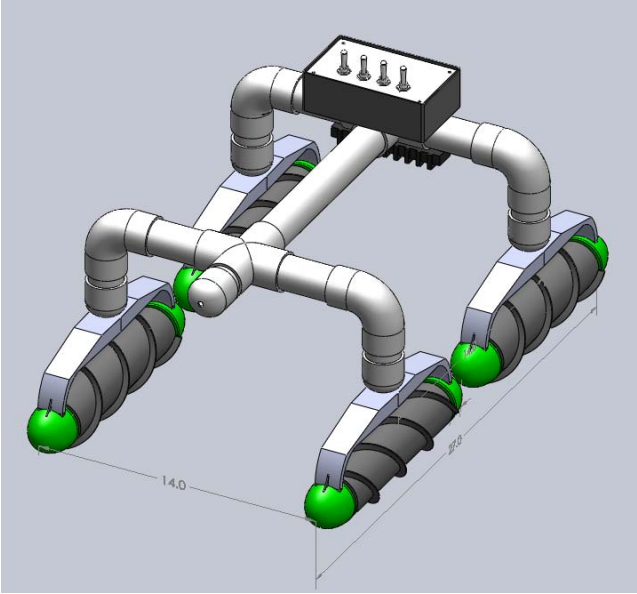


Figure 38: Trimetric, test-bed model.

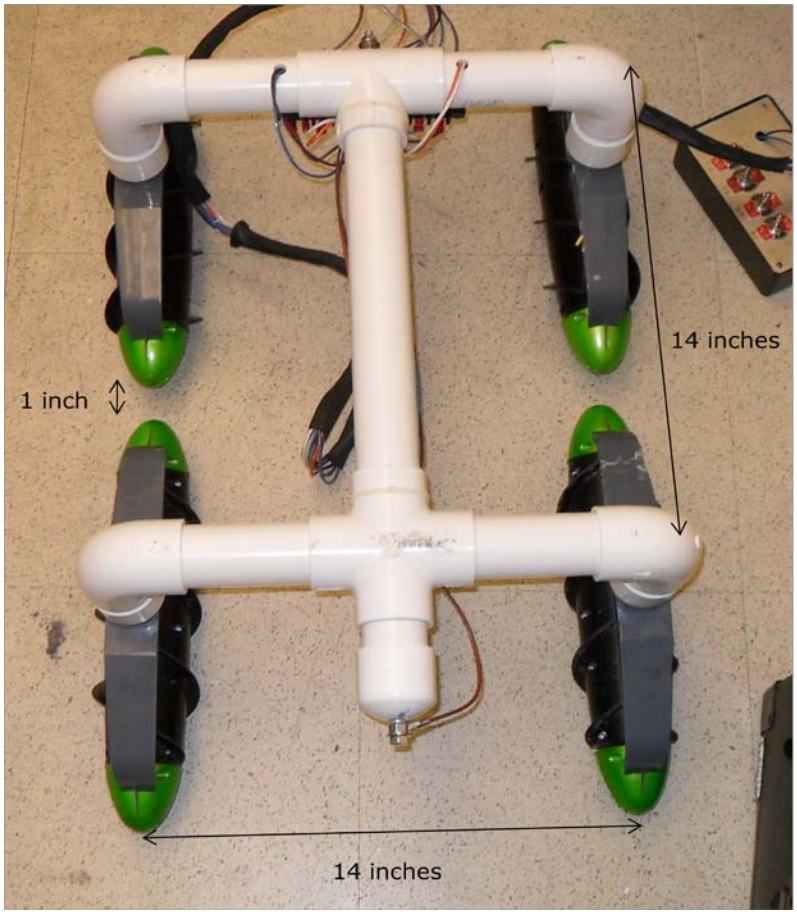


Figure 39: A photograph of the test-bed.

6.2 Screw-Assemblies

The screw-assemblies consisted of a fork-assembly, a motor and the screw. More detail is provided, regarding the components of the screw-assemblies, in section 5.1. The two screw-assemblies were permanently removed from the body of the Tyco® Terrain Twister to mount to the frame of the test-bed. Since the test-bed used four screws, two Terrain Twisters were utilized. Bolts were fed through the center of the forks to attach to the PVC end-caps. The end-cap was able to twist about the PVC legs to allow the screws to be positioned for the inline-screw, cross-screw, or diamond-screw configurations.

6.3 Wiring and Controls

Several considerations had to be made concerning the wiring in order to build a successful test-bed. The wiring of the test-bed had to be able to withstand frequent transportation, rough off-road terrain and watery conditions. Furthermore, it had to be easy to access the wires to make modifications or repairs. Finally, the wiring had to result in logical controls that would be easy to remember.

The wires within the Terrain Twister motors were utilized in the test-bed circuitry. The motor wires were soldered to longer wires and insulated with shrink-tubing. With four motors containing two wires per motor, a total of eight wires were connected to an electrical barrier strip. The barrier strip, located on the underside of the T-fitting, consisted of eight pairs of terminals and two holes for mounting it. Each wire that led from the motor to the barrier strip had a corresponding 6-foot wire that led from the barrier strip to the switch box. Sections of shrink tubing were placed around all of the 6-foot wires to neatly hold them together like a cable tether.

The wires leading to the barrier strip were all color coded to prevent confusion. Specifically, the right-handed screws had purple and blue wires while the left-handed screws had orange and white wires. The purple wires were the same polarity as the orange wires, while the blue and white wires shared the same polarity as well. Wires from the front-screws led to the outer barrier strip terminals and wires from the rear-screws led to the inner barrier strip terminals. Furthermore, the screws on the left side of the vehicle led to the left terminals on the barrier strip and vice versa.

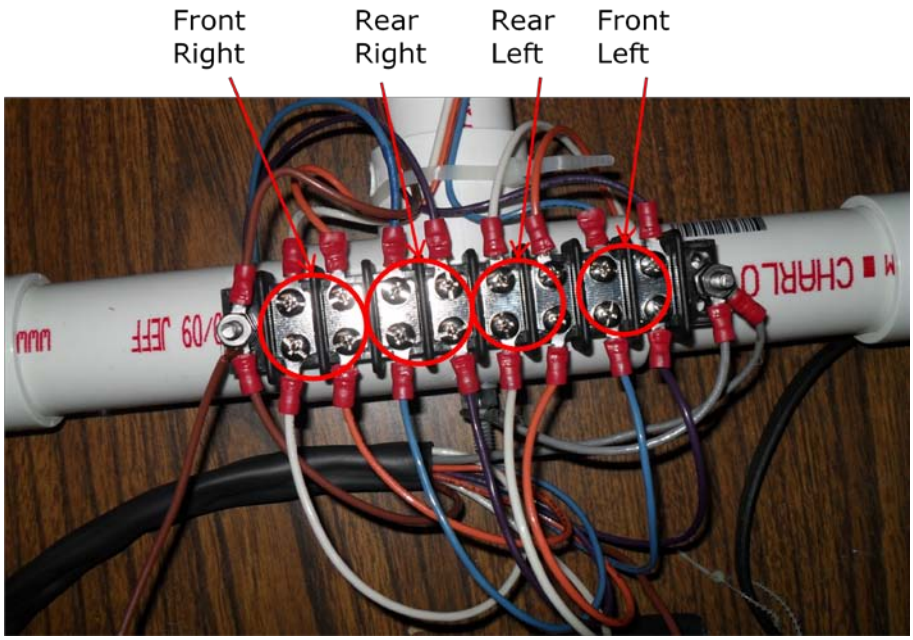


Figure 40: The barrier strip wiring.

To supply power to the circuit, a brown wire was attached to the bolt at the end-cap and a gray wire was attached to the bolt at the rear T-fitting. The bolts that the brown and gray wires were connected to were used to hold springs that contacted the D-cell batteries. The brown and gray wires were connected to the barrier strip with a ring terminal secured to the bolts that mounted the barrier strip to the frame. In total, there were ten wires leading into the barrier strip.

Each wire leading to the barrier strip consisted of a corresponding wire that was soldered to a switchbox. The switchbox contained four 3-position switches. On each switch, the center position did not supply power and the forward- and backward-positions did. The switches were positioned in the same order as the barrier strip. In other words, the outside switches were for the front-screws and the left switches were for the left-screws.

The individual switches consisted of six terminals; two in the front, two in the middle and two in the back. For a given motor, a wire of one polarity was soldered to the back-left-terminal and the wire of opposite polarity was soldered to the back-right-terminal. A wire from each terminal was directed to the terminal diagonal from it to reverse the polarity when the switch was flipped to the front. The wires that provided the power were soldered to the middle terminals such that one polarity was soldered to the middle-left terminal and the opposite polarity was soldered to the middle-right terminal. The first switch, for the front-left-screw, was directly connected to the power. The remaining switches were provided power by wiring them in parallel with the first switch. The described wiring was done by chaining the middle terminals to the middle terminals of the adjacent switch until all were electrically in contact.



Figure 41: The switchbox wiring.

In order to have the correct amount of batteries, a spacer assembly was built. The spacer assembly consisted of a 0.75-inch diameter PVC pipe with two caps placed on either end. The overall length of the spacer was 3-inches. Each cap had a hole drilled in the center so a screw could pass

through them. The spacer was then bolted to the inside of the T-fitting so one end was firmly in contact with the inside surface of the T-fitting. Finally, a spring and washer were secured to the opposite end of the spacer. The purpose of the spring and washer was to provide an electrical connection between the batteries.

The entire system was wired so that pushing the switches forward causes the screws to rotate outward from the frame. Pushing the switches back causes each screw to rotate in the opposite direction of the forward position. Finally, the center position was the off position, and the motors would not spin.

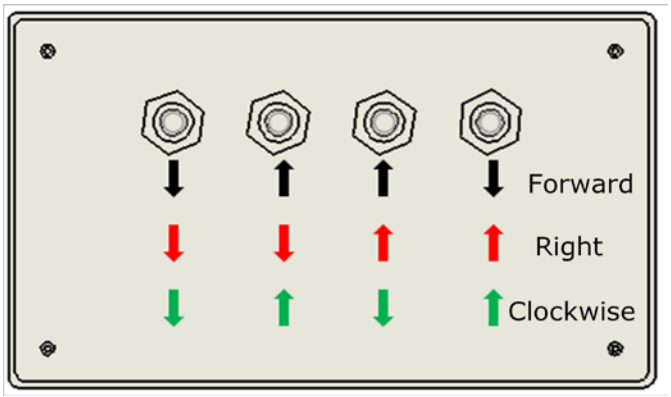


Figure 42: Switch patterns for forward, right and clockwise locomotion.

6.4 Modifications

After initial testing to see if the test-bed functioned, various changes were made. Some of the changes were made to facilitate ease of use, other changes were necessitated by unforeseen issues, and some were required for specific studies.

The six D-cell batteries used did not provide enough power to the motors to move the vehicle, so a motorcycle battery was used. The negative

battery terminal was wired directly to one of the barrier strip mounting bolts. The positive terminal was wired to a kill-switch that was wired to the other barrier strip mounting bolt. Since the battery was bulky, it was kept in a backpack and worn on the tester while the vehicle was driven. Likewise, since the long cable used for the switchbox was clumsy and all of the testing occurred with one locomotion at a time, the switchbox tether was removed and the switchbox was mounted to the rear of the test-bed with Velcro.



Figure 43: The author shown alongside the test-bed. A motorcycle battery in a backpack is utilized to power the test-bed.

Over time, PVC began to expand at the joints. Initially, the joints were held together with tight press-fits. However, the expansion of the PVC caused each joint to become loose, and the vehicle flexed during testing. In order to remedy the situation, PVC cement was used for permanent joints. Since the screws had to be able to hinge for the cross-screw and diamond-screw, the end-caps that the screw-assembly mounted to were not glued.

Instead, masking tape was used to allow easy adjustment of the screw's hinge-angle.

