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Toroidal Skin Drive for Snake Robot Locomotion

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Abstract—**Small robots have the potential to access confined spaces where humans cannot go. However, the mobility of wheeled and tracked systems is severely limited in cluttered environments. Snake robots using biologically inspired gaits for locomotion can provide better access in many situations, but are slow and can easily snag. This paper introduces an alternative approach to snake robot locomotion, in which the entire surface of the robot provides continuous propulsive force to significantly improve speed and mobility in many environments.**

I. Introduction

Mobility is a challenge for small robots. Conventional drive systems, such as wheels and tracks, do not necessarily scale down well. Many small robots have trouble maneuvering over human-scale terrain, such as curbs and stairs. Conventional configurations (e.g., mini-cars or tanks) have trouble with high-centering on stiff grass, rocks, and other ubiquitous terrain features.

Yet, there is a demand for small highly-mobile robots. Military and civil applications range from search and rescue (SAR) in rubble, to indoor and outdoor surveillance, to IED detection in complex urban and industrial spaces. Commercial applications include cable-pulling in buildings and inspection of architectural structures, bridges and pipelines.

One biologically inspired configuration is the robotic snake. These devices use a configuration of many identical actuators to move a long, thin body through terrain. The smooth, narrow shape of a snake lends itself to moving through small gaps, while the long muscular body enables climbing into holes above ground, and climbing trees and other vertical objects.

Most robotic snake designs have fallen into one of two categories: 1) those that use undulation of the internal structure – the spine – to move the body along; and 2) those that use some sort of surface mounted wheels or tracks to move the body. The former approach is slow and requires high duty cycles from the angular actuators. The latter approach adds mechanical complexity and increases the likelihood of becoming high-centered or entangled.

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This paper introduces an alternative approach to snake robot locomotion: a toroidal skin drive (TSD). The TSD is composed of a flexible toroidal skin and mechanical drive mechanism. In forward motion, the skin slides from the head of the body to the tail, then recirculates internally. In this context, the term "snake robot" may be somewhat misleading since biological snakes use undulatory motion, not a moving skin, to locomote. Although it may be accurate to categorize this as a form of amoeboid locomotion, we refer to the system as a snake robot because of its long and slender shape.

The advantages of this approach include:

- There are no exposed mechanisms to snag or high-center.
- Every point on the surface of the robot provides forward locomotion. Environmental obstructions that would snag and impede mobility for other systems actually help this device move by providing good sources of traction.
- Since the skin provides rectilinear motion, the angular actuators are used only to maintain body configuration. This greatly simplifies the kinematics of motion.

The result, as demonstrated by our prototype, is a small robotic platform with remarkable speed and mobility.

II. Related Work

Snake robot research began with Hirose's pioneering work in 1971 with the active chord mechanism [1] which was designed to mimic the behavior of real snakes [3][4]. Research then continued in early 1990's with Chirikjian and Burdick's work on hyper-redundant mechanisms [2]. Other researchers, such as Yim [6] at PARC, Miller [7] on his own, and Haith at NASA Ames [8], have extended Hirose's work on snake robot locomotion with undulatory mechanisms, while Yim and Haith used Yim's polybot modules to form a modular hyper-redundant robot. All of these robots are undulatory in the sense that the mechanism uses its internal degrees of freedom to propel itself forward. Recently, Hirose developed a new undulatory snake robot that is capable of locomotion, both on the ground and in the water [19].

We are interested in building a snake robot which is capable of maneuvering in three dimensions. The Pacific

Northwest Labs developed a three-dimensional mechanism which is a sequence of linearly actuated universal joints stacked on top of each other. Unfortunately the design was too bulky and slow for present applications. Takanashi developed at NEC [9][10] a new two degree-of-freedom (DOF) joint for snake robots that allowed a more compact design, again based on a universal joint. Researchers at JPL [11] iterated on Takanashi's design creating a more compact design, but it came at the cost of strength. Other known designs use cable/tendon actuation systems for driving the robot, yet these designs are somewhat cumbersome and require quite a big external driving system [3][12][13].

Recently, researchers have pursued alternative designs to achieve locomotion with snake robots. Researchers at Draper Labs built a snake robot with active wheels to provide forward propulsion. Borenstein's group developed the Omnitread series [17] which has a square extruded shape with a pair of tank treads on each face of the robot. This type of robot moves more like a multi-body tank or a train with tank treads instead of rail-wheels. Arai et. al. are also developing a family of articulated tracked vehicles called the Souryu series [18]. These robots have modular units which are connected by a two-degree of freedom joint, and although they are not snake robots per se, they have achieved great maneuverability in rough terrains.

