The Design of an Omnidirectional All-Terrain Rover Chassis

Timothy C. Lexen

Cumberland, WI 54829 USA
novustcl@charter.net

Abstract—**This paper presents a rover chassis design providing holonomic motion on rugged terrain, with a simple design using three screws and having multiple benefits. The design offers an extremely robust and versatile alternative to wheeled and tracked rovers for use on a wide variety of ground materials and rugged terrains. The paper describes a prototype design and discusses design optimization, concerns and options.**

Keywords-component; holonomic, rover, terrain, design, mobile robotics, traction, screw

I. INTRODUCTION

There is a need for a rover design having an optimum of efficiency, robustness, versatility, mobility, and cost effectiveness, for travel over a wide range of natural surfaces and terrain. Of increasing importance is the ability to traverse difficult terrain, materials and obstacles without getting stuck. This has led to the development of wide range of traditional wheeled and tracked vehicles, and also variations of these vehicles including adaptable, articulated or re-configurable chassis, hybrid locomotion systems, "rocker-bogie" suspensions and tracked flipper arms. The performance of these designs over the years has been well developed and documented

However, all the above rovers have limited maneuverability, especially in tight quarters, which limit their ability to deal with difficult terrains and materials. Current designs may easily tip over or get stuck or blocked by a wide range of obstacles, discontinuities, or soft surface materials. A rover with more maneuverability has more options when traversing difficult materials/terrain in order to avoid slipping or getting stuck, or when trying to get out of a terrain trap; it also has more options in avoiding or surmounting obstacles, or when recovering from flipping over. In particular if a rover is stuck and essentially can only move forward or backward before or while turning, it has limited options. In traditional tracked and wheeled rovers orientation is constrained, non-holonomically, by the direction of travel.

One way to improve the maneuverability and overall functionality of a rover is to use a three-degree-of-freedom (3DOF) drive system, also referred to as an omnidirectional or holonomic drive. These drive systems are of one of two main types.

The drive system may use independently powered and steered standard wheels, in the form of casters, also referred to as an "all-steerable wheels" concept. These may use self-contained "intelligent" wheels or wheel modules. Essentially the wheel units are casters, in which either the caster rotation is powered separately or, in another design, two wheels of each caster are offset and powered [1, 2]. However, problems which arise in using this kind of system outdoors are centered on the complexity of controls, linkages, gears and extra motors: a design with three steerable wheel units requires six motors. Secondary concerns include the need for a sophisticated suspension if there are more than three wheel units; turning friction beneath each wheel; the need to turn the wheels before going in a new direction; and the height of assembly needed, that is, the vehicle is usually not compact in height.

Alternately, the drive system may use special wheels, which have been used indoors for the past 30 years. Universal or Meccanum wheels contain passive, rolling components placed orthogonal to the driven direction, so the wheels can roll freely in this orthogonal direction. There are variations of these designs with various the ground contacting elements [3]. These wheels work well on smooth, flat surfaces. However, all these vehicles encounter problems in outdoor environments, such as dealing with dirt and uneven terrain, low obstacle climbing ability, lack of traction, and overall complexity.

In short, omnidirectional drive systems do not seem to have been considered practical for outdoor, all-terrain use, primarily because they are unduly complex mechanically, with corresponding expense, weight and bulk. Also these designs have either high turning friction or low traction

II. A ROVER DESIGN SOLUTION

This paper describes the design of a small holonomic rover chassis for outdoor, all-terrain use; this chassis could be controlled either as a robot or as a remote controlled device. This is a very simple design using ground-contacting screws that has many benefits in terms of robustness, flexibility, and utility.

Figure 1 shows the innovative design using three helical screw elements extending from a central frame. Each screw is a helical coil, providing a round "edge profile" with an abrasion resistant, low friction material on its outer surface. The device rides on the low friction edge profiles and relies on the combined effects of the multiple drive screws against the ground surface.