Though an advantage of a screw-vehicle is the potential for floating screws, the test-bed did not have adequate screw buoyancy to keep it afloat. Instead, the Terrain Twister utilized a plastic hull, filled with Styrofoam, to maintain buoyancy. Therefore, in order to investigate various quad-screw configurations in water, a floating hull was constructed. Hollow cylindrical foam was used to provide buoyancy on water for the test-bed vehicle. Twelve-gauge wire provided a sturdy framework to hold the foam in position when the vehicle was in water. Finally, to provide stability, small sections of foam were placed between the front- and rear-screws. When the vehicle was in the cross-screw or diamond-screw configuration, the screws held the long foam cylinder in the center so that the additional small sections of foam were not needed.

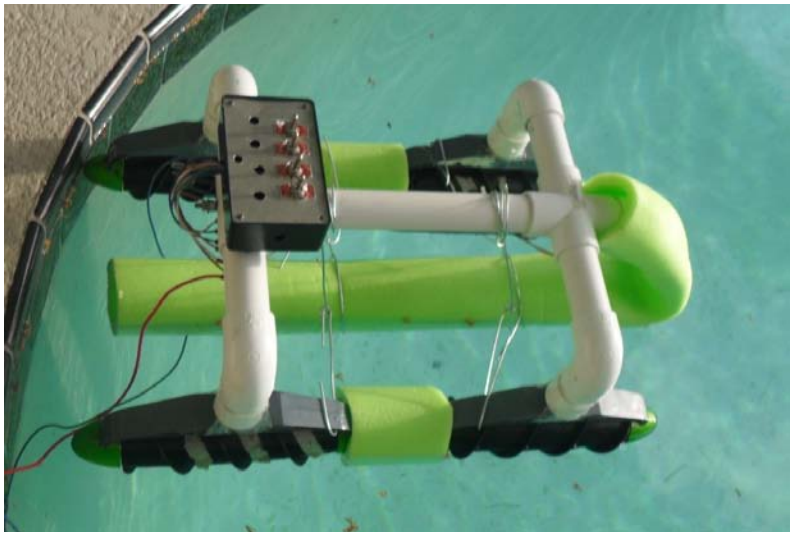


Figure 44: The floating test-bed setup.

A final modification was required for underwater tests. Four 4-pound dive weights were tied to the horizontal portion of each leg to submerge the test-bed. To provide the appropriate buoyancy, the test-bed was tied to canvas wrapped around a floating tube. The motorcycle battery was placed in a 3-gallon bucket, and the bucket was kept in the middle of the tube. As a result, the test-bed was fully submerged and suspended underwater.



Figure 45: The inflatable tube used to suspend the test-bed.

CHAPTER 7: EXPERIMENTS

7.1 Experimental Goals

The goal of the experiments herein was to provide insight into the locomotion of the inline-screw, cross-screw and diamond-screw in different terrains when attempting longitudinal, lateral and rotational locomotion. Initial tests were performed to observe the direction of locomotion for each configuration on each terrain. Further tests were performed to determine the maximum velocity of each configuration on each terrain.

In the literature reviewed, drawbar-pull capacity and power and torque requirements were of interest for designing a full-scale tank. However, in this study, power and torque requirements and drawbar-pull capacity were not a concern. Again, the primary goal of this study was to investigate alternatives to the double-screw to find the best configuration from the standpoint of omnidirectional locomotion. Therefore, vector analyses, observations on vehicle trafficability and calculations of maximum velocity were adequate to determine which configuration had the best omnidirectional capability.

As discussed in chapter 2, the double-screw was thoroughly researched on a wide gamut of terrains. Therefore, since the behavior of a double-screw was already known, it was also tested for the purpose of

comparison. In particular, the Terrain Twister was used for the double-screw tests.

From the previous research available, screw-vehicle performance due to screw design parameters and screw-to-terrain interaction was given. Therefore, further testing on screw design optimization was unnecessary for the research in this thesis. In addition, as discussed in chapter 5, the screws utilized by the Terrain Twister and the test-bed closely matched the screw geometry of an all-terrain vehicle. Therefore, testing could be performed on nearly any surface.

The force-vector analyses in chapters 3 and 4 and compiled in appendices A through C provided a model for predicting the direction of locomotion for each configuration. Since no benefit was predicted from the split-screw, the S-cross-screw, or the S-diamond-screw over their counterparts, the inline-screw, cross-screw and diamond-screw, minimal testing was performed on them. Nonetheless, testing was performed on the split-screw in grass, pavement and water to validate the force-vector diagrams used.

7.2 Methodology

7.2.1 Test Locations. Specific test locations were selected to test omnidirectional locomotion on a variety of terrains. The locations were chosen such that each terrain consisted of a single medium over a large, level surface. Each terrain was located as follows:

- Grass: Since grass was easy to find, several locations were used. The requirements were that the ground was level with minimal bumps and the grass was maintained at a height of 1- to 2-inches.
- Dirt: A large area of loose dirt was found in Palm Harbor, FL. A large section of flattened dirt was utilized for testing.
- Marsh: A marshy surface was exposed during low tides in the Gulf of Mexico in the Palm Harbor, FL area. The marshy surface was flat and consisted of seaweed vegetation on top of a mixture of water-saturated dirt and sand.
- Sand: Dry sand was located in a volleyball court at the USF Riverfront Park in Tampa, FL. The sand was raked to provide a smooth testing surface.
- Clay: Dry clay was located at a baseball field at the USF Riverfront Park in Tampa, FL. The clay was characterized by a thin layer of loose clay particles at the surface and hard, compact clay underneath.
- Pavement: The pool deck around the swimming pool used for water testing was utilized for tests concerning pavement.
- Gravel: A gravel parking lot near a boat launch in Palm Harbor, FL provided the gravel testing surface. The size of the gravel averaged approximately 1-inch in diameter.
- Water: A swimming pool 30 feet long, 12.5 feet wide, and 4 to 8 feet deep was used for testing on the surface and underwater.

- Snow: The Tampa Bay Skating Academy in Oldsmar, FL provided snow for testing. A large deposit of snow was provided from the skating-rink's ice resurfacing vehicle. The powdery snow was leveled and spread using a rake to provide a large, flat testing surface.

7.2.2 Testing Directions. Several directions of locomotion were tested on each test site. The directions tested varied between the double-screw and quad-screw configurations, because the double-screw could not perform the same combinations of screw rotations. The directions tested in each terrain were as follows:

- Double-screw: Longitudinal locomotion, lateral locomotion, skid-turning
- Quad-screw configurations: Longitudinal locomotion, lateral locomotion, rotational locomotion

In this thesis, lateral locomotion for the double-screw included straight lateral movement, arc-turning and pivot-turning. While arc- and pivot-turning were expected from the double-screw, only straight lateral locomotion was acceptable for the quad-screw configurations.

Another distinction between the double- and quad-screw configurations was they each rotated in a different manner. The quad-screw configurations could rotate the front- and rear-sets of screws in the opposite direction to rotate, so they had specific tests for rotational locomotion. Since the double-screw could not rotate in the same manner as the quad-screw, the effectiveness of skid-turning was observed for the double-screw instead.

7.2.3 Test Setup. At each test location, two pairs of cones were set up. The first pair of cones marked the starting line and the second pair of cones marked the finish line. Measuring tape was used to maintain 10 feet between the inside of each pair of cones. The 10-foot course was used to observe the behavior of the quad-screw configurations during longitudinal locomotion on each terrain. As will be discussed, the diamond-screw was an exception due to the limited capability of its longitudinal locomotion. The cones were not used for the double-screw because it was not being compared for speed or slip tests.



Figure 46: An example of the test setup.

For the inline-screw, the slip percentage was desired to be known to understand its efficiency. In order to calculate the slip percentage, the number of screw revolutions and the distance the vehicle moved in a given time had to be known. White tape was placed on the screws of the test-bed to count the number of revolutions, while the time it took to cross 10 feet provided the speed. Since the screws moved at relatively high speeds,

Virtual Dub video editing software was used to observe the video frame-by-frame to count the number of times the white tape showed up. Since the screws were measured to rotate no faster than 550 RPMs, the camera method was adequately accurate since it had 900 frames per minute. Finally, the time to cover 10 feet was determined by the time elapsed on the video when the back of the vehicle crossed the inside of the start and finish cones.

All tests were recorded with a digital camera so that a video library could be compiled. The library was useful for discussing the behavior of each configuration, troubleshooting issues that occurred in the field, determining the velocity of the quad-screw, and finding the RPMs of the screws.

7.3 Test Observations

7.3.1 Grass. On grass, longitudinal and lateral locomotion showed no issues for the double-screw. Skid-turning was generally effective, but occasionally the rotating screw would lose traction with the ground and no movement would occur. In cases where skid-turning failed, the double-screw was not immobilized because it could immediately move longitudinally. Lateral locomotion for the double-screw resulted in arc-turning.

The inline-screw worked well on grassy surfaces. When it was set to move longitudinally, it moved in a straight line with no issues. When it was set to rotate, it rotated in a tight circle about its center-point. Finally, when it was set for lateral locomotion, it moved in a straight lateral direction as

anticipated by the force-vector diagrams. In summary, no issues or surprises arose for the inline-screw in grass.



Figure 47: Test setup for grass terrain.

The cross-screw was able to move longitudinally with no issues on grass. Furthermore, it rotated much faster than the other configurations, because the rolling-forces on each screw directly contributed to the rotation. Unfortunately, the cross-screw did not move in a predictable manner for lateral tests. When set to move right, based on the switch combination to move the inline-screw right, it attempted to move right but it quickly and frequently altered its path. Also, in some cases it did not go anywhere when set for lateral motion. Clearly, since the rolling-forces attempted to pull the cross-screw to the right while the tractive-forces tried to pull it to the left, the system was unstable.

Unlike the cross-screw, the diamond-screw moved laterally in the set direction with no issues. However, it did not rotate as fast as the inline-screw or cross-screw. The diamond-screw relied only on tractive-forces for turning. Finally, the diamond-screw did not successfully move longitudinally. Similar to the cross-screw when attempting lateral locomotion, the diamond-

screw, when set to move longitudinally, encountered opposing tractive- and rolling-forces. In the diamond-screw tests, it stayed in place while the screws rotated.

7.3.2 Dirt. Most of the observations made from testing in grass applied to the testing in dirt. Nonetheless, each configuration performed slightly different in dirt compared to grass.

In dirt, the double-screw was able to move longitudinally, but it did not perform as well as it did in grass. When it encountered inconsistencies in the dirt, such as small hills or loose patches of dirt, it would slightly alter its path or become immobilized; immobilization was infrequent. Lateral locomotion rarely resulted in immobilization, but the double-screw followed a wide arc. In addition, when attempting to skid-turn, the double-screw often became immobilized. In nearly all cases of immobilization, it could be extricated by lateral or longitudinal locomotion.

The inline-screw behaved similar to the double-screw during longitudinal locomotion because it sometimes altered its path or became immobilized when it encountered terrain inconsistencies. During lateral and rotational locomotion, no issues were observed. Similarly, the cross-screw performed as it did in grass, except it also did not perform as well longitudinally. There were no cases of the cross-screw becoming immobilized.



Figure 48: Tracks from the inline-screw deviating in dirt.

Regarding lateral motion, the diamond-screw behaved as expected by moving in the proper direction and path with some path deviation due to terrain inconsistency. However, when set to move longitudinally, the diamond-screw behaved much different than in grass. Rather than going nowhere, when set to move forward it attempted to go in reverse and quickly buried itself or deviated its path erratically. In the case of the diamond-screw on dirt, the reverse rolling-forces had slightly overcome the forward tractive-forces. Finally, when attempting rotation, the diamond-screw could make no more than two rotations before becoming immobilized. Since the screws rotated at a fast speed, the diamond-screw may have kicked up the dirt and buried itself when attempting to rotate. It is possible that slowing the RPMs of the screws may resolve the issue of the diamond-screw burying itself during rotation.