Our novel device achieves snake-like locomotion using the entire skin to propel itself forward. Anhalt and Herron developed and patented the toroidal skin drive mechanism [20] which is the basis for this work. Ingram and Hong have since developed a mechanism similar in concept to the toroidal skin drive described in this paper [21][22]. Their device is capable of traveling in a forward direction and maneuvering through small holes and can expand to nominal size. Breedveld developed an endoscope whose "head" has a rolling skin device which pulls the endoscope through luminal spaces in the body; he terms this device the rolling stent endoscope [15].

One of the principal benefits of our device is that we can steer it. This is a result of the internal actuated two degree of freedom joints, described in a previous paper [14]. We have since iterated on that design creating a gear-based universal joint which is described in [16]. The latter device is described in summary in a later section as it is part of the mechanism described in this paper.

III. Component Technologies

The robot described in this paper combines two novel pieces of technology: (1) toroidal skin drive and (2) angular actuators. The toroidal skin drive mechanism, as its name suggests, "locomotes" the robot via the skin; the angular actuators are used to control the shape of the snake body.

A. Toroidal Skin Drive

The toroidal skin drive (TSD) system consists of an elongated toroidal skin that covers the entire length of the robot, and a drive unit that propels the skin. The outer (tubular) layer of the skin slides axially from the head to the tail of the snake robot, and wraps inside itself over a captured ring at the tail. The skin then recirculates from the tail to the head (through the center of the outer tubular layer), and changes direction again (over a second captured ring at the head) to again become the outside layer. In this configuration, the skin forms a continuous toroidal loop.

The drive unit produces the sliding action of the skin through rolling contact with the inner (recirculating) layer of the toroidal skin via friction. The skin drive mechanism (Fig. 1, left) consists of a motor (A), a worm (B), and three pairs of worm gears (C) which also function as the drive wheels. A tension ring (D) captured inside the skin maintains pressure between the skin (E) and the drive wheels, so that as the drive wheels rotate, the skin is pulled through. The tension ring itself is constructed from a tension spring wrapped into a circle and attached one end to the other. The spring provides both the normal force necessary to maintain contact between the skin and the drive wheels, as well as a means of expansion to allow wrinkles and folds in the skin to pass through the drive unit without jamming.

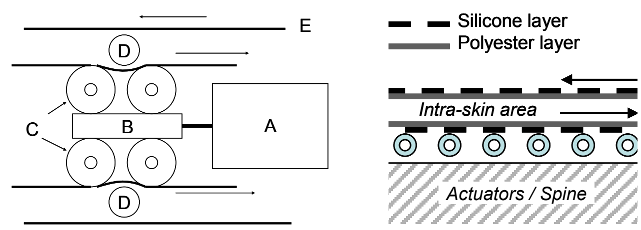

Fig. 1. Schematic of the skin drive mechanism (left); detail of composite skin configuration, including free-wheeling, anti-friction rollers (right).

As a result of using worm gears coupled with the high rolling resistance inherent to the nature of a friction drive, this configuration has a theoretical maximum efficiency of approximately 30%. While this value is not particularly high for a mechanical system powered by electric motors, the nature of the skin allows virtually all of that energy to be translated into forward motion regardless of terrain. A simple experiment of fixing a drive mechanism to a stand and lifting weight directly attached to an open length of skin demonstrated that using one 100W electric motor, a single skin drive mechanism is able to produce 5.5kg pulling force at a rate of nearly 2.5m/s.

B. Angular Actuators

The internal shape of the robot is controlled via nine actuated universal joints (Fig. 2). The basic actuator components (motor and gears) are taken from a commercial hobby servo (Hitec HSR-5995TG) and remounted in a custom, aluminum housing that provides the overall structure and appropriate cylindrical envelope. Torque is transmitted from the coreless DC motor through a 4-stage 305:1 gear train, the standard components of the hobby servo. A custom gear is attached to the servo output gear, and drives one sector gear of the universal joint cross; this provides an additional 40:12 reduction, yielding an overall ratio of 1015:1. The servo output gear assembly rotates on a needle bearing and a full-complement ball bearing. The gear-cross has four needle bearings for each pivot to support the high gear reaction forces and structural bending loads that can exceed 450N. The inboard needle bearings in the cross are needed to restrict bending of the pivot pins that can cause edge loading and premature failure of the needle bearings. Maximum angular travel of the joint is about ±50°.