The design works because for each screw, motion is constrained in one direction—perpendicular to ground contact line—and unconstrained in the perpendicular direction—parallel to the ground contact line. It is thus very similar to the Universal and Meccanum wheels, but without the moving rollers. The sliding friction parallel to the ground contact line is much less than the friction—actually a sort of macro-friction due to the profile sinking into the ground or catching on the ground--- perpendicular to the ground contact line, due to the difference in radii. The profile either sinks somewhat into the ground material, or catches on the roughness of the ground material, and the side of the profile can apply a force to the ground material. Note the edge profile does not grip the surface absolutely: the profile can slide over the ground at any angle of attack Thus the traction is limited to an extent; however, it is this slippage which allows the drive system the 3DOF capabilities. This the same effect used when a downhill snow skier uses the edge of a ski to prevent motion in one direction while allowing sliding in the perpendicular direction. This is also like the motion of both real snakes and robotics snakes [4] that both slide over and push against the ground surface.

Figure 1 shows the basic mechanical drive elements. A frame or plate holds the three gearmotors--in this case having strong front bearings--and drive screws in the proper relationship, nominally in the same plane.

The angle between the drive screw axes is about 120 degrees, but this is not critical. Each drive screw has a ground tangent line**,** tangent to the helical edge profile where it contacts a flat level ground surface, as illustrated in Figure 2. This force s applied perpendicular to the ground tangent line. Because the drive screws are identical, the angle between the

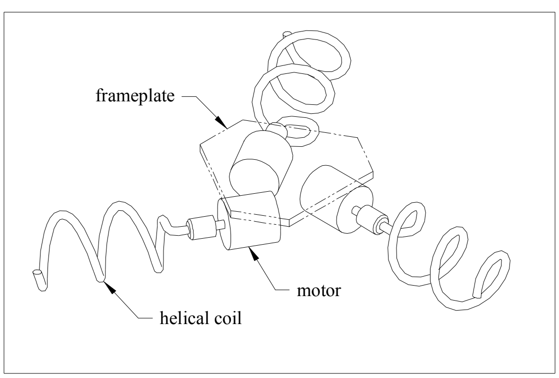

Fig. 1. Simplified concept drawing.

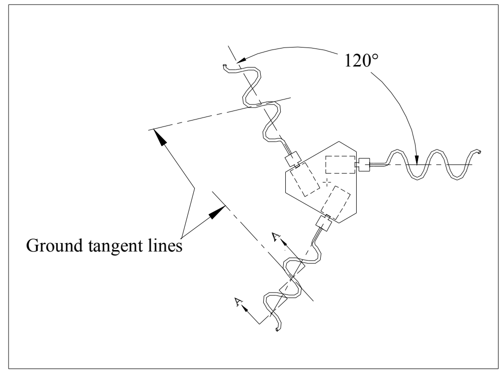

Fig. 2. Rover screw layout.

ground tangent lines of two adjacent drive screws is also 120 degrees.

The low-friction edge profile must dig into or catch on the ground or obstacle surface, and also there must be a friction differential parallel to and perpendicular to the edge profile. Thus the rover works well on grass, dirt, sand, mud, gravel, carpet, and rocky and rough surfaces, but not on snow, ice, or other smooth or low-friction surfaces. The rover can travel over flat asphalt or concrete, to the extent that the edge profile can catch on its surface roughness. The rover design can deal with obstacles by driving one screw over and then rotating to get the second screw over, then pulling the body and third screw over last.

Since this screw drive is similar to a long Meccanum wheel without the rollers, and to a lesser extent similar to an elongated Universal wheel, the control issues will be similar to those seen in the dozens of applications of Universal and Meccanum wheels for indoor omnidirectional rovers. The desired motion vector and rotational velocity are resolved into the individual screw speeds that will create the desired motion. However note that ground contact points move with screw rotation, shifting with respect to the body

Screw or helical elements have been used for mobility for over one hundred years [5], but virtually always in pairs with axes in parallel, with a few exceptions [6]. Many of these used rotating pontoons with helical blades, where the pontoons supported most or all of the weight. However these have used simple metal square- or triangular-edged helical vanes, fins, or blades; they did not use a curved edge profile or a low-friction coating.

