Continuum Robotic Elements for Enabling Negotiation of Uneven Terrain in Unstructured Environments

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Abstract: - We address the potential for continuous “continuum” robot elements to transform the nature of robotic traversal of uneven terrain. Continuum robots are “dual” to traditional robot structures, with their inherent capabilities featuring strengths in areas that are key weaknesses for conventional robots. These capabilities match well to current challenges in robot mobility, particularly in unstructured environments featuring uneven terrain. We demonstrate these capabilities via new and innovative mobile robot hardware, based on the combination of novel continuum body elements with wheel/leg (“whegs”) elements. This combination offers performance not possible with conventional “monolithic” wheeled or tracked mobile robots, or with current robot snakes.

Key-Words: - Continuum robots, design, mobility, locomotion

1 Introduction

Traditional robot elements (arms, fingers, legs) are “vertebrate” in the sense of being comprised of a series of rigid links connected at a finite number of discrete joints. This is very effective for accurate positioning of end effectors in highly structured environments and in tasks with predictable manipulator/environment interaction forces. However, traditional robots have proved significantly less effective in non-engineered environments, and also in situations where a wide range of interaction forces is required.

The emerging class of continuum robots [23], [49] by contrast features continuous backbones, with bending possible at any point throughout the structure, similar to invertebrate tongues [36], trunks [2], [10], [21], and tentacles [39], [41], [59], see Fig.1. This allows this new form of robots to adapt their shape to environmental features [8], wrap around objects of arbitrary shape [9], and maneuver in tight and complex obstacle fields. Continuum robot designs are also inherently compliant, enabling them to more smoothly accommodate external loads [61], [67].

While continuum robots have been the subject of much recent attention in the robotics research community, most efforts thus far have concentrated on applications as manipulators [61], [67]. One appealing possible application of continuum robot manipulators in uneven terrain traversal is as “tunable active hooks”, anchoring into holes or niches in the terrain to assist in climbing. In this way the appendages could function as both arms and legs, similar to the underlying concept in NASA’s ATHLETE [68].

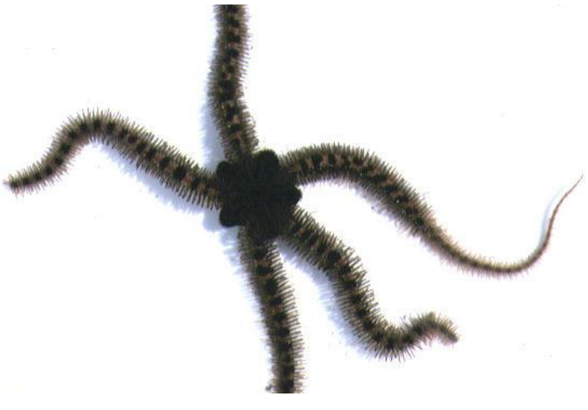

Fig.1 Continuum appendages in nature (Brittlestar: source:http://www.theseashore.org.uk/theseashore/SpeciesPages/Brittlestar.jpg.html).

Additionally, while lacking their accuracy, continuum appendages offer increased natural compliance and maneuverability compared with traditional rigid-link appendages, as used in ATHLETE. This in turn suggests a wider range of possible deployment options. The potential application of continuum robot appendages as manipulators in mobile robot systems is discussed in section 2.

The potential of continuum robot elements in mobile robots has thus far received little attention. However, we anticipate that use of continuum elements as limbs would enable novel robotic locomotion modes. Continuum robot appendages could be used to enhance mobility over uneven terrain in several novel ways. Deployed as "feet", they could provide significantly enhanced terrain adaptation at the ground contact surface, compared with tires or tweels, improving local stability. Alternatively, as "legs" or "whegs", they offer the ability to traverse high obstacles, while enhancing shock absorbance due to their inherent (and potentially tunable) compliance. A key but previously unexplored mode of operation, explored in detail herein, is to utilize continuum elements as the body structure for mobile robots. These applications of continuum appendages in mobile robots are discussed in detail, supported by novel hardware development, in section 3. Conclusions are presented in section 4.

2 Continuum Elements as Manipulators and Hooks

The inherent ability of continuum limbs to conform to local terrain shape may be used to assist robot locomotion in novel ways. In areas of steep gradient, one or more continuum limbs could be effectively deployed as "tunable active hooks", anchoring into holes or niches in the terrain to assist in climbing or descent. Such hooks could provide stability for operation in steep or unstable terrain, with the hook, or hooks, essentially allowing the rover to "take root". Similar to skilled human climbers, robots adopting such a strategy would take advantage of existing crevices or prominences. Continuum limbs however, can be designed to reach deeper into crevices and to wrap more closely around rock formations than human - or robot - rigid-link arms and fingers.