7.3.3 Marsh. The marshy terrain provided interesting information for each configuration. The wet soil provided low friction between the screws and soil, but was not slick to the point of causing the vehicle to slide uncontrollably on uneven surfaces. Furthermore, the cohesion in the terrain provided an adequately strong surface for the screws to push off of. Finally, since the marshy ground left behind easily visible tracks, pictures could be taken to illustrate the paths taken.



Figure 49: Tracks in marsh left by the inline-screw.

In the longitudinal tests, the double-screw performed successfully and even navigated slightly bumpy terrain. During lateral locomotion, the double-screw was able to pivot-turn. However, sometimes, on seemingly identical terrain, it would arc-turn with an increasingly narrow turning radius until it pivot-turned. Interestingly, during skid-turning the double-screw had a turning radius approximately the same as for pivot-turning. There were cases of immobilization due to skid-turning, but this was not frequent.

The inline-screw performed perfectly in all modes of locomotion during marsh testing. The cross-screw had no difficulties with longitudinal or rotational locomotion. However, during lateral locomotion, sometimes the screws lacked enough torque to rotate, and other times the screws rotated and kicked up mud. In either case, it did not go anywhere. Similarly, the diamond-screw could not move longitudinally because it either lacked torque or kicked up mud, but it had no issues during lateral and rotational locomotion tests.

7.3.4 Sand. From the literature reviewed, dry sand is a known challenge for screw-vehicles because it has minimal cohesion and high frictional properties. The tests performed in this thesis confirmed the literature because each configuration encountered difficulty in dry sand.

The double-screw was able to move longitudinally. However, when it encountered any uneven terrain, it often plowed into the sand and buried itself. During lateral locomotion, the double-screw followed a wide arc on flat sand but when it encountered uneven terrain the turning radius tightened temporarily. The tighter turning radius from uneven terrain was attributed to increased interaction between the blades and the sand. During the skid-turning tests, the double-screw quickly buried itself in all cases. The lack of cohesion between sand particles caused the moving screw to kick up sand, and the increased friction between the sand and stationary screw resisted the skid-turning locomotion. Furthermore, the low hull of the Terrain Twister quickly became grounded on the sand as the screw pushed sand away.

The inline-screw also had difficulty on the loose, dry sand. In longitudinal tests, the inline-screw quickly buried itself when it encountered hills of sand. The tendency of the inline-screw to bury itself was attributed to the rigid nature of the screw's mounting, wherein each screw was forced to plow through the sand. If the screws were allowed to pitch, each screw could individually conform to hills and pass over them.



Figure 50: Sand terrain test setup. The rake used to flatten the sand is shown.

The sand was eventually raked flat enough to test the different modes of locomotion. The forward locomotion was improved on flat sand, but even slight hills resulted in burial or large path deviations. The inline-screw performed better during lateral locomotion. On flat terrain, and usually uneven terrain, the inline-screw successfully moved in a straight, lateral path. While attempting lateral locomotion in uneven terrain, the inline-screw sometimes buried itself. Finally, the inline-screw successfully rotated about its center in sand without any evidence of trouble.

The cross-screw was able to move longitudinally, but frequently deviated from a straight path. Since the screws pointed outward, a larger

contact area with the sand was made. Therefore, the cross-screw was observed to contact hills of sand easier and alter its course. An advantage was the cross-screw seemed to bury itself less frequently during longitudinal tests. Lastly, similar to most terrains, the cross-screw could only move very briefly before burying itself during lateral locomotion, but it could rotate with ease.

The diamond-screw attempted to move in reverse when set to move forward longitudinally and it quickly immobilized. Furthermore, it could not make a single rotation when set to rotate. Nonetheless, it was able to cross the 10-foot test course without burying itself during lateral locomotion. However, in all lateral trials, the diamond-screw moved in a large arc. The reason for the arc was likely the terrain was not perfectly level, or the screws were not rotating at the same RPMs.

7.3.5 Clay. For the double-screw tests, longitudinal locomotion was possible and lateral locomotion resulted in a wide arc. Skid-turning was unsuccessful because the rotating screw could not produce enough traction to turn it.



Figure 51: The test setup for clay terrain.

For the inline-screw the longitudinal, lateral and rotational locomotion were all possible. For the double-screw and inline-screw, the hard clay was difficult for the screws to penetrate, but not impossible. Therefore, longitudinal locomotion for both cases was occasionally unsuccessful due to lack of traction. Furthermore, the rigid surface created unequal ground contact for the individual screws. Therefore, since the screws and terrain did not always have full contact, each screw did not always play an equal role in the direction of travel.

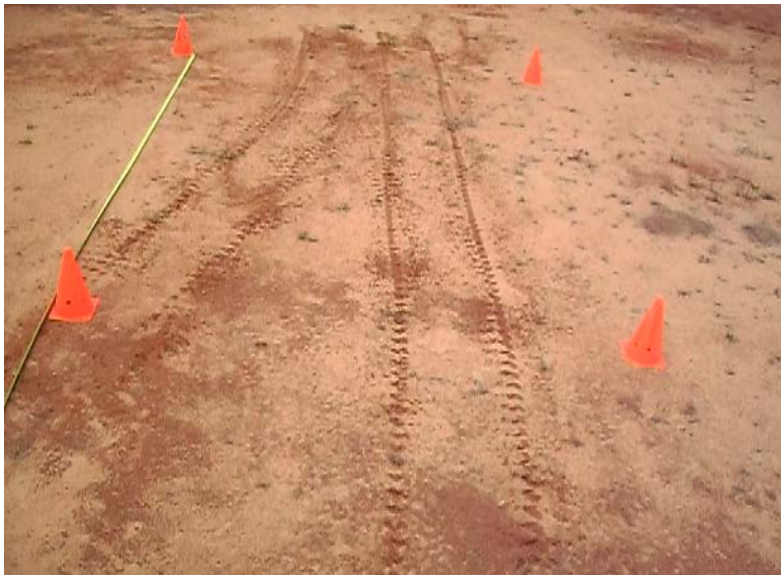


Figure 52: Inline-screw tracks in clay. The tracks were from longitudinal tests.

The cross-screw was not able to complete the 10-foot course for longitudinal locomotion; the wide angle of the screws may have exacerbated terrain-to-screw contact issues. Lateral locomotion was nearly successful for the cross-screw because the blades played a reduced role in the direction of travel. Finally, there were no issues for the cross-screw while rotating.

The diamond-screw performed the similar to the cross-screw, except its performance was better for lateral locomotion than the cross did for longitudinal. In addition, since the rolling-forces, which opposed the set direction for longitudinal locomotion, overcame the tractive-forces, the diamond-screw moved in reverse when the switches were set to go forward. Lastly, the diamond-screw could not complete a single rotation. When attempting to rotate, it turned briefly and removed the top layer of loose clay.



Figure 53: Diamond-screw rotation tracks in clay.

7.3.6 Pavement. Clearly, pavement is the least friendly surface for a vehicle employing screw locomotion. Both the double-screw and inline-screw failed longitudinal locomotion, because the threads had minimal traction. Also, both configurations behaved the same for lateral locomotion because the blades played minimal role in the path. The critical difference between the double-screw and inline-screw was that rotation was possible for the inline-screw. Specifically, the inline-screw proved capable of rotating about

its center on pavement. If a screw-vehicle operator comes across a surface such as pavement or solid rock, they can navigate it by using a combination of lateral and rotational locomotion.

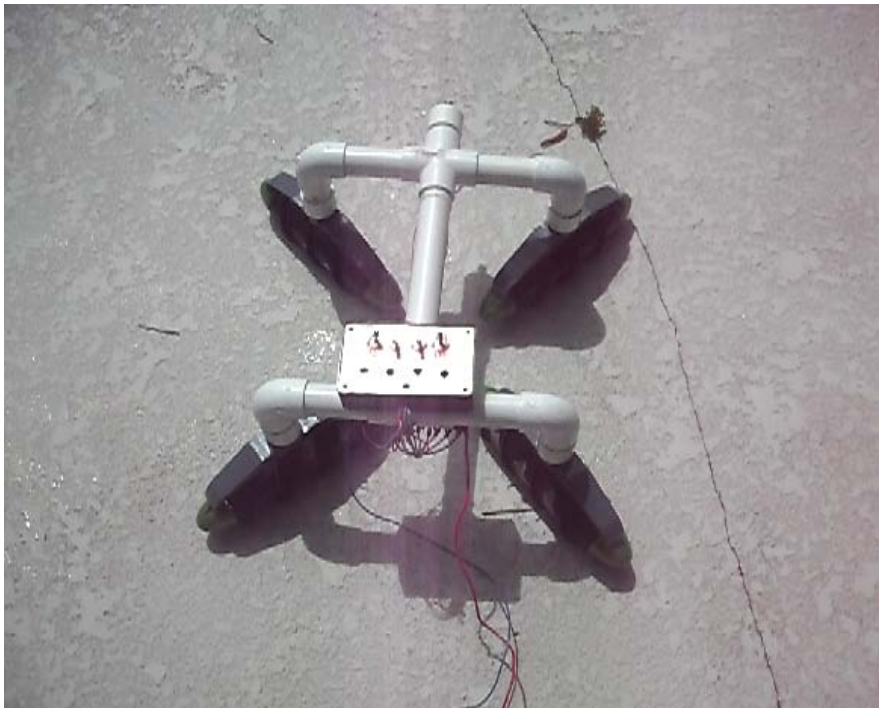
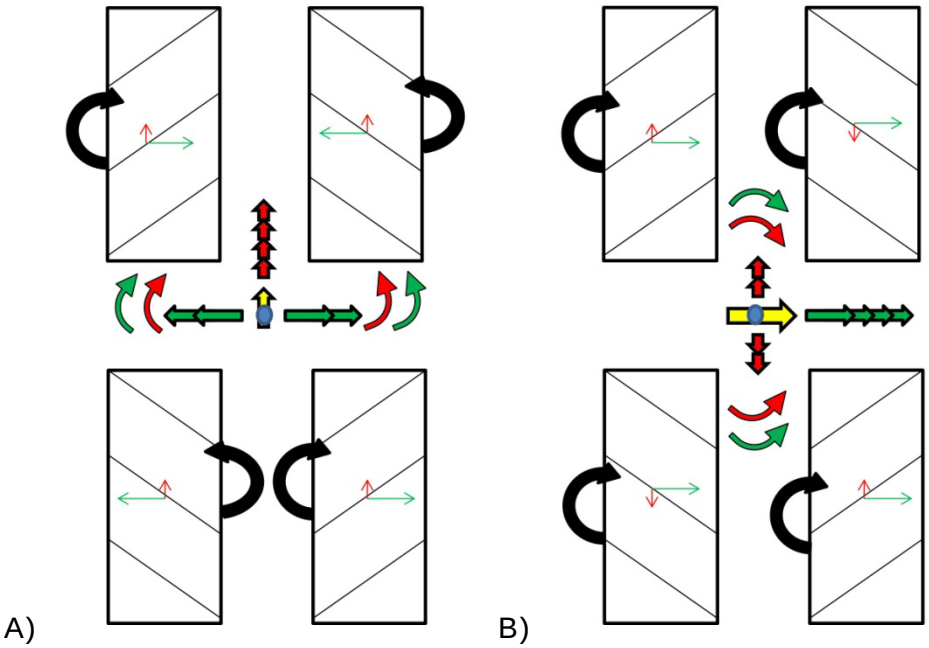


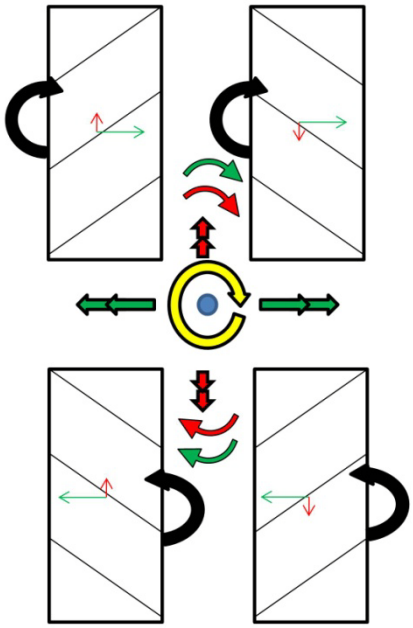
Figure 54: The cross-screw on pavement.