III. PROTOYPE DESIGN

The prototype has been developed with the following design features and layout concerns as shown in Figures 3 and 4. The central body is designed to allow the inboard ends of the screws to be as close together as practical, within the limitations of the length of the bearing system and servo motor. The body is roughly triangular, about 18 cm (7 inches) on a side. The chassis weighs about 0.6 kg (1.2 lb). The body also gives good ground clearance with minimum hang-up

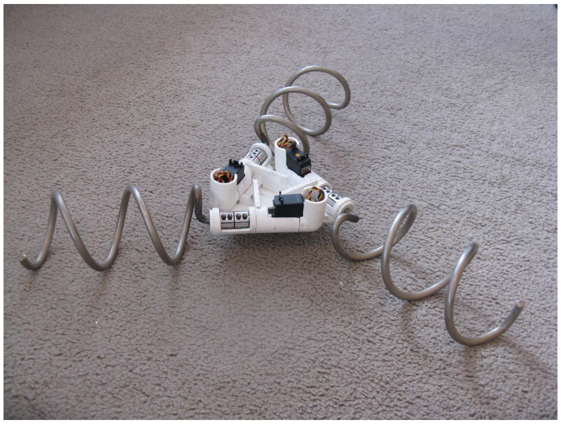

Fig. 3. Prototype rover.

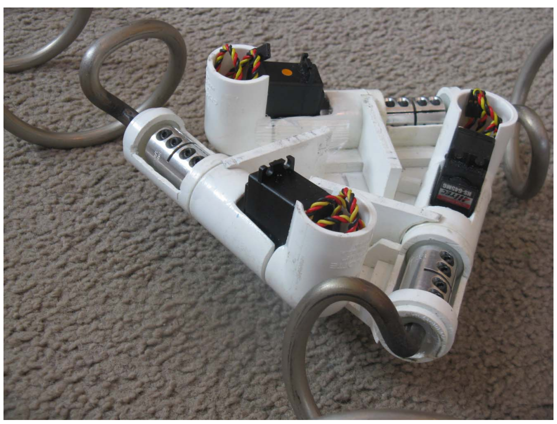

Fig. 4. Close-up of prototype body, showing servo motors but not additional controls.

points on the underbody. The body is made of PVC, selected for ease of fabrication and modification.

The helical coil was the easiest way to make screws, although what is important is the support of a helical curved edge profile. The coils are of 3/8” stainless steel with 4 inch outer diameter, with a 15 degree helix angle and 8.6 cm (3.4 in.) pitch, and 2-1/3 turns. Along each screw’s length there is range of ground contact of about 20 cm (8 inches). Each screw if formed into a reduced diameter at the outer end and a central shaft at the inner end.

While early prototypes used DC gearmotors with strong front bearings to handle the overhung loads, the current prototype uses a dual bearing design which isolates the overhung loads and axial loads from the servo motor at each screw. The servo motors are Hitec HS-645MG with maximum 0.6 kg-cm (133 in-oz) torque, about 1 rpm, running on a 6 volt battery pack. Each motor is connected to its screw via a spline connection to a short shaft, and via a rigid coupling between two plastic bearings.

The radio control system is standard Futaba 4 channel FM transmitter and receiver, with one joystick on the transmitter control direction, and one of the other channels controlling rotation. The radio control system seems appropriate for this stage of prototype development, where the main purpose is proof of concept and testing on various terrains and materials. In addition is uses an OMX-3 Mixer from Robot Logic, designed for use with three wheel omnidirectional chassis; this is installed between the receiver and the motors. Also an E-Flite G110 R/C helicopter gyro has been added for rotational stability; this is installed between rotation channel on the receiver, and the mixer.

IV. Benefits

The most obvious benefit of this rover design is omnidirectionality in and of itself, meaning the ability to move in any direction without turning. In this case it gives true holonomic motion on rough terrain and materials. It maximizes maneuverability, and eliminates the need for y-turn and parallel parking maneuvers, or the need for skid steering.