Fig. 2. Joint angular actuator with onboard electronics.

IV. INTEGRATION

Integration of the component technologies into a working prototype system was performed to demonstrate concept feasibility. The research sponsor, the Defense Advanced Research Projects Agency (DARPA), specified a detailed list of performance objectives, including physical dimensions of obstacles and testing fixtures. The robot configuration – including number of joints and size of components – was selected to meet these requirements, considering realistic size, weight, and operational parameters for each component technology.

The final integrated prototype (Fig. 3) consisted of nine 2-DOF joint actuators and six TSD drive units, with off-board power and control provided via a tether. The prototype measured 156cm long, 6cm in diameter, and 4.1kg (excluding tether). A segmented, two-skin design (one fore, one aft) allowed for easier installation and removal of the skin; future versions will combine the two skins into a single, long skin.

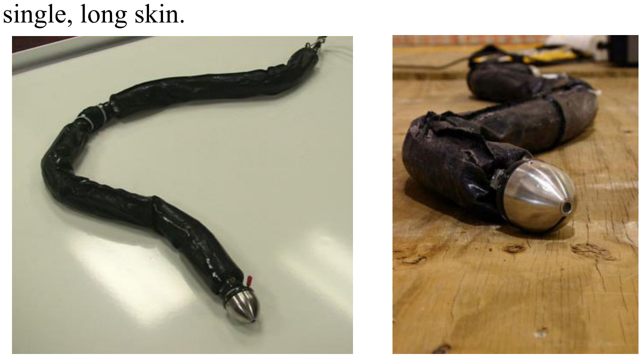

Fig. 3. The 156cm integrated TSD test system used for experiments.

Intra-skin friction is defined as the friction occurring between the two opposing layers of skin in the enclosed portion of the toroid as the skin circulates. The large surface area and normal forces imposed by the environment and by joint bending necessitate a very low intra-skin coefficient of friction. In addition, the external surface of the skin must maintain a high coefficient of friction with the environment of the robot, yet have very low internal friction against the skeletal body of the robot. Finally, it was determined empirically that the skin material must be thin and pliable, with good radial but minimal longitudinal elasticity for the TSD to function properly.

Numerous composite skin materials were evaluated before converging on a polyester-silicone composite (polyester side inward). This material combined very low intra-skin and high external coefficients of friction. To solve the apparent paradox between high external friction and low internal (body) friction, a series of small, free-wheeling rollers were installed over the entire skeletal body of the robot, as shown in Fig. 1 (right). The combination yielded sufficiently low friction even in the presence of steep joint angles and external normal forces on the robot body from its environment.

All components within the robot were powered from two DC power busses (+12V and +5V). Independently addressable controllers within each actuator received commands via an RS485 communication bus to directly control the motors. A laptop computer with a USB to RS485 converter computed all joint angles and transmitted the actuator solution to each controller.

Human interaction with the robot was achieved with a single gamepad-style controller. One 2-axis thumbstick was used to directly "steer" the first ("head") 2-DOF joint in the snake left-right and up-down. The second thumbstick was used to control the speed of the TSD. As the skin moved forward, the joint angles were propagated fore-to-aft in direct proportion to the speed of the skin. This achieved fluid, intuitive control of the robot in nearly all situations.

V. EXPERIMENTS

A number of qualitative experiments were conducted to test and demonstrate the system capabilities, some of which are summarized below. Many of these tests were dictated by DARPA to represent real-world terrain navigation challenges. Tests were conducted at various locations in Denver, Colorado and at Southwest Research Institute (SwRI) in San Antonio, Texas.

A. Speed

Simple experiments were performed to measure the average maximum linear speed of the prototype system over a flat, level, non-compliant surface. The approach for this experiment was to maintain all joints in a straight and rigid configuration, using the TSD as the only locomotion mode. Over several runs, the robot achieved an average speed of 0.26 m/s (936 m/hr).

B. Gap Crossing

A symmetric-gap test apparatus was used to evaluate the ability of the system to cross a gap in a flat surface (Fig. 4). The test fixture consisted of two flat plywood surfaces with an adjustable width gap between them. Test timing began when any part of the robot extended over the edge of the gap, and stopped once the robot was completely on the other side. The operational approach for this experiment was to maintain all joints in a straight and rigid configuration, and use the TSD to propel the system across the gap. During regimented experiments at SwRI, the robot fully traversed a 30cm gap in 8 seconds. Additional testing has demonstrated the ability to cross gaps of nearly 50% of the body length.