The cross-screw and diamond-screw displayed similar performance on pavement as they did on clay. However, since the pavement was more rigid than the clay, the blades played even less of a role, and most of the motion produced was due to rolling forces. In addition, the rigid ground created inconsistencies in the screw-to-ground contact which exacerbated the path deviation. In summary, the cross-screw performed equally poorly in longitudinal and lateral locomotion and excelled in rotating. Alternatively, the diamond-screw moved poorly and in reverse during longitudinal motion and performed poorly during lateral and rotational locomotion. It is possible that the cross-screw and diamond-screw could have been more effective in

lateral and longitudinal locomotion if the screws rotated slower, were made of a material with better grip, such as rubber, and there was a suspension system to allow equal ground contact between all of the screws.



A) B)



C)

Figure 55: Inline-screw performance with minimal tractive-force influence such as on pavement.
A) Longitudinal (small force) B) Lateral C) Rotational

7.3.7 Gravel. In all cases, locomotion in gravel was bumpy, but this was expected in such a terrain. Regardless, the results were encouraging and the paths were surprisingly straight.

The double-screw was able to move longitudinally with no issues. During lateral locomotion, the turning was not a tight circle like in marsh, but it did have a tighter radius than in dirt. It was presumed that the jutting rocks contacted the blades, causing them to play a large role in the direction of travel. Finally, skid-turning was effective in gravel with the vehicle nearly pivoting about the endpoint of the stationary screw.



Figure 56: Test setup for gravel terrain.

The inline-screw also performed well on gravel. When moving longitudinally it would occasionally hit a jutting rock and be bumped off track. However, the path was nearly straight because the numerous jutting rocks self corrected the vehicle to its original path. The lateral locomotion was also effective, but it did have a tendency to go off track due to rocks

contacting the blades. Rotation about the inline-screw's center worked effectively and with minimal deviation.

The cross-screw and diamond-screw were not as successful on gravel. During longitudinal testing, the cross-screw frequently deviated from its path and stayed off track. It was possible that since the rolling-force contributed to the forward motion, the cross-screw was going fast enough to exacerbate the path deviation. Again, similar to all of the terrains discussed thus far, the cross-screw performed poorly during lateral locomotion, but rotated with ease.

The diamond-screw produced no meaningful locomotion during longitudinal testing in gravel. The rolling- and tractive-forces must have been nearly equal because it exhibited paths in many directions. Lateral locomotion was successful for the diamond-screw and less path deviation was observed in comparison to the longitudinal cross-screw locomotion. Finally, rotation was also successful for the diamond-screw in gravel.

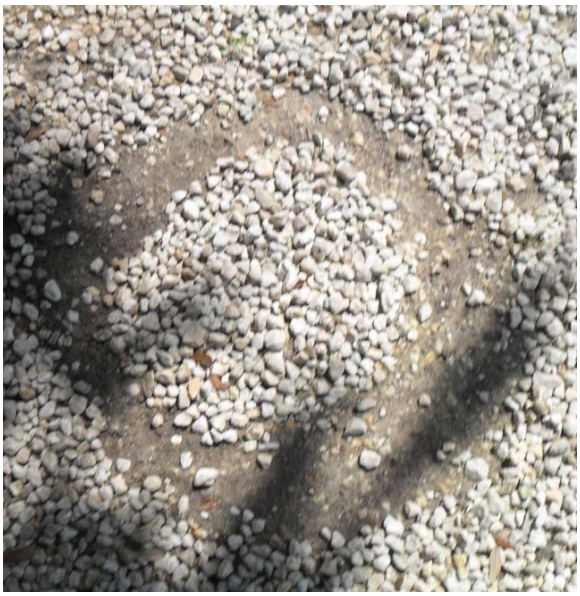


Figure 57: Path from the diamond-screw rotating in gravel.

7.3.8 Surface of Water. From the testing on water, it was clear that the tractive-forces dominated while the rolling-forces were negligible. In all cases where rolling-forces were the only forces contributing to locomotion, no locomotion resulted. Furthermore, each configuration moved in the direction that the net tractive-forces dictated.

On top of water, the double-screw moved in a similar fashion to solid surfaces. As in every surface, except pavement, counter-rotating the screws moved it forward and backward. However, for the double-screw, lateral locomotion on water resulted in turning about its center.

The inline-screw yielded interesting results on the surface of water. When set in the longitudinal setting, the vehicle moved with ease across the water. A unique aspect of the inline-screw in water was its limited movement during lateral locomotion. The locomotion of the vehicle during lateral testing appeared to be a straight, lateral path. However, the speed was minimal to the point that there was uncertainty if it was moving due to the screws. Clearly, forward and rotation are common means of travel in water, so the inline-screw not being able to move laterally should not be a setback. Fortunately, when set up for rotation, the inline-screw turned about its center.



Figure 58: Test setup for the surface of water.

The cross-screw showed no issues with longitudinal motion on top of water, but when set to move right or left it went in the opposite direction. During longitudinal and lateral locomotion, the cross-screw was equally effective when ignoring the reverse nature of its lateral locomotion. The cross-screw exhibited no capability of turning in water. Contrary to the cross-screw, the diamond-screw performed the best in all tests from the standpoint of omnidirectional locomotion. It moved in the desired directions for longitudinal, lateral and rotational locomotion.

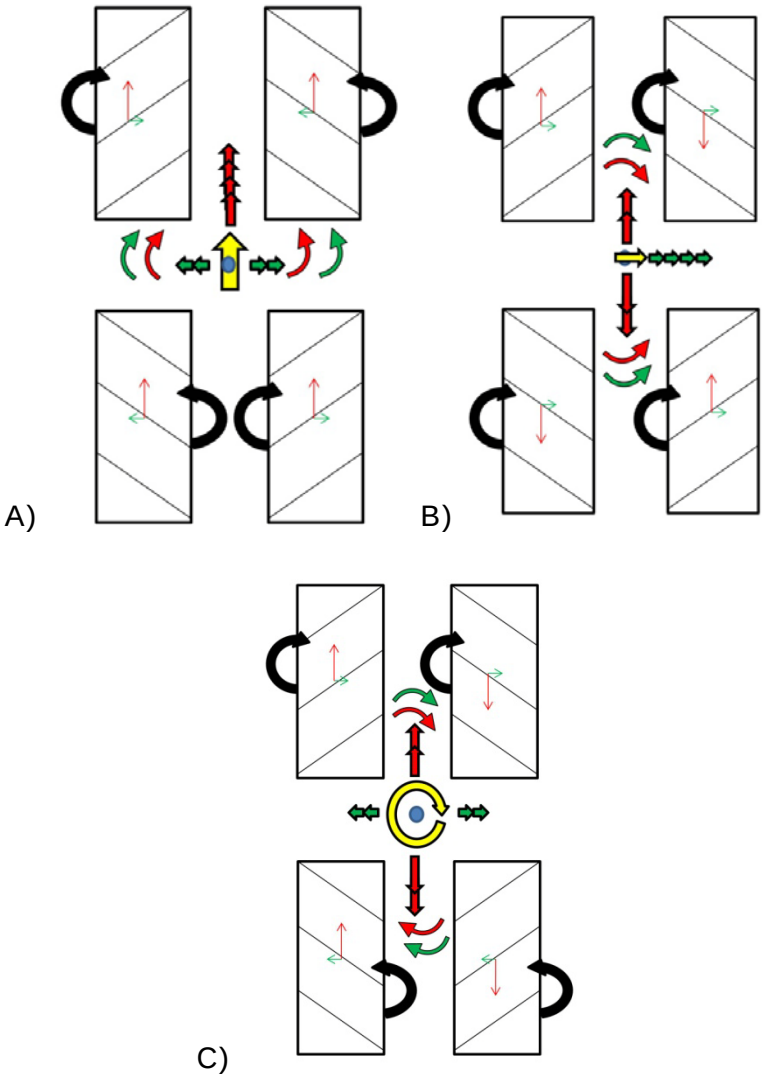


Figure 59: Inline-screw performance with minimal rolling-force influence such as on water.
A) Longitudinal B) Lateral (small force) C) Rotational

7.3.9 Underwater. During underwater testing, videos were taken above the surface and below the surface of the water. The author, equipped with a snorkel and waterproof camera, operated the test-bed and took underwater video while an assistant took video from the surface.

For every quad-screw configuration the underwater testing showed the same directions of locomotion as on the surface of water. As outlined in Dr.

Cole's work, the only difference the depth of submersion makes is the driving torque and thrust. In particular, the driving torque and thrust reduce as air is introduced to the screws [14]. Therefore, it was expected that each condition would result in similar paths as the surface of water.

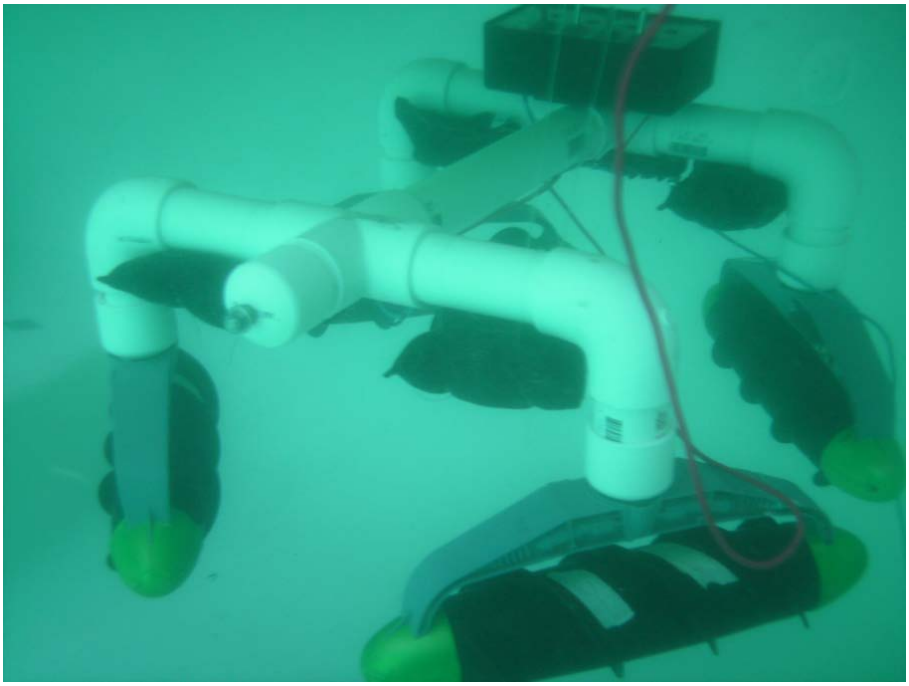


Figure 60: Underwater view during testing.



Figure 61: Test setup for underwater testing.

7.3.10 Snow. The double-screw easily navigated in snow. In all modes of locomotion, the double-screw performed successfully. Lateral locomotion resulted in pivot-turning for the double-screw. The double-screw did occasionally bury itself. Burial occurred regardless of the mode of locomotion, but the frequency in which it buried itself was much less in snow than in sand. In fact, it only buried itself when navigating tough obstacles. The primary cause for the Terrain Twister burying itself was its low hull contacting mounds of snow.



Figure 62: The test course for snow

The inline-screw proved capable of moving in each of the desired directions. It was adept at moving longitudinally, though flexibility to pitch would have been beneficial for crossing piles of snow. Rotational locomotion was also effective; however, the low friction of the snow caused it to slide down slopes easily when rotating. Lateral locomotion also worked for the

inline-screw, but since it fully relied on rolling-forces the slick surface caused it to slide around on the snow. Any portion of the snow that was not perfectly level played a large influence in changing the direction of the inline-screw when it was tested for lateral locomotion. Lastly, the inline-screw frequently buried itself during lateral locomotion.