2.1 Example: Octarm Continuum Manipulator

The practicality of realizing tunable continuum robot hooks has been demonstrated recently by our group [37], see Fig. 2. In [37], the shape of an active hook was controlled in real-time for the Octarm series of pneumatically actuated continuum robots ([64], Fig.2 and Fig.3). The Octarm robots were inspired by the morphology of octopus arms (as the name suggests), with a key design goal to have as few "hard" components in the design as possible. Consequently, the Octarm bodies are comprised almost entirely of pneumatic "Mckibben" "air-muscles – which also serve as the actuation for the robots.

The actuators are arranged longditudinally to comprise the (continuum) backbone of the robot. Functionally, distinct "sections" (typically three or four, depending on the prototype) are formed by terminating (three or four) sets of actuators at distinct points along the backbone. The supply tubes for actuators corresponding to more distal sections are passed through the backbone inside those for more proximal sections. Terminating sets of actuators are grouped in threes, arranged in 120 degree increments around the arm. This arrangement allows each section to independently bend in two controllable dimensions (via differentially varying the pressure in the three associated actuators), and also for each section to extend and contract.

The actuators are supplied via a remote pneumatic source (scuba air tanks "stepped down" in pressure, or from a commercial air pressure generator), at about 90 psi. Commercial pressure regulators are used to servo the pressure to values generated by custom kinematic algorithms. String encoders routed through the continuum, backbone provide shape feedback [36].

Notice that the deployment of continuum robot hooks would not necessarily require revolutionary changes to mobile robot design and operation – one or more limbs deployed as tunable hooks could be easily mounted on and integrated with a conventional rover. See for example an Octarm continuum robot deployed on a conventional Foster-Miller Talon robot in Fig.3. A different option could be to augment robot tumbleweeds [22] with continuum "tendrils".

Fig.2 Octarm continuum manipulator - hook mode.

The use of continuum hooks is an example of their versatility as manipulators. The vast majority of continuum robots developed have been manipulators [61], [63]. Much of the development has been inspired by biological tongues, trunks, and tentacles. The notion of manipulation using continuum members is very old, and the potential is rapidly being realized. Continuum manipulators have been developed for numerous applications including medical procedures [57], [70] and search and rescue operations [3], [46]. Commercial versions of the technology have been produced [6], [19], [25], [26] and at this time the field appears sufficiently mature to support continuum manipulators as viable practical alternatives to conventional manipulators on mobile robots.

Fig.3. Octarm manipulator performing whole arm grasping of a priori unknown object.

Deployed as manipulators, continuum limbs could augment (or potentially supplant) conventional rigid-link manipulators. While not as accurate as conventional manipulators, the superior maneuverability of continuum robots would make them prime candidates for missions where grasping of arbitrarily shaped and scaled objects (see Fig.3) or penetration of complex obstacle fields (for example, to locate sensors in tight spaces) is important.

Note that continuum robot systems could be deployed either with, or independent of, conventional robot manipulation or locomotion technology. As discussed here, one key advantage of continuum limbs is their adaptability. This makes their “dual use” as both locomotor and manipulator elements in a mobile system very appealing. Using continuum limbs as both arms and legs in a single rover system would result in the most efficient use of hardware. However, in the case of continuum limbs, the additional adaptability inherent in the limbs would likely open up a wider range of feasible applications for the technology.

3 Continuum Elements for Locomotion

Traditional approaches to mobile robots have focused on wheeled designs [7]. This well-understood technology has proved effective on the generally (locally) smooth terrain thus far traversed by mobile robots. The main handicap of wheels is the reduced climbing ability they present. Although the use of different materials or treads in tires can improve the grip of the wheel, maximum reachable height is constrained by its radius. This is a severe limitation in the numerous environments presented by uneven terrain.

Another means of locomotion used in exploration vehicles is the track. For example, the PackBot robot [71] is a tracked vehicle used by the military in Afghanistan and Iraq. It is a man-portable, all-terrain mobile robot that has four different configurations for a variety of applications, including chemical and nuclear-weapon searching, autonomous urban navigation, bomb deactivation, and battlefield casualty extraction among others. This robot, fairly typical of tracked mobile robots, is very robust and reliable over different environments, such as uneven terrain and stairs. It is not, however, capable of floating and swimming or climbing some extreme rocky surfaces such as found in caves or in hilly terrain.

3.1 Continuum Wheels/Legs (Whegs) and Feet

In order to overcome the inherent limitations of wheels and tracks, Quinn, et al., at Case Western

Reserve University [30], [48], [52], inspired by the locomotion principles of cockroaches, used Whegs^{TM} as an alternative. Whegs are made of flexible spokes symmetrically distributed about a hub, combining the advantages of both wheels [13] and legs [31]. This configuration, featuring a passively compliant mechanism allowing wheel-legs to passively change their phase, permits whegs to reach obstacles higher than their radius, which is the length of each spoke. Whegs also have a high power-to-weight ratio because they (for the most part) use a single large drive motor.

Several different whegs-based robots have been developed by the Biorobotics Lab at Case Western Reserve University for diverse applications. Various designs of whegs were implemented in mobile robots with rigid body elements featuring no or one degree of freedom [4], [43], [66].