In addition, the variable orientation of the drive can be used to optimize traction, stability, and ability to negotiate difficult terrain, adding versatility without physically reconfiguring itself. Thus when approaching a terrain feature one can choose whether to have one particular screw forward, or two screws forward, or whether to make first contact with the side of the screw. Also, because of the “Y” layout of the screws, the screw placement can be oriented to straddle holes or crevasses.

This flexibility can also be enhanced by taking advantage of unique features of the helical screw drive elements. For instance the free end of the helical screw can approach a step obstacle from a range of angles and rotate to catch on it. Or if one screw is longer than the others, the long screw of the rover can be oriented downhill to improved stability while on a slope, or for other purposes. The rover can be oriented to get optimal traction, for instance by climbing a slope with the downhill screw position so that its contact lines are perpendicular to the direction of travel—this would be particularly helpful when the rover has a higher center of gravity so that more weight is transferred to the downhill screw.

The two above aspects of a holonomic system--omnidirectionality and variable orientation—combine to give additional benefits due to maximum maneuverability. A camera or other sensor could be oriented with the body, possibly eliminating the need for a turret or other actuator. This would also be useful in missions requiring docking with another vehicle or structure, or in the precise positioning of equipment.

In addition to the above benefits of holonomic motion, there are several benefits of the overall design configuration and the screw action. Firstly, the basic layout has a minimum of open space between the drive elements, reducing the chances that the rover will become hung up on an obstacle. At the same time the ground contact forces are spread out over a wider area, to reduce point contact and pressure, and to gain a footing. This wide distribution of contact forces is the result of a unique layout of a central body with three near-radial screws, and the nature of the screw ground contact. The area of potential contact—as the rover is rotated—is large compared to the body size: in the prototype the potential contact area is about 15 times the area under the body. The screws give continuity of ground contact as the vehicle moves forward, as there is with tank treads, which is helpful in getting traction and for crossing positive or negative obstacles.

Secondly, the screws themselves give advantages over wheels or treads. Also if the rover gets mired in sand, it can spin to rise up and get free. With the helical coil screw design it is possible to use a very large fraction of the drive screw's height in stepping over, surmounting, or gripping onto obstacles or ground/terrain features. A screw has the unique ability to drive against surfaces that are on its sides, and just on surfaces under the screw. The ends of the screws may be considered actuators, as they can be used to apply force in various directions, such as for lifting upward at ground level. The screws are easy to remove and attach, and since they are mostly open space they can be nested for compact storage.

Thirdly, the screws, bearing system and body can be designed to be very tough: damage-resistant and damage-tolerant, able to survive a roll-over or fall. The main design of body and screws does not require fabrication with, or maintenance of, tight tolerances; and the rover would work even with a screw or frame bent. Furthermore, the rover can work in an effective manner with one on the motors inoperative and not free-wheeling but locked in a stalled position. This also means that a non-rotating screw can be maneuvered into any position by the rover, so that any screw end in any rotated position can be used as an actuator. The toughness of the overall design is also a function of the extreme simplicity of the design, with a minimum of moving parts, which means a more reliable and robust rover. The rover's complexity is roughly an order of magnitude less than that of the most all-terrain rover designs.

V. Further design considerations and opportunities.

The design can be further improved to take advantage of the rover's potential. The main route to this is to take advantage of asymmetry. The discussion above and the prototypes have used 120 degrees between screws and ground contact lines for convenience. But best use of the freedom of orientation might be made by using other angular spacing**.** This allows the stance to be varied from wide to narrow, and can affect traction and approach to an obstacle. This can also be accomplished--or heightened-- by use of screws of different lengths or different designs. There are many possible "screw" designs possible, as long as one supports a helical, rounded cross-section edge profile.

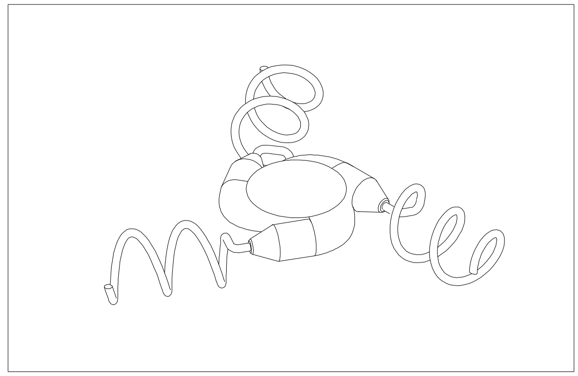

Fig. 5. Flippable rover concept.