As anticipated, the cross-screw could not move laterally, while the diamond-screw could not move longitudinally. Furthermore, the cross-screw performed well longitudinally as did the diamond-screw when moving laterally. An interesting observation was the cross-screw quickly buried itself during rotation while the diamond-screw had no issues during rotation. It was presumed that the minimal friction in snow was detrimental to the rolling-forces of the cross-screw, while the cohesion in the snow was beneficial to the tractive-forces that the diamond-screw relied on for rotation.

7.3.11 Split-Screw Tests. The split-screw was tested on a limited number of surfaces because it was similar to a double-screw with limited improvements. The split-screw was tested on grass, pavement, and water. Therefore, each extreme of terrain was tested for the split-screw. That is, the rigid-screw was tested on a rigid surface, a compliant surface and a fluid. Testing on the split-screw demonstrated that it could not move in a straight, lateral direction on grass. Instead, it arced like a double-screw because there were no counteracting tractive-forces to straighten its path. On pavement and in water, the split-screw was identical to the inline-screw with respect to its possible directions of locomotion.

7.4 Turning Radius

For this study, the circle that circumscribes a screw-vehicle is defined as its plan. The plan for a double-screw, inline-screw, cross-screw, and diamond-screw are given in figure 63. For each configuration, a line is drawn connecting the vertices to indicate the diameter of its plan.

Measurements were made to determine the plan-diameter of the double-screw, inline-screw, cross-screw, and diamond-screw. Testing was performed in marsh because visible tracks were left behind. The tracks were used to determine the turning diameter for each configuration. Marsh was also useful because the double-screw was able turn by pivot-turning, skid-turning and arc-turning.

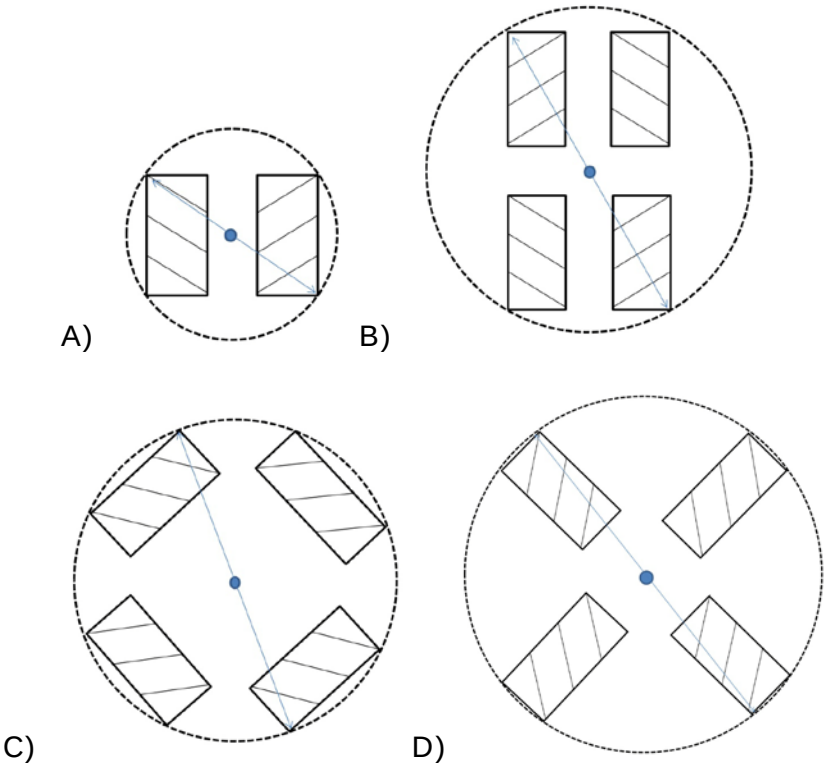


Figure 63: The plan and turning diameter.
A) Double-screw B) Inline-screw C) Diamond-screw D) Cross-screw

Table 2: Turning-diameter and turning-ratio in marsh

	Double-screw			Inline-screw	Cross-screw	Diamond-screw
Steering	Skid	Pivot	Arc	Rotate	Rotate	Rotate
turning-diameter (inches)	28	29	61	30	29	26
plan-diameter (inches)	14.5	14.5	14.5	29	29	25
turning-ratio	*1.931*	*2*	*4.207*	*1.034*	*1*	*1.04*

Table 2 clearly illustrates the quad-screw configurations had a 1:1 turning ratio while the double-screw had a 2:1 ratio for pivot- and skid-turning. The data makes sense because the double-screw turns about its end rather than its center. Figures 64 and 65 show tracks from the turning tests.

A)  B) 

C) 

Figure 64: The double-screw's rotation tracks left in marsh.
A) Pivot-turning B) Arc-turning C) Skid-turning

A)  B) 

C) 

Figure 65: Test-bed rotation tracks left in marsh.
A) Inline-screw B) Cross-screw C) Diamond-screw

7.5 Test Summary

Table 3 is a performance matrix that summarizes the three types of locomotion. Each quad-screw configuration is rated on a scale from 0-5. The scale was based on each configuration's ability to move in the set direction without deviating from their path or becoming immobilized.

- 0: No movement or the path cannot be determined
- 1: Brief motion in the set direction followed by immediate and consistent immobilization or path deviation.
- 3: Clearly moves in the set direction with occasional immobilization or path deviation.
- 5: Clearly and consistently moves in the set direction with no instances of immobilization and minimal path deviation.

Table 3: Quad-screw performance matrix

	Inline			Cross			Diamond			
	Long.	Lat.	Rot.	Long.	Lat.	Rot.	Long.	Lat.	Rot.	*Average*
Surface										
Grass	5	5	5	5	1	5	0	5	5	*4*
Dirt	4	5	5	4	1	5	1*	4	2	*3.75*
Marsh	5	5	5	5	0	3	0	5	4	*3.556*
Sand	3	4	5	3	1	5	1*	3	1	*3.125*
Clay	2	5	5	2	1	5	1*	2	1	*2.875*
Gravel	5	4	5	2	1	5	0	4	5	*3.444*
Pavement	0	5	5	1	1	5	1*	1	1	*2.375*
Above Water	5	0	5	5	5*	0	5	5	5	*3.75*
Underwater	5	0	5	5	5*	0	5	5	5	*3.75*
Snow	5	3	4	3	0	1	0	4	5	*2.778*
Average	*3.9*	*3.6*	*4.9*	*3.89*	*0.67*	*3.78*	*1.111*	*4.22*	*3.78*	

An asterisk indicates reversed locomotion.
Note: All values are generic units.

There are several points of interest in table 3. Namely, the inline-screw scored the same or higher than the other configurations in every

category except lateral locomotion in water and longitudinal locomotion on pavement. Nonetheless, it should be noted that the cross-screw and diamond-screw, though they didn't score a 0, performed poorly for lateral and longitudinal locomotion on pavement.

Another point of interest was the cross-screw experienced reversed lateral locomotion on water, while the diamond-screw experienced reversed longitudinal locomotion on solid surfaces. For the cross-screw, the tractive-force of the blades pushed it laterally in reverse, explaining the low scores on solid surfaces and the reversed locomotion in water. Alternatively, for the diamond-screw, the rolling-forces were what pushed it longitudinally in reverse.

The double-screw could not be graded on the same performance matrix as the quad-screw configurations because it could not rotate in the same manner. Also, the double-screw usually did not move in a straight, lateral direction, which could be considered a useful function in cases where skid-steering is not effective. Therefore, in the lateral direction, the double-screw was scored based on how often it became immobilized or deviated from its general path.

Table 4: Double-screw performance matrix

	Double-Screw		
	Long.	Lat.	Skid
Surface			
grass	5	A 5	4
dirt	4	A 5	3
marsh	5	P 5	4
sand	3	A 4	1
dry clay	3	A 5	2
gravel	5	A 5	5
pavement	0	S 5	0
above water	5	P 5	5
underwater	-	-	-
snow	5	P 4	4
Average	3.5	4.3	2.8

S=straight, A=arc, P=pivot
Note: All values are generic units

Figure 66 shows the relationship between the longitudinal velocity of the inline-screw and the percent the screws are slipping. The data confirms the studies reviewed by showing cohesive terrain of low friction being optimal for reducing slippage. From the literature, sand was characterized by being loose and highly frictional. The dirt tested was located in Florida which can also be characterized by a high sand content. Therefore, the loose sand and dirt showed a relatively high slippage and low velocities. In comparison, grass, wet marsh, and snow were described as being cohesive and low friction surfaces. Again, grass, marsh, and snow moved the quickest and experienced the least slippage. It should be noted that the underwater configuration experienced greater drag and was a much heavier setup than the above water configuration. Therefore, it was expected to experience far greater slippage.

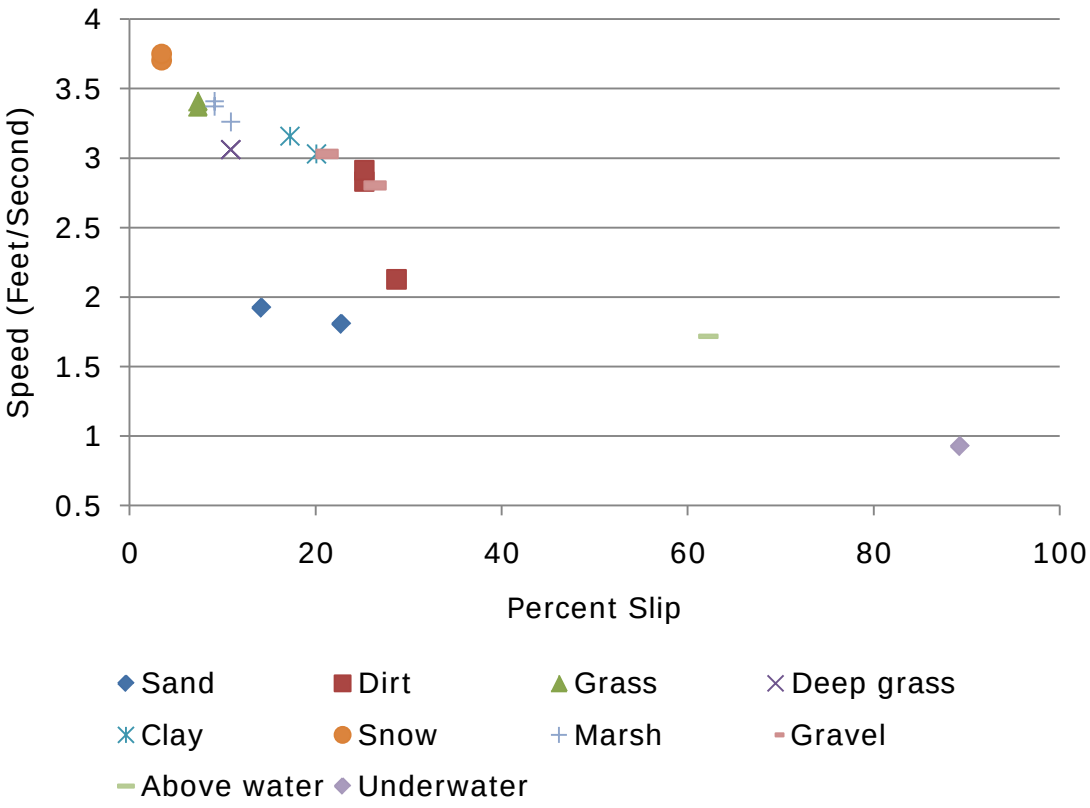


Figure 66: A graph illustrating the correlation between forward speed and percent slip. Above water and underwater data

$$\text{Percent slip} = \frac{(L \times N) - T}{L \times N} \times 100 \qquad (4)$$

Where:

L= Screw's lead

N= number of blade revolutions

T= Travel distance

Figures 67, 69 and 70 are charts comparing speeds for the inline-screw, cross-screw and diamond-screw.