An alternative mode of locomotion using a similar concept and applied in rough terrain is the one included in RHex [1], [50]. This hexapod mobile robot is also biologically inspired. The robot's design consists of a rigid body with six simple compliant legs that rotate full circle. (The RHex series predates the whegs series of robots, and their developers do not use the term whegs for the RHex appendages.) The use of a single spoke [18] diminishes the restriction of contact angles with surfaces presented by the multiple spokes in multi-spoke whegs. This method, while improving the locomotion over rough terrain, also reduces the contact surface, and RHex requires active gait control [38], [47].

The PROLERO robot [33], which preceded RHex, used a very similar locomotion method, of six single spoke legs each driven by a separate motor. However, PROLERO featured rigid legs and simpler control.

Another application of whegs was used by the German Research Center for Artificial Intelligence (DGKI) in which the robot ASGUARD [14] uses what the authors term "legged-wheels". ASGUARD has four five-spoked wheel-legs. This robot is able to move over rough terrain at a considerably high speed as well as swimming. Although it has proven its effectiveness in different sorts of terrain, ASGUARD is not intended for climbing higher obstacles, being limited by the flexibility and dimensions of its body (despite the body having an interesting passive body-joint).

The Biologically Inspired Robotics Group (BIRG), directed by A.J. Ijspeert presented an amphibious vehicle based on the spinal cord model of a salamander [24]. This mobile robot has multiple active body segments than bend laterally, as well as rigid single-spoked legs. It is capable of switching between swimming and walking like the animal itself, but presents significant limitations, since it is only reliable on flat surfaces.

Regarding the climbing abilities on vertical or steep surfaces, various specific robots have been built by different research groups. Mini-Whegs [11], [12], [29], and Waalbot [44] are light robots capable of walking on smooth surfaces regardless of the direction of gravity by using compliant adhesive feet. In porous surfaces such as those in bricks or stone the adhesive feet are not reliable. The Gecko Robot [40], [58] and the Spinybot II [28] are biologically inspired robots that use mechanisms similar to those found in gecko and insect feet, respectively. These robots use micro or nano spines-hairs that adhere to porous surfaces quite effectively.

The above efforts concentrate on continuum elements as wheel-legs. Wheel-leg robots have been combined with maneuverable bodies, via the incorporation of body-joints. Examples include ASGUARD [14] and the salamander robots of [24], as noted above. Whegs-based robots incorporating body-joints have been developed in [5] and [30]. However, there remain inherent restrictions in body maneuverability due to the small finite number of degrees of freedom.

All these robots work quite well in their optimal situations where the conditions are close to those they were designed for [17], but when the surroundings turn to be a little bit more complex and variable in nature, such found as in cave exploration operations, with more than one kind of fundamental environment involved, they are not practical. Therefore, a more versatile and adaptable design is desired. This factor strongly motivates our novel design approach featuring continuum body elements, detailed in the following subsection.

Notice that whegs inherently feature continuum appendages (they can be viewed as "tentacle wheels"). Indeed, the very success of whegs-based systems is due to two properties deriving directly from the continuum nature of the wheg spokes: (1) the ability of the flexible spokes to adapt to variability in ground geometry; and (2) the ability of the spokes, via their inherent compliance, to directly handle ground reaction forces. The performance of whegged vehicles can be tuned (off-line) by varying the shape and material (in particular compliance properties) of the whegs themselves [1]. Note that, in contrast to the continuum appendages discussed below and in the preceding section, neither the shape or the compliance properties of the whegs are actively controlled during operation of the robot.

Mobile robots based on actively controlled continuum limbs (where the shape and/or compliance can be actively controlled) have recently been developed [16], [34], [65]. However, in these cases the body elements have been solid, with the aim of showing the ability of the robot legs to carry the body on generally flat terrain. In the following, we introduce mobile whegs-based robots with continuum body elements.

3.2 Flexible Robot for Exploration of Subterranean Environments (FRESE): Whegs plus Continuum Body

In this subsection, the novel design and construction of a series of prototypes of a novel mobile robot for cave exploration (FRESE, Flexible Robot for Exploration of Subterranean Environments) is detailed. Our underlying goal [55], [56] was a flexible (ultimately continuum) body and novel propulsion based on the whegs concept. See Fig.4.

The target application for the FRESE robots, as the name suggests, was to explore caves and underground pipes. Thus the key design criteria (in a robot of maximum length of about two feet), was to climb over vertical obstacles of at least one foot in height, and for a lateral turning radius of two feet or less. These dimensions match environments and culverts available locally to the team for experimentation.

In order to be able to move over complex terrain and through narrow openings [72], a flexible body is desired. In order to provide the robot with this flexibility, the body of our initial design (FRESE I) was conceived as a head-torso, providing a passive degree of freedom in the form of a ¨neck¨ body-joint (Fig.5).