The design concept also allows for the possibility of a flippable design as shown in Figure 5. This is helped by a lack of suspension. This has some advantages in high risk terrain when the rover might tip over or tumble down a ravine. An invertible design—coupled with a large footprint, low center of gravity, and greater ability to recover after encountering an obstacle-- might allow higher ground speeds or more access to high risk terrain. Also an invertible design combined with the toughness of the body and screws might increase chances of the rover surviving a fall. However this severely constrains the vertical space available in the central body while keeping ground clearance. Also one must consider the screw contact lines, angles and layout to ensure getting proper action in both arrangements, regardless of where along each screw's length the ground is contacted.

There are many screw parameters and features that can be modified to optimize the design for particular settings. For instance, to help drive in soft material such as sand, each screw could incorporate use a helicoid auger-type feature inward of the ground contact surface, or a larger edge profile radius could be used to reduce ground pressure. Also there are various possible shapes for the edge profile, besides round, as long as it is curved. Note that the edge profile cannot be pointed or sharp-edged, since that would create too much friction whenever the screw is sliding and not completely driving; therefore the overall traction of the rover is limited. The overall diameter of the screw and the size of the edge profile can be designed to fit the ground material. The screw need not be helicoid but may any shape or structure that can support the edge profile. It is important to select the best low-friction coating not only for the screw contact surfaces but for the body of the rover, which will be in contact with the rough terrain and obstacles.

While many other screw arrangements are possible, it is not recommended to use more than three screws, or to use screws only in orthogonal arrangements. These layouts result in a more complex, less optimum design.

The automatic or remote control of such a rover is more complex than in traditional designs. : The control system, including human interface, must be designed to take advantage of the opportunities. The rover is very simple mechanically; the complexity is in the controls. An autonomous control system would of course need to be able to sense, map and plan for travel over rough terrain [7, 8] and would use some kind of visual odometry [9]. The main challenge is that it will take some work to develop a feel for the use of a holonomic rover; there is not yet the experience and intuition to help anticipate how the vehicle will behave in various situations.

VI. CONCLUSION

The rover chassis design in this paper is an extremely simple, robust and versatile alternative to wheeled and tracked rovers for use a wide variety of ground materials and rugged terrains. The design is suitable for applications requiring high maneuverability, reliability and toughness.

VII. REFERENCES

[1] Yu, H., Dubowsky, S., Skwersky, A., "Omni-Directional Mobility Using Active Split Offset Castors",Massachusetts Institute of Technology.

[2] U. S. Patent Number 6,491,127, Powered Caster Wheel for use on Omnidirectional Drive Systems, December 10, 2002, Holmberg, R., et al.

[3] Ferriere, L., and Raucent, B., "ROLLMOBS, a New Universal Wheel Concept", Proceedings of IEEE Int'l Conference on Robotics and Automation, Leuven, Belgium, pp1877-1882, (1998).

[4] Dowling, Kevin, "Limbless Locomotion: learning to Crawl with a Snake Robot", Doctoral Thesis, The Robotics Institute, Carnegie Melon University, December 1997.

[5] U. S. Patent 661,427 in 1900.

[6] U. S. Patent 3,420,326.

[7] Goodsell, T., Flann, N., Davidson, Morgan, 1999, "Mobility Planning for Omnidirectional Vehicles In Natural Terrains", SPIE Conference on Unmanned Ground Vehicle Technology, SPIE Vol. 3693, Orlando, Florida

[8]. Yoshida, Kazuya, "Achievements in Space Robotics", IEEE Robitics &Automation Magazine, December 2009.

[9] Nagatani, K., Tachibana, S., Sofue, M., Tanaka, Y., "Improvement of Odometry for Omnidirectional Vehicle using Optical Flow Information", Proceedings of the 2000 IEEE/RSJ International Conference on Intelligen Robots and Systems.