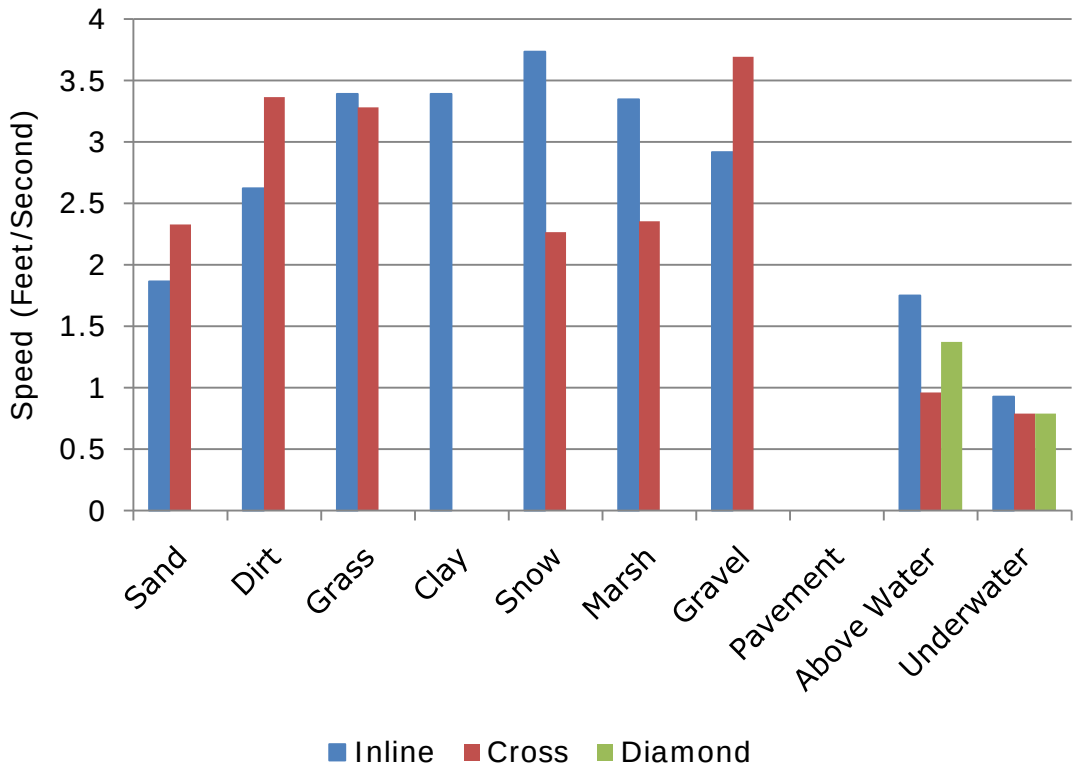


Figure 67: Longitudinal speeds for the test-bed configurations in different terrains.

From figure 67, on loose, frictional surfaces such as sand, dirt and gravel the cross-screw was fastest. However, in cohesive, low friction surfaces the inline was fastest. The above observation makes sense when considering the rolling-forces, which exist only for the cross-screw, rely on friction, while friction works against the tractive-forces. On water, the inline was faster because the tractive-forces were exactly in the direction of motion. It was presumed that the cross-screw was slower than the diamond-screw for above water tests because of the test-bed's setup. The float blocked the wake generated by the front-screws of the cross-screw configuration during forward locomotion.

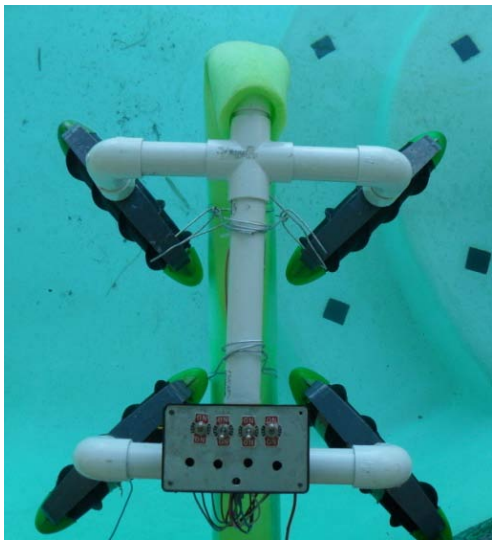
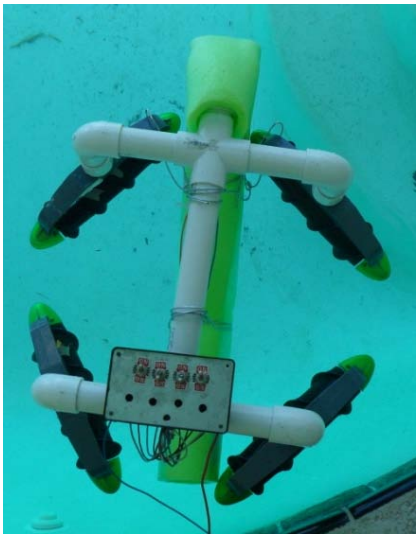
A)  B) 

Figure 68: The test-bed setup for the cross-screw and diamond-screw in water.
A) Cross B) Diamond

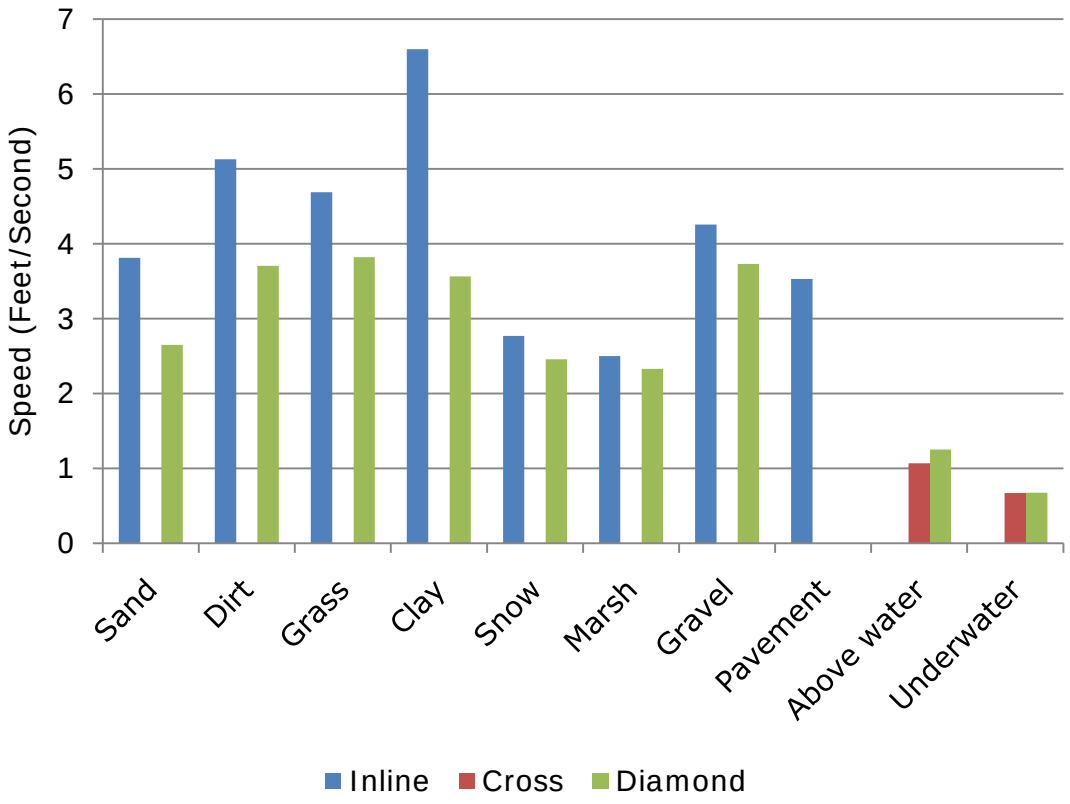


Figure 69: Lateral speeds for the test-bed configurations in different terrains.

For lateral locomotion, the inline-screw was always faster than the diamond-screw. The reason was likely because the rolling-forces of the inline-screw directly contributed to its locomotion. Appendix D shows the screws used for the test-bed roll laterally further per revolution than they screw forward. Finally, in water the cross-screw and diamond-screw travelled at nearly the same lateral speed because the test-bed's float blocked screws in both configurations.

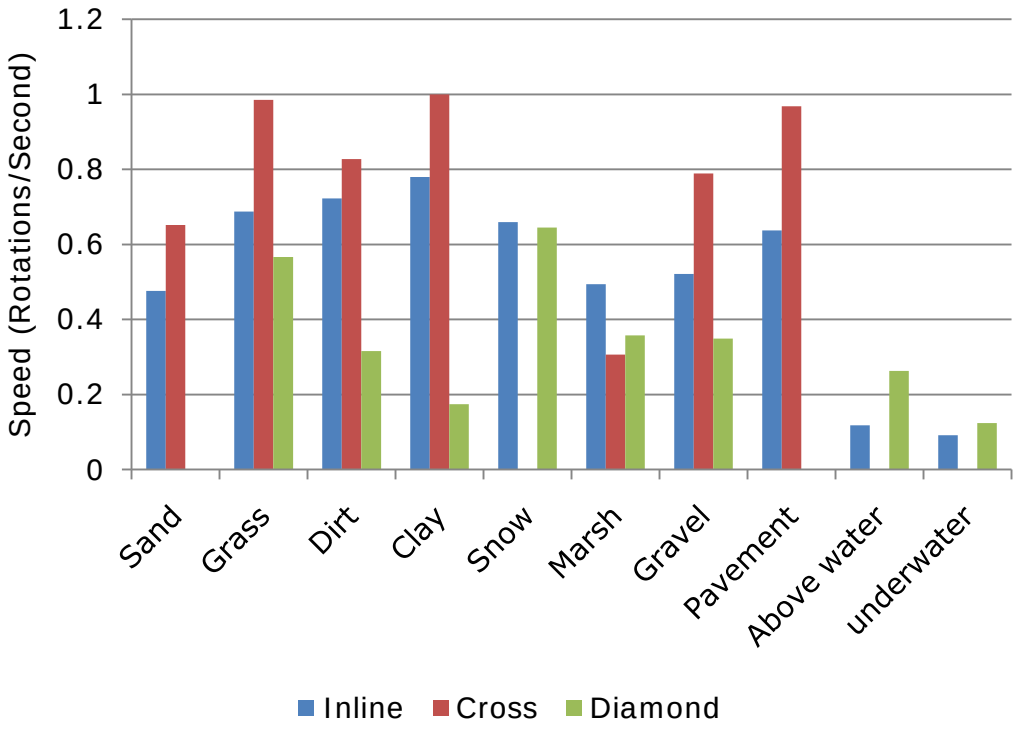


Figure 70: Rotational speeds for the test-bed configurations in different terrains.

The cross-screw was always fastest because the rolling-forces directly contributed to rotation. Again, water was an exception because the importance of the rolling-forces and tractive-forces are flipped. The diamond-screw was fastest in water for rotation because its tractive-forces were exactly in the direction of rotation.

CHAPTER 8: CONCLUSIONS

In this study, a thorough investigation of the double-screw was performed. From the research, it was determined that improvements could be made from the standpoint of omnidirectional locomotion. In particular, the double-screw could not follow a straight, lateral path, except on the most rigid of terrains, and could not turn about its center unless on water. Furthermore, the double-screw had only limited potential for turning on pavement.

A number of solutions were given an initial investigation, and three were selected for a full study of omnidirectional locomotion. Specifically, the inline-screw, the cross-screw, and the diamond-screw were selected for this study. The study consisted of a force-vector analysis, a mobility study, and maximum speed tests.

The mobility studies showed the inline-screw was the most versatile and predictable configuration compared to the cross-screw and diamond-screw. Basically, the inline-screw was fully omnidirectional on all surfaces except pavement and water. Nonetheless the inline-screw was able to navigate pavement and water by rotating about its center. On the contrary, the cross- and diamond-screws exhibited limited lateral or longitudinal

capabilities, respectively. Furthermore, the direction of locomotion for the cross-screw and diamond-screw varied depending on the surface.