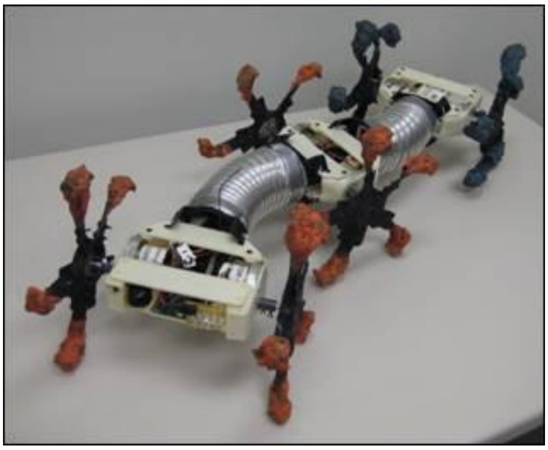

Fig.4 FRESE (Flexible Robot for Exploration of Subterranean Environments) IV. A six-whegs mobile robot with flexible continuum body.

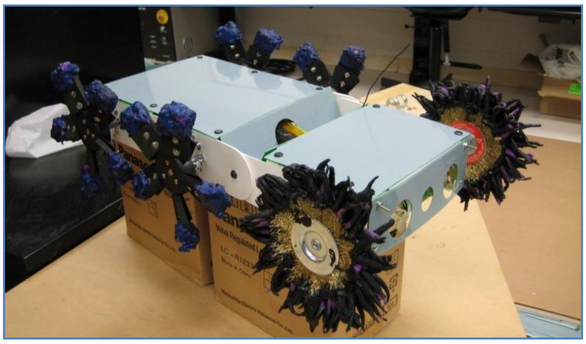

Fig.5 Initial prototype, FRESE I. Note front “tentacle-wheels” and rear whegs.

The chassis was designed in a way that makes it easy to access all the parts placed inside of the robot. The modular chassis was composed of lateral parts where the motors were attached; a base floor where all the electronics were fixed; and some bars on top providing the body with sufficient rigidity. The chassis was then covered with a plastic case, sealing the contents of the robot to prevent water incursion.

In order to facilitate exploration activities, a wireless camera and a light source were incorporated into the vehicle. These devices, as well as the robot’s movement were controlled through a main board based on the PIC18F1330 with wireless serial communications and a PC with LabView. The main control panel in LabView allowed control of the direction of the robot and showed the images acquired by the camera in real time. A single Li-Poly battery ensured the supply of power for at least 45 minutes. The battery life depends highly on the conditions on the terrain, since the current drained by the motors depends on their torque.

As the means of locomotion, the notion of whegs was adopted and extended to allow the robot to overcome a wide variety of obstacles. In particular, novel whegs operation shapes, and contact conditions (e.g. adhesive material attached to the whegs to facilitate the climbing maneuvers) form a key and novel aspect of our overall design.

Six DC gear motors were distributed throughout the body, three on each side. Each motor, selected to provide a torque sufficient to lift the weight of the whole body by itself, was attached to wheel/whegs. With this constraint we ensured that in the worst-case scenario where only one of the whegs is in contact with the surface, the robot would keep moving. By using a technique similar to military tanks, the ("skid") steering of the robot was achieved by turning the motors of each side in opposite directions. (The underlying model for this is given later.)

The desired initial requirements of the wheels/whegs were sufficient flexibility and high adhesive properties. For the initial tests, propeller-like whegs with five spokes were used (Fig.5). When testing them, due to the hardness of the material and the reduced contact surface, the spokes proved to be too short and slippery, showing marked inefficiency when walking or climbing smooth surfaces.

According to these findings, some modifications were introduced. The front whegs were replaced by a "tentacle-wheel" covered in latex to allow it to stick to different surfaces (Fig.5), significantly improving the climbing capabilities. The tentacles, due to their flexibility, adapt to any kind of surface. Flexible foam tips were also coated with latex and then attached to the rear propeller-like whegs (Fig.5). These, while being less flexible than the front ones, provided the robot with a more powerful pushing force, thanks to the high adaptability of the whegs as well as the grip given by the latex.

Initial experiments were carried out with the first prototype (Fig.5) in the robotics laboratory at Clemson, where an artificial environment composed of a set of obstacles (pipes, boxes, etc.) was created.

The set of images in Fig.6 shows typical results. In this case, the tentacle wheels were placed in the front, and the whegs in the middle and rear positions. The tentacle-wheels present a high grip making the robot capable of climbing almost any kind of surface regardless of the contact conditions. The flexibility of the neck greatly contributes to the climbing abilities. The ability of the combination of whegs-like appendages with a flexible body to aid in obstacle handling is clearly demonstrated.

In the case where the front tentacle-wheels were substituted by whegs and the tentacle wheels were placed in the rear position, the robot tended to get stuck due to the lack of traction in the rear, and insufficient mobility of the body elements.