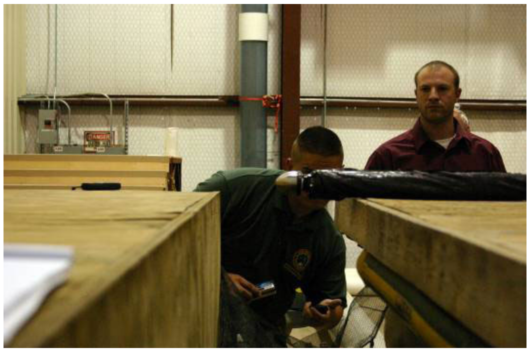

Fig. 4. Symmetric-gap crossing experiments.

C. Brush Navigation

The robot was tested many times through various types of extremely dense foliage and underbrush. The longest of these was a 15m continuous stretch during testing at SwRI (Fig. 5). The TSD was the primary mode of locomotion through brush, with the joints providing steering as necessary. The 15m course was completed in 10 minutes 7 seconds.

Fig. 5. The robot traverses through dense brush.

D. Stair Climbing

Experiments were conducted at SwRI to evaluate the ability of the system to climb a standard flight of stairs. The stair fixture provided by SwRI for testing consisted of 12 steps, each with a 12.7cm rise and a 30.5cm run. Timing started when the robot touched the first step and concluded the robot was completely on the landing at the top. Our approach used the TSD to drive perpendicularly up the stairs while the joint actuators controlled steering, stability, and contact with the stair surfaces. Traversal of the flight of stairs was completed in 3 minutes 28 seconds.

E. Hole Entry

Test apparatuses at SwRI were used for experiments for entering and traversing a 10cm hole in an otherwise flat, vertical wall. Timing began when any part of the robot touched the wall, and concluded when the robot was entirely through the hole. The joint actuators were used to form a stable S-shaped "base" from which the head was cantilevered upward and aligned with the hole (Fig. 6). The skin drive then propelled the robot into and through the hole. Using this strategy, a low hole (6 cm above the ground) was fully traversed in 10 seconds; a high hole (42 cm above the ground) hole was navigated in 2 minutes, 45 seconds.

Fig. 6. Entering a 10cm hole, 42cm above the floor.

F. Vertical Step

Experiments were conducted to evaluate the system's proficiency in traversing a single, large, vertical step (Fig. 7). Timing of the traversal was the same as used for the hole entry experiments. The strategy used was to approach the step sideways to form a stable S-shaped "base", and then cantilever the head upward to reach the top of the step. The TSD then propelled the robot forward onto the step as the joint angles were propagated toward the tail. This provided a very smooth and biologically reminiscent traversal. The largest step traversal during experiments conducted at SwRI was 38.5cm in 38 seconds, representing 25% of the body length of the robot.

Fig. 7. Climbing a vertical step.

G. Chain-link Fence

In several experiments, the robot demonstrated proficiency in penetrating a chain-link fence with standard 5 x 5cm links (Fig. 8). The joints provided steering and control as the robot approached the fence, using the TSD for forward locomotion. After cantilevering the head to enter one of the links, the TSD gripped the fence on all sides and pulled the robot through to the other side in 1 minute, 23 seconds.

Fig. 8. Traversing through a standard chain-link fence.

H. Vertical Pipe Climb

Climbing the inside of a vertical pipe was demonstrated several times with 7.5 cm and 10 cm cylindrical pipes. To achieve this, the joints formed a soft sideways "U-shape" to apply firm pressure with three points of contact between the body of the robot and the inside of the pipe. The TSD was then simply driven forward to provide vertical locomotion. Pipes of up to 2 m in length were traversed in this manner.

I. Steep Incline Climbing

To demonstrate climbing ability resulting from the large traction area of skin drive system, several experiments were performed in which the robot was propelled up a smooth, flat, painted plywood surface at a steep incline. In these experiments, the robot was able to successfully climb a slope 55° above horizontal using only the skin drive.

VI. Discussion

The experiments conducted clearly demonstrate the feasibility and advantages of this TSD system as a means of snake robot locomotion in real-world scenarios. One advantage of the TSD over robots with biologically inspired gaits is a significant improvement in overall speed. Over flat ground, the rectilinear motion produced by the TSD exceeded 0.25 m/s, a significant improvement when compared with undulatory gaits.