The vector analyses in this study verified all of the mobility test results. Therefore, it can safely be confirmed that the inline-screw was the most versatile of the three test-bed configurations. In addition, according to the vector analyses, the inline-screw is the only configuration that experiences no inherent indeterminate or impure locomotion. Furthermore, the inline-screw resolved issues of the double-screw by allowing for straight, lateral locomotion and rotation about its center on all surfaces. A distinct advantage is the potential to maneuver over paved surfaces through a combination of lateral and rotational locomotion.

Each of the quad-screw configurations that were tested demonstrated a strong point. In water, the diamond-screw was clearly the optimal configuration from the standpoint of omnidirectional locomotion, because it was the only configuration capable of locomotion in all directions. Alternatively, the cross-screw proved to be the fastest in highly frictional soil such as sand or dirt and was the fastest on gravel. All in all, the inline-quad-screw, which is proposed for the first time in this thesis, represents the best overall versatility and performance in an omnidirectional screw-drive.

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APPENDICES

Appendix A: S-Diamond-Screw Force-Vectors

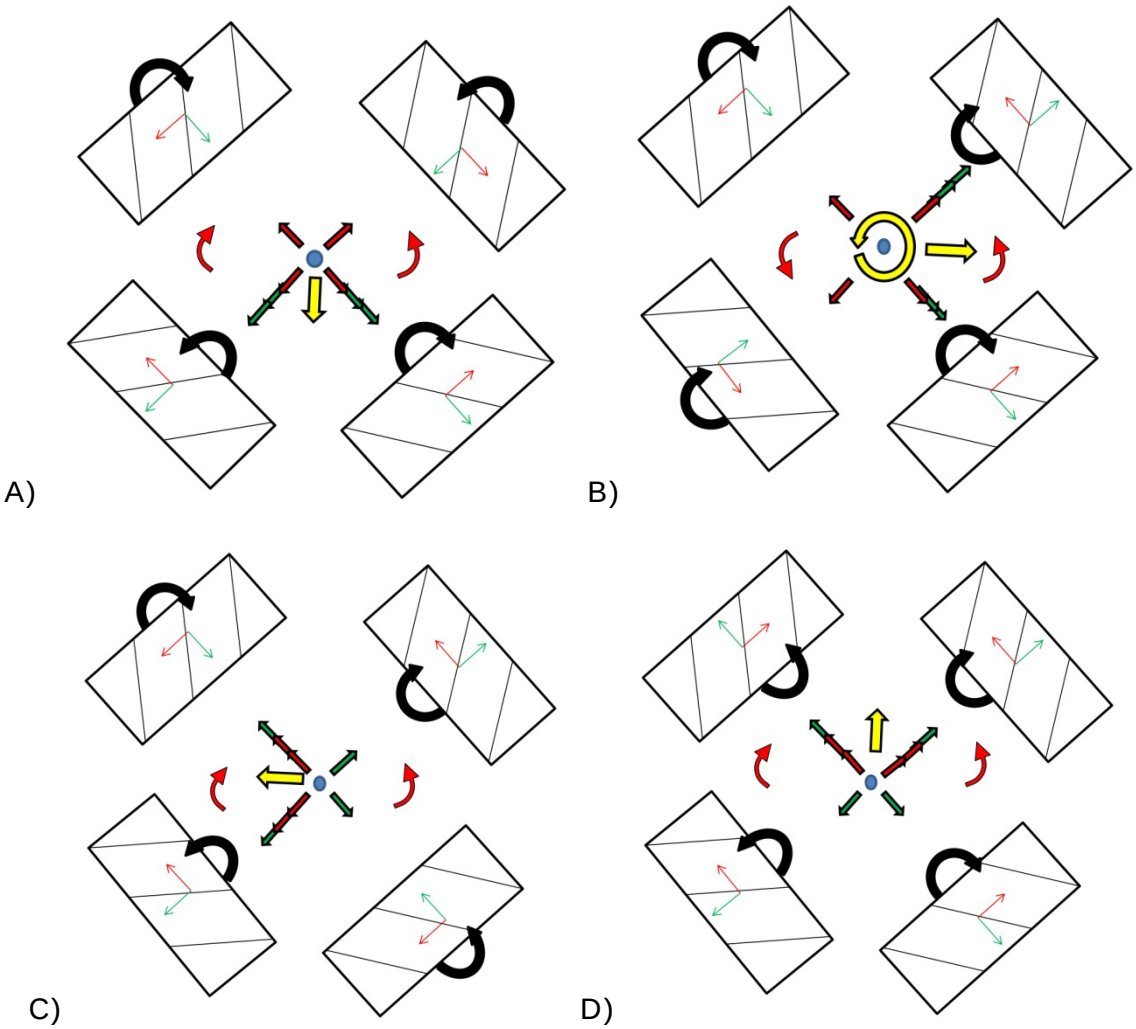


Figure A1: Four symmetric screw rotations for the S-diamond-screw. A) Longitudinal (roll dominated) B) Rotational (impure skew motion) C) Lateral D) Longitudinal (traction dominated)

Appendix B: S-Cross-Screw Force-Vectors

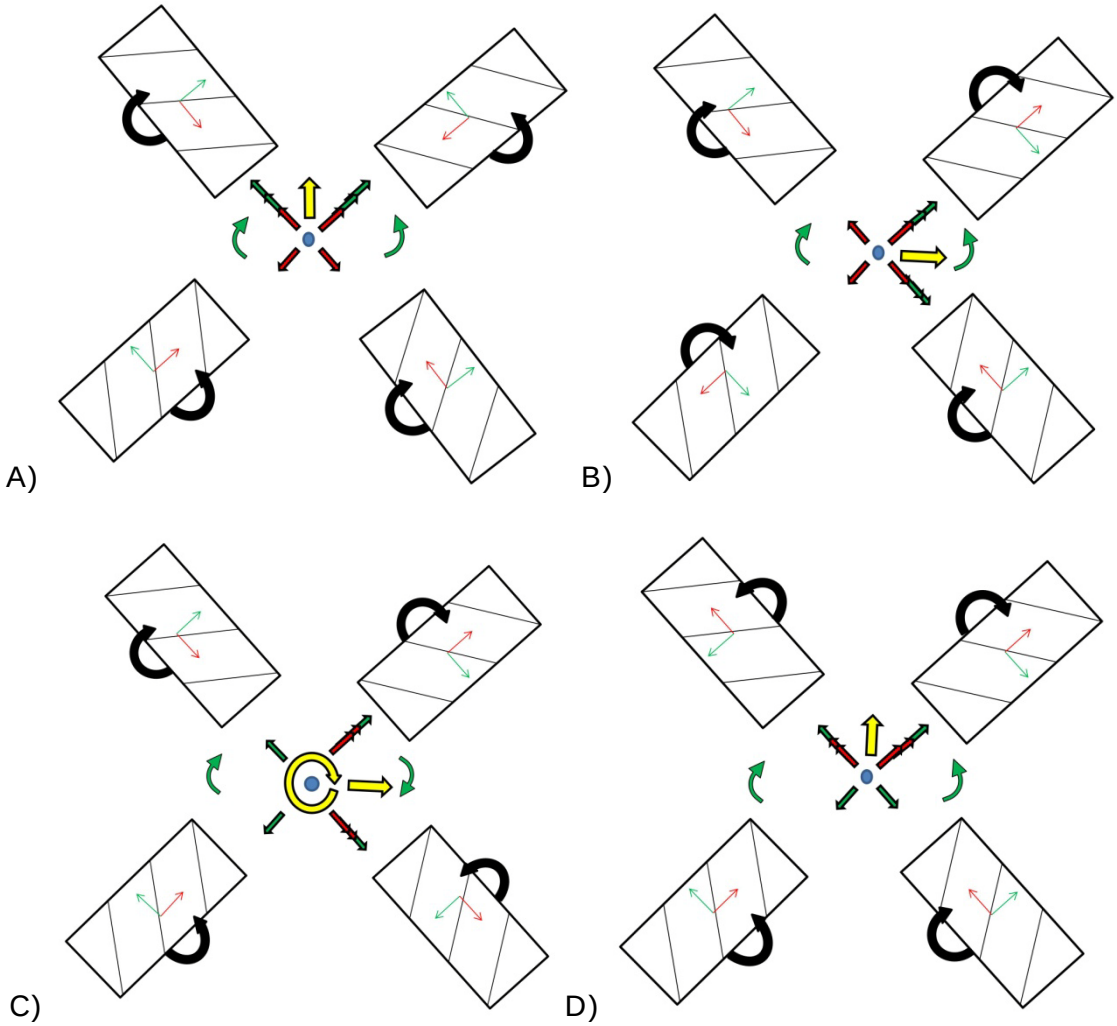


Figure B1: Four symmetric screw rotations for the S-cross-screw.
A) Longitudinal (roll dominated) B) Lateral
C) Rotational (impure skew motion) D) Longitudinal (traction dominated)

Appendix C: Mirrored-Test-Bed Force-Vectors

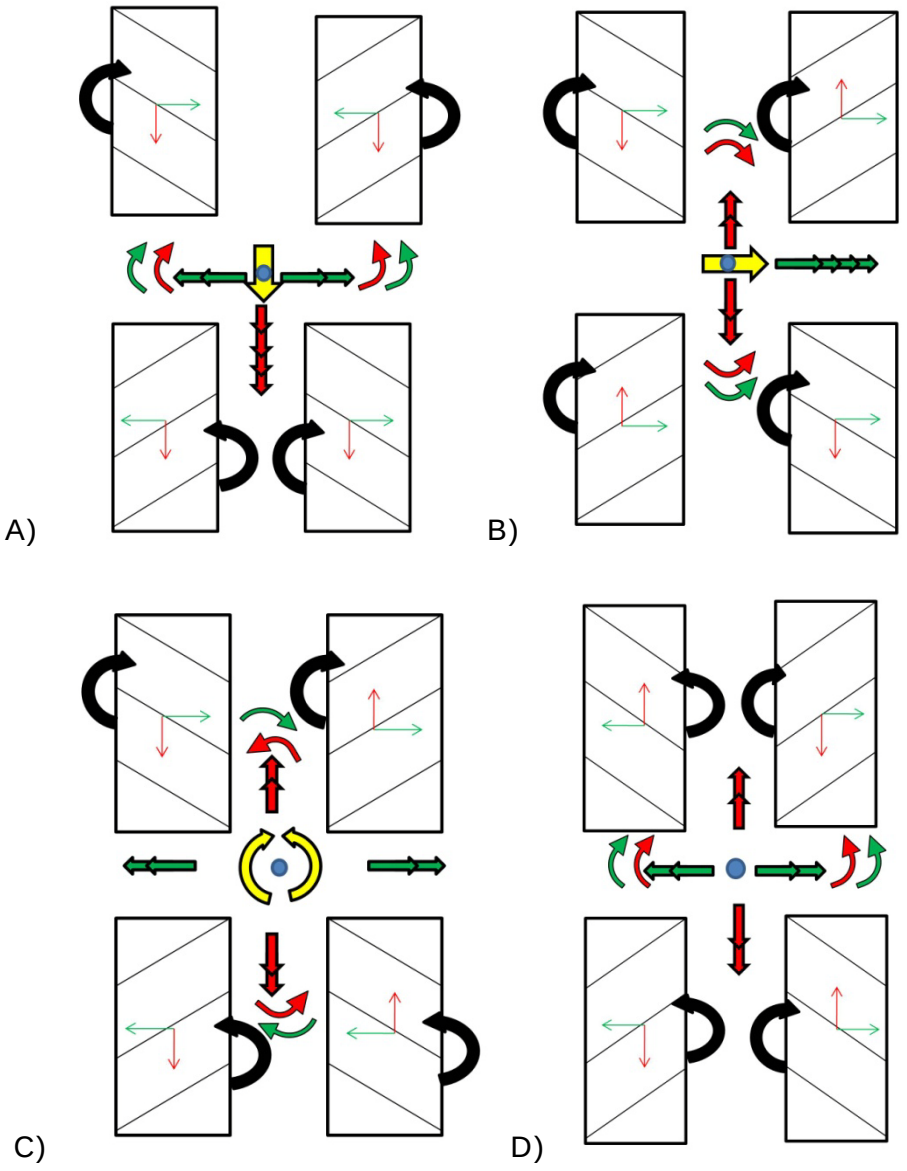


Figure C1: Four symmetric screw rotations for the mirrored inline-screw.
A) Longitudinal B) Lateral
C) Rotational (indeterminate rotation direction) D) No locomotion