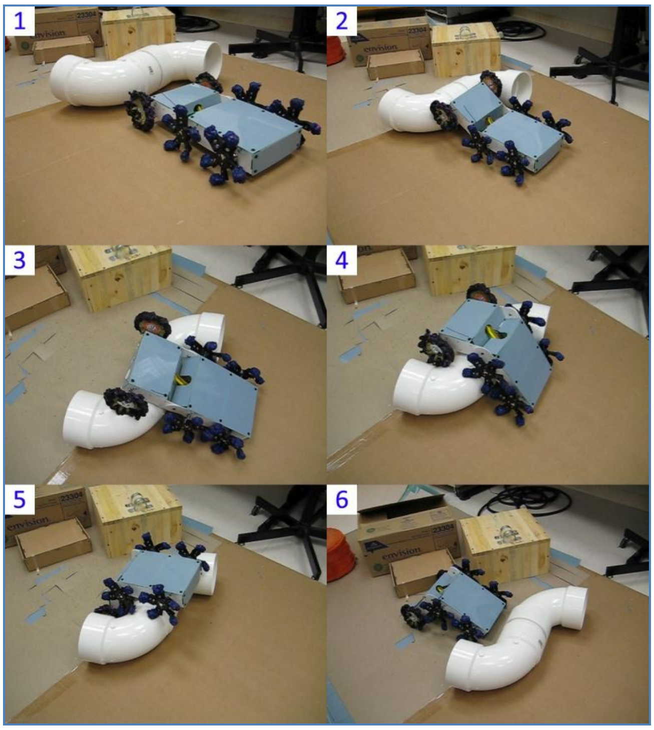

Fig.6 FRESE I Climbing over a pipe.

The main conclusion derived from these initial tests was the need for a body with more degrees of freedom. Longer whegs and tentacles would also improve the grip and climbing capability. On the other hand, the existence of a neck with a rotating range of ±90 degrees was observed to be a key practical advantage to get through most kinds of obstacles tested. The maximum vertical height climbed was about 3 inches.

The molded tips of the whegs proved highly effective in providing stable high friction contacts in a variety of environments, including in outdoor tests featuring loose leaves and dry soil. The non-uniform contact conditions created by the uneven tip shape proved helpful in shedding acquired dust.

In order to overcome the limitations of body flexibility presented by the first prototype, an improved second prototype (FRESE II) was designed, based on segmented robots [32], [42],

[51], [53], [62], [69]. In this case, all the components used before were placed in the interior of a flexible segmented pipe composed of equal modules that fit one into each other (Fig.7). The same set of wheels/whegs from FRESE I was used. In this case, the whegs were separated by 10 inch sections of the 2.5 inch diameter pipes.

Fig.7 Modular (2.5 inch diamter) pipes from Loc-Line used for FRESE II.

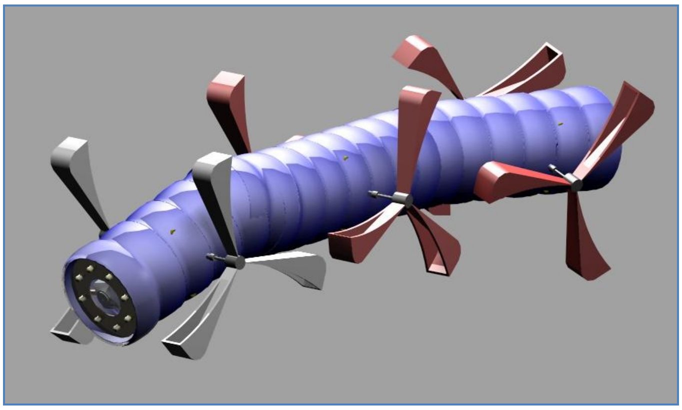

Fig.8 Snake-like design showing in SolidEdge.

A 3D-model of the second prototype is shown in Fig.8. This snake-like body provides many more degrees of freedom since it is formed by individual modules. Each section had three ball in socket joints, for 21 degrees of freedom per section. Note that this provides many more degrees of freedom than in previously demonstrated whegs-based mobile robot bodies. In order to be able to fit the components in the body however, the degrees of freedom between some modules (such as those containing the motors or the control boards) were restrained. The friction between the modules created a body with higher friction than in the body joint of FRESE I, which aided mobility.

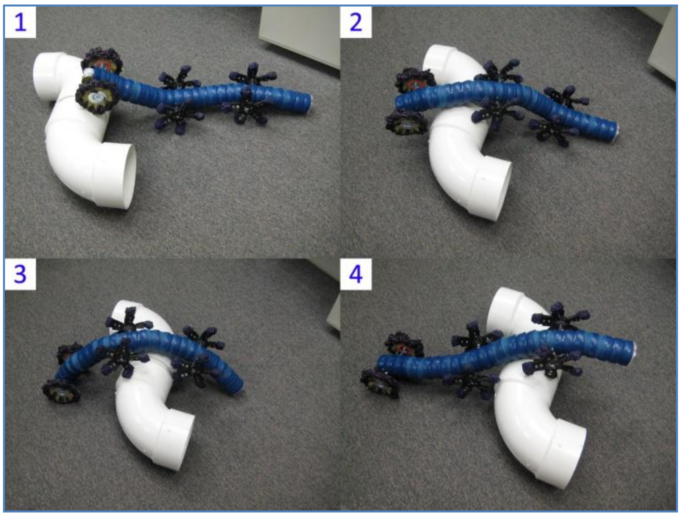

Fig.9 FRESE II Climbing over a pipe.