The brush navigation experiments demonstrated one of the most important strengths of the TSD: mobility in confined, unstructured, cluttered and chaotic environments. For many systems, exposed mechanisms and protruding edges provide abundant opportunity for the robot to become snagged or tangled in its environment – above, below or to the side. Sticks, rocks, and rubble have a tendency to grab every exposed point of the robot. Even without edges or corners to become caught, contact between the environment and any non-moving surfaces of other robots becomes a source of friction and drag which must be overcome. This is especially true in SAR applications, where cluttered and jagged environments are the norm. In extreme cases, robots can easily become high-centered to the point that the actuators are unable to free them.

Tank-track style actuators exacerbate this problem in cluttered environments. While the bottom surface of the track maintains good contact with the environment to propel the vehicle forward, the top surface moves the opposite direction. In tight environments where both the top and bottom of the track are in contact with their surroundings, the track surfaces "fight" against one another, preventing the vehicle from moving in either direction. Even worse, in an unstable environment such as a collapsed structure, opposing upper and lower track surfaces sliding against the environment can cause additional instability and even further collapse.

The TSD has a uniquely advantageous relationship with cluttered environments. First, it uniformly covers the underlying skeletal actuation structure of the robot, so that there are no exposed edges or corners to snag or grab the environment and impede the motion of the robot. In addition, sharp contact and pinch points in the environment do not pose a problem for the TSD system. Because the skin is in motion with respect to the robot body but stationary with respect to the environment, snags and obstructions that would impede the mobility of other systems actually *improve* mobility for the TSD system by providing good traction points. This was demonstrated repeatedly in numerous experiments.

Since every point on the surface of the skin moves at the same speed and in the same direction, the entire skin forms a locomotive surface. This distributes both ground pressure and locomotive force over the entire surface of the robot to every point of contact with the environment. The result is better traction and less disruption of the surface than with conventional wheeled or tracked vehicles. Experiments over solid surfaces demonstrated the ability to traverse up to a 55° slope. It is expected that the TSD robot will also be capable of traversing significantly steeper inclines over loose surfaces (sand, dirt, etc.) than many conventional systems.

Most control strategies for high-DOF robotic systems, especially serpentine robots, rely on highly complex kinematic undulations which emulate biological gaits. The TSD, however, provides a greatly simplified approach to performing rectilinear motion. The operator guides only the first segment (the "head") of the snake in 2-DOF space (left-right and up-down); joint angles are then propagated rearward to the rest of the joints at a rate proportional to the velocity of the TSD. This simplified control strategy was demonstrated to be highly effective and intuitive for most of these experiments.

Similarly, the TSD provides a simplified and improved climbing strategy for trees, poles and pipes. The joint actuators are used to wrap helically around the outside (or press helically on the inside) of a roughly cylindrical object; driving the TSD then allows the robot to “spiral upward” (Fig. 9). Initial simulation and experiments conducted at SAIC’s Austin Robotics Lab have already demonstrated the feasibility of this strategy. Future work is expected to fully exploit and demonstrate this technique.

Fig. 9. Pole climbing strategy with TSD.

A final important advantage of the TSD system is that it works equally well with many different platforms, yielding a net increase in capabilities and performance. The addition of the TSD does not preclude the use of undulatory mobility modes of a spine-actuated robotic snake. These modes (e.g., inchworm, sidewinding) can be used as redundant mobility modes in case of mechanical failure; as supplemental modes to navigate complex and variable terrain where no single mode performs adequately; or even hybrid modes in conjunction with the TSD to produce new and gaits useful for navigating unusual terrain. These concepts are currently being investigated.

VII. Conclusion

In this paper we describe a new method of locomotion for snake robots. The system consists of two core technologies: toroidal skin drive and angular actuators. The skin drive provides a moving skin that covers the entire robot and provides locomotion; the angular actuators provide a means for steering and controlling the shape of the robot.

Numerous experiments were performed which demonstrate the advantages of this approach. The possibility of snagging and high-centering in cluttered environments is virtually eliminated; the kinematics required for control are greatly simplified; and new highly efficient and capable locomotion strategies can be achieved by combining skeletal actuation with the toroidal skin drive.

Future work will focus on techniques for climbing poles, pipes and other structures. More complex and hybrid control strategies which combine skeletal gaits with the TSD can now be investigated. In addition, we will concentrate on improving the drive train efficiency, integrating on-board power, and eliminating the power and control tether.

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