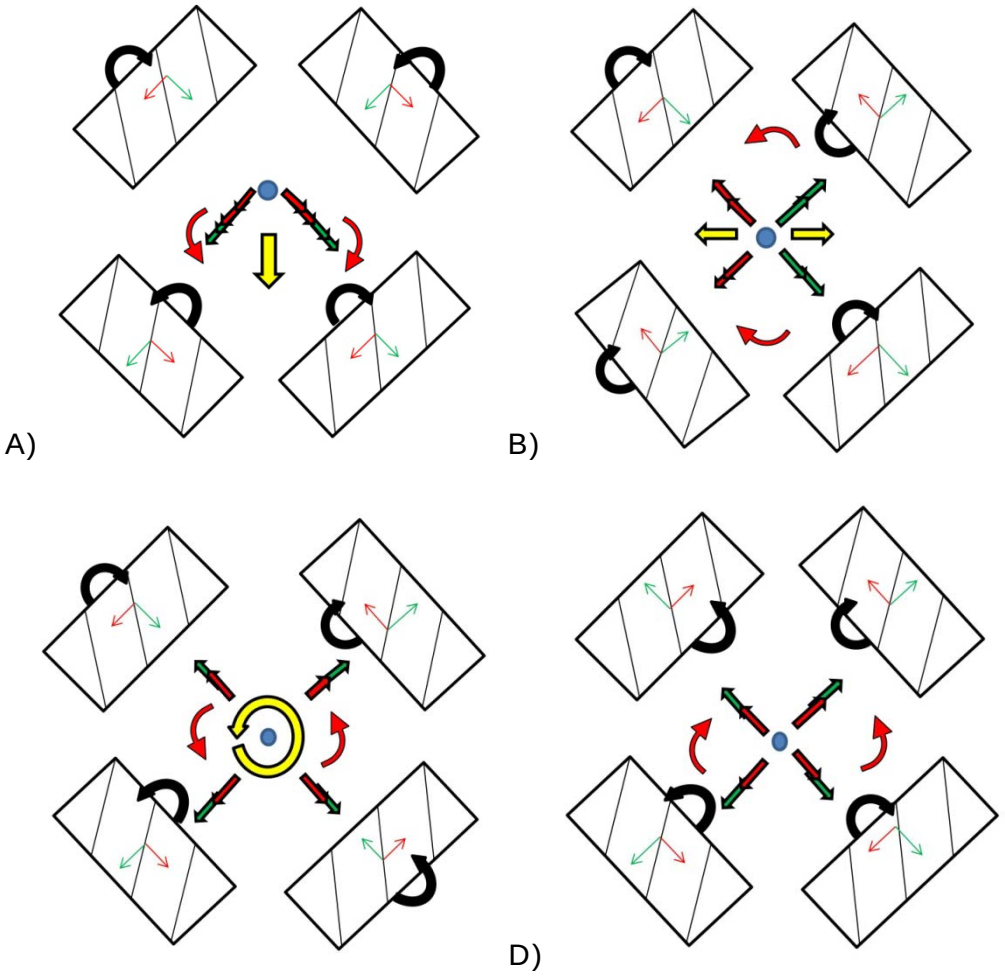


Figure C2: Four symmetric screw rotations for the mirrored-diamond-screw.
A) Longitudinal B) Lateral (left or right is indeterminate)
C) Rotational D) No locomotion

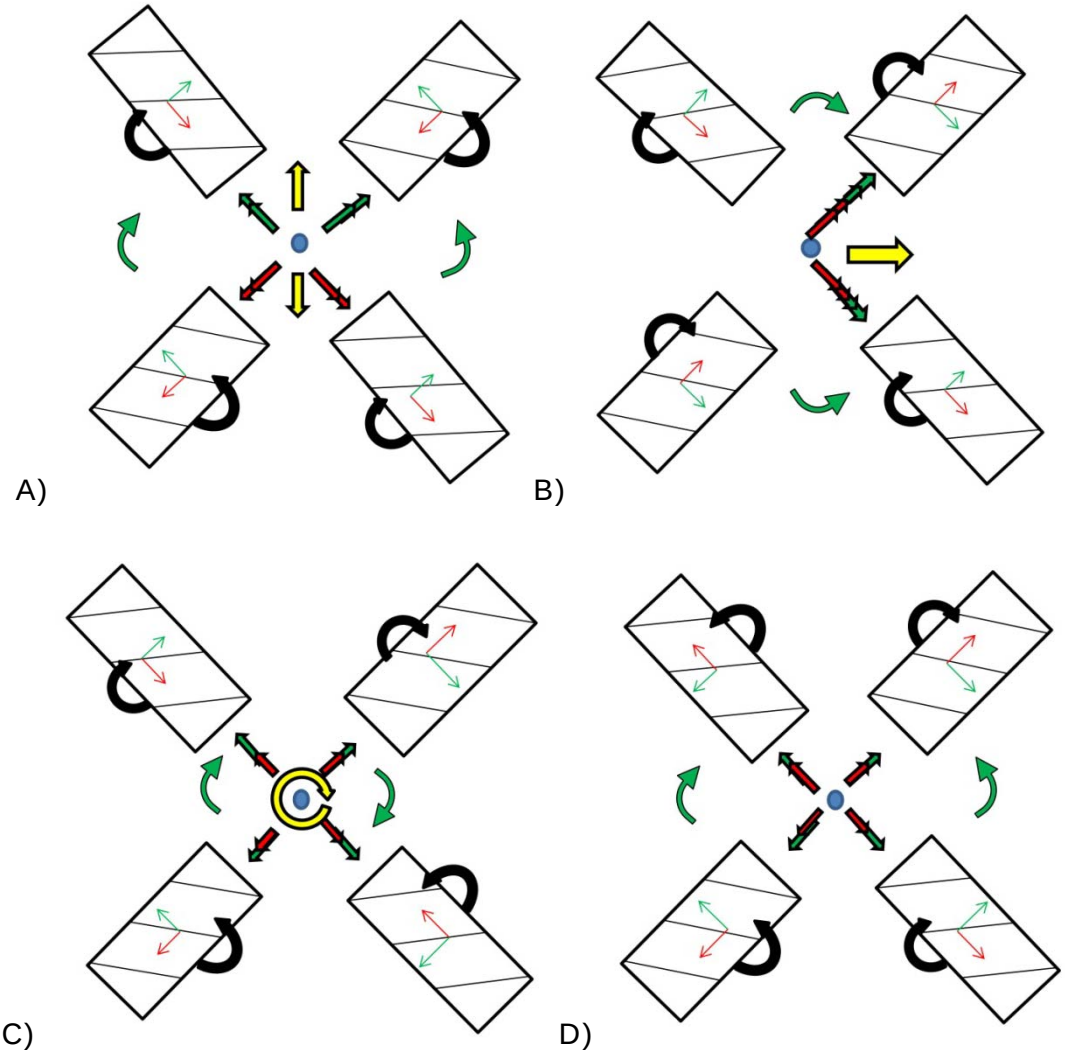


Figure C3: Four symmetric screw rotations for the mirrored-cross-screw. A) Longitudinal (forward or reverse is indeterminate) B) Lateral C) Rotational D) No locomotion

Appendix D: Terrain Twister Screw Calculations

The screw for the Terrain Twister was unique because the drum was shaped like a barrel with the middle of a larger diameter than the ends. The blade-height varied so most of the tips could contact level ground. The minimum and maximum values for each measurement are located in Table A1.

Table A1: Terrain Twister screw measurements

	Ends	Center
Drum-Diameter	2.25	2.5
Length (inches)	9.125	9.125
Lead (inches)	5	5
Blade-Height (inches)	0.313	0.375

Calculations were made using the minimum and maximum values. The values that were furthest from being ideal, according to the reviewed research, were used to be conservative. The formula used to calculate the helix-angle was:

$$\phi = \tan^{-1}\left(\frac{L}{\pi \times (D+h)}\right) \times \frac{180}{\pi} \quad (5)$$

For one revolution, the distance travelled due to rolling is equal to the circumference of the outer diameter of the screw. Alternatively, the distance travelled in one revolution due to screwing is equal to the screw's lead.

Appendix D: (Continued)

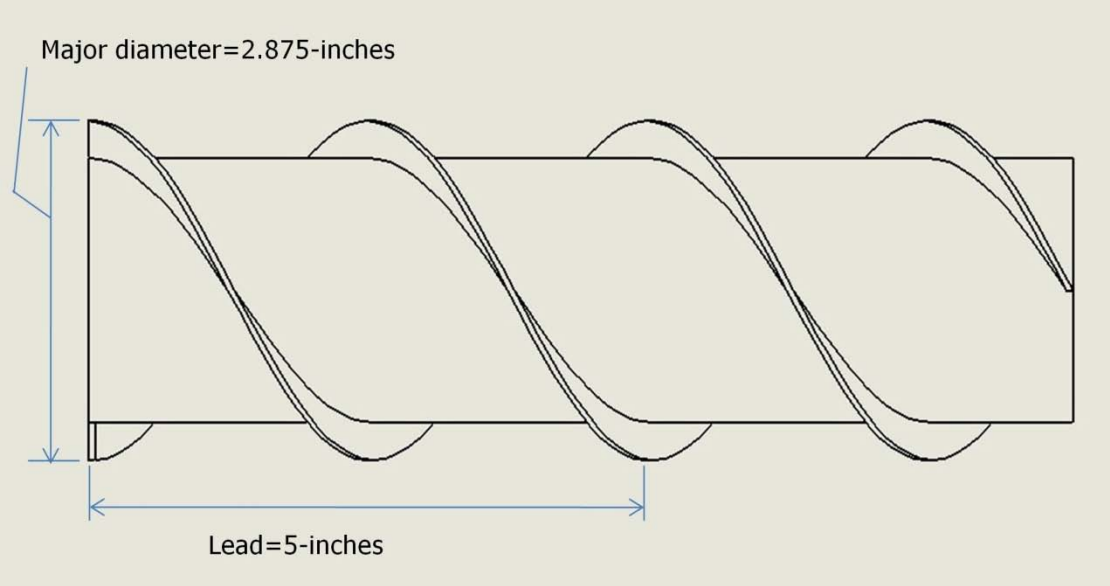


Figure D1: The Terrain Twister's major diameter and lead.

$$\text{Circumference} = \pi \times \text{Dm} \quad (6)$$

Where:

Dm= major diameter

Since the travel distance, T, for rolling is the same as the circumference:

$$T = \pi \times 2.875 \text{ inches} = 9.03 \text{ inches} \quad (7)$$

The screws that were used had a lead of 5-inches. Therefore, a vehicle using those screws will travel 1.8 times further per revolution for rolling compared to screwing.

ABOUT THE AUTHOR

Jon Timothy Freeberg was born in Arcadia, California in 1984, and in 2007 he earned a Bachelor of Science in Mechanical Engineering at the University of South Florida. For two years he worked as a manufacturing engineer intern at Conmed Linvatec in Largo, Florida where he worked in the shaver blade factory. His responsibilities, among others, included validating packaging equipment, investigating pyrometers on induction bonder equipment, and introducing a new process of lubricating arthroscopic shaver blades. In 2009, he returned to the University of South Florida to pursue his Master of Science degree in Mechanical Engineering.