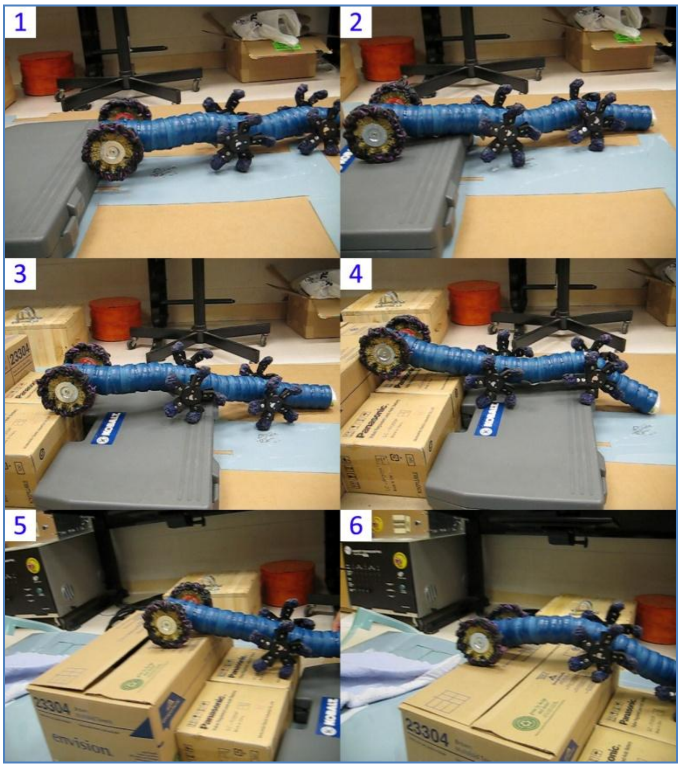

Fig.10 FRESE II Climbing over boxes.

Fig.9 and Fig.10 show the results of two different tests carried out by FRESE II. Once again, the combination of flexible body and whegs-like appendages enabled agile behavior. However, even though the number of passive degrees of freedom in the body was increased with respect to the previous prototype, the net rotating angle range actually decreased. The ±90-degree rotation of the initial passive neck was substituted by several ±40-degree links. This feature limited considerably the size of obstacles traversable by the second prototype, constraining the environment for the tests to vertical heights of a maximum 2 inches. However, the shape of the snake-like body allows the robot to go into smaller openings, due to the combination of both reduced width and flexibility.

Exploiting the lessons learned from FRESE I and FRESE II, two new designs were constructed. Whegs modules were next connected with two different kinds of flexible continuum "body" segments (plastic strips for FRESE III, flexible pipes for FRESE IV). The intent was to expore the improvements enabled by continuum body elements.

For FRESE III (Fig.11), each of three wheg pairs was encased in a hard plastic module, of dimensions 6 inches (width) by 5 inches (front to rear) by 1 inch (depth). The modules were then connected by strips of flexible plastic. We evaluated various shapes and types of plastic for the strips, finally selecting a "bowtie" shape and a material (flexible plexiglass) which was highly flexible. See Fig.11.

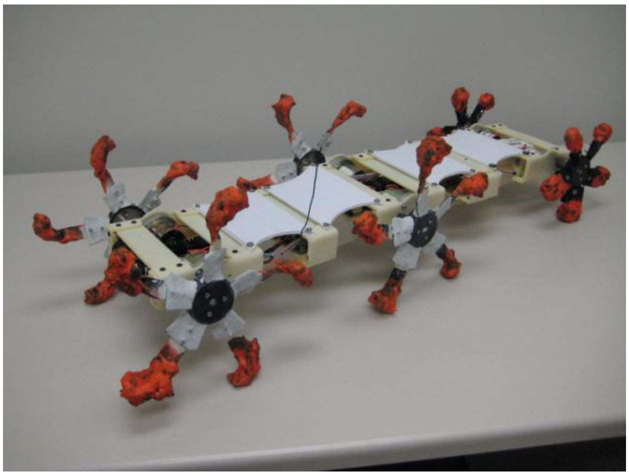

Fig.11 FRESE III.

Testing was conducted on uneven rocky ground and in culverts on the campus of Clemson University (Figs 12, 13, 16, 17). No modifications were made to the environment, which featured some smooth (Fig.13), but mostly uneven (Figs 12, 16, 17) terrain. Rocks of sizes up to 1.5 feet by 1 foot by 1.5 feet were scattered about a slope. The grade of the slope was quite steep in places (the ground rises about 4 feet in Figs 12, 16, and 17). The average gradient on the slope was approximately 1:1.5, and the highest vertical or near vertical height was about 1.5 feet. The ground was marshy at the foot of the slope (right of Fig.16, where there is a small stream) and sandy at the top of the slope. The opening of a culvert (diameter 2.5 feet) in which the robots were also deployed [55] can be seen to the right of Fig.16.

FRESE III's design proved an improvement on both FRESE I and FRESE II, in terms of maneuverability and terrain adaptability (see Fig.12) of the system. The robot was able to navigate the slope at almost all places. The vertical bending allowed by the continuum strips enabled the body to passively bend in response to environmental forces, allowing the whegs to grip and gain traction.

However, while the strips allowed significant vertical bending (theoretically an infinite number of degrees of freedom), they did not provide FRESE III's body with lateral degrees of freedom. The design was modified to feature "holes" in the body sides to enable some lateral maneuverability. However, the range of motion remained limited, and this feature sometimes resulted in the robot becoming caught in environmental obstacles. For example, the environment of Fig.17 proved too difficult for FRESE III to navigate, as it was unable to manuver its body sufficiently laterally, becoming stuck.

Given the above limitations for FRESE III, we developed prototypes of a fourth design, FRESE IV. Since FRESE IV ultimately proved successful in meeting our design criteria, we discuss its design and capabilities in most detail.

Fig.12 FRESE III climbing a rocky slope.

For FRESE IV, the key innovation was to link the wheg modules with “full body” continuum elements using thin flexible metaillic pipe sections. This allows bending in any direction about the body, with the goal of eliminating the problems encountered with FRESE III.

The initial concept was to have one monolithic continuum body. This concept was implemented in an initial FRESE IV, shown in Fig.13.

Fig.13 Initial FRESE IV prototype on smooth terrain.

However, the design in Fig.13 proved to be too low to the ground near the whegs, and also problematic in containing all the hardware inside the body. Therefore, we utilized the whegs modules from FRESE III (greater volume and higher off the ground near the whegs) in a two continuum section version (Fig.4). Note that the pipe sections were able to bend freely in two dimensions, providing the body with a theoretically infinite number of degrees of freedom both laterally and vertically. Table 1 details the FRESE IV dimensions and its core capabilities. A comparison of the four FRESE designs is given in Table 2.

Table 1. Details of FRESE IV.

Feature	Detail
Number of Whegs	6
Actuators	1 d.c. motor per whegs
Power	Single Li-Poly battery
Software/control Architecture	PIC18F1330-based local board, wireless communication to PC running Labview
Motor housing module dimensions	6 inches (width) by 5 inches (front to rear) by 1 inch (vertical depth)
Wheg to wheg separation (across body)	9 inches
Wheg radius (max body width)	5 inches
Body sections	2
Body section radius	1.5 inches
Body section length	6 inches
Overall body length	2 feet 3 inches
Turning radius (lateral)	2 feet
Turning radius (vertical)	3 inches
Speed	~3 inches per second
Weight	10 pounds

Table 2. Comparison of FRESE robot designs, including body degrees of freedom (d.o.f.).

Robot	Legs	Body	Largest obstacle surmounted
FRESE 1 (Figs 5,6)	2 tentacle-wheel, 4 whegs	2 rigid segments, 1 vertical (neck) joint, 1 body d.o.f.	3 inches
FRESE II (Figs 9,10)	2 tentacle-wheel, 4 whegs	2 compliant sections (each with 7 ball and socket joints), 21 total body d.o.f.'s (limited rotation)	2 inches
FRESE III (Figs 11, 12)	6 whegs	2 continuum sections, infinite d.o.f.'s in bending (vertical)	1 foot vertically, 1 inch laterally
FRESE IV (Figs 4, 16, 17)	6 whegs	2 continuum sections, infinite d.o.f.'s vertically and laterally	1.5 feet vertically, 1 foot laterally

For steering control, by considering the flexible sections as horizontal hinged links and the whegs as wheels, a model to perform skid steering with FRESE IV is next detailed. Note that FRESE does not feature active suspension [74]. Fig.14 shows the simplified model of FRESE IV used to obtain the equations.

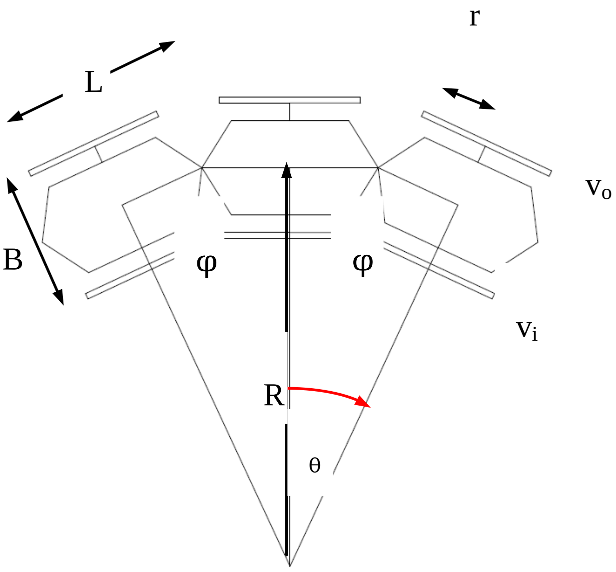

Fig.14 FRESE IV steering diagram.

The variables in fig 14 and below are:

v_o = outside wheel velocity

v_i= inside wheel velocity

V = vehicle velocity

φ = link bending angle

R = vehicle turn radius

B = separation between whegs

L = segment length

r = whegs radius

The turning radius of each of the individual segments can be calculated from similar triangles with v_o and v_i known.

$$\frac{v_o - v_i}{B} = \frac{v_o}{R + \frac{B}{2}} \qquad (1)$$

$$(v_o - v_i)\left(R + \frac{B}{2}\right) = v_o B \qquad (2)$$

$$v_o\left(R + \frac{B}{2} - B\right) = v_i\left(R + \frac{B}{2}\right) \qquad (3)$$

$$\frac{v_o}{v_i} = \frac{\left(R+\frac{B}{2}\right)}{\left(R-\frac{B}{2}\right)} \qquad (4)$$

$$R = \frac{B}{2}\left(\frac{v_o+v_i}{v_o-v_i}\right) \qquad (5)$$

In the above, slippage between the whegs and the ground has been neglected. Knowing the relationship (6), the radius of curvature R can be calculated as a function of the link bending angle.

$$\theta = 180 - \varphi \qquad (6)$$

$$\tan\left(\frac{\theta}{2}\right) = \frac{\left(L/_2\right)}{R} = \frac{L}{2R} \qquad (7)$$

$$R = \frac{L}{2\tan\left(\frac{\theta}{2}\right)} = \frac{L}{2\tan\left(\frac{180-\varphi}{2}\right)} \qquad (8)$$

Equations (4), (5) and (8) can be used to position each of the segments to obtain the desired shape of the robot. Given sensed angles, v_o and v_i can be adjusted to rotate the robot at an arbitrarily specified radius of curvature R. Nominal curvatures could be obtained via a fuzzy [73] rule-based motion planning approach such as [45], [54], although we selected them directly via a human operator in the reported experiments.

However, R has some physical limitations due to the constraint in the link bending angle, which needs to be accounted for. If this angle becomes too small, the whegs overlap, blocking the system. Fig.15 illustrates this case. By using the diagram below, we can readily calculate the turn radius for this limiting case.

The following equations model the situation in fig 15 for FRESE IV (with L = 1 foot, B = 9 inches, and r = 5 inches.

$$\tan\left(\frac{\varphi_{min}}{2}\right) = \frac{\left(\frac{B}{2}\right)}{\left(\frac{L}{2}-r\right)} = \frac{0.11m}{0.03m} \qquad (9)$$

$$\varphi_{min} = 149.49° \approx 150° \qquad (10)$$

By applying equation (8) we obtain:

$\varphi_{min} = 150°$ R=1foot 10 ins (minimum turn radius)

$\varphi = 180°$ $R_{max} = \infty$ (straight line walking)

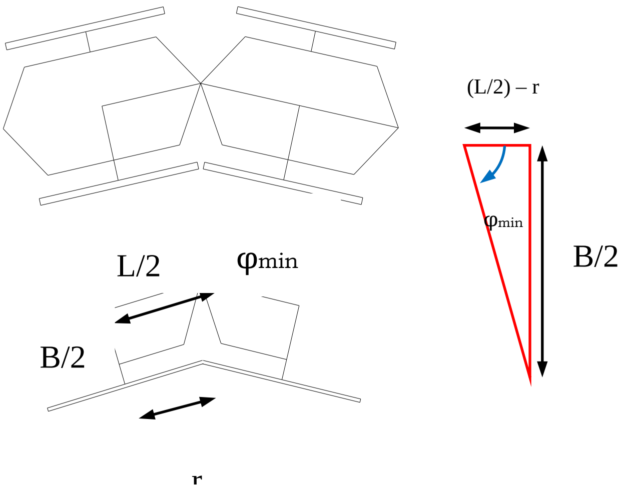

Fig.15 FRESE IV maximum steering angle.

As above, we infer that the theoretical minimum radius of curvature for FRESE IV is R = 1 foot 10 inches. This calculation matched well with the empirically observed value of 2 feet.

Overall, the continuum pipe sections in FRESE IV enabled a navigation capability within the original design specifications (see turning radii in Table 1) in contrast to the plastic pipes of FRESE II or the plastic strips of FRESE III, with correspondingly improved results. In testing, using the same environment as for FRESE III, the modified FRESE IV prototype of Fig.6 proved highly successful (Fig.16 and Fig.17). It was able to negotiate the slope at any point, using its continuum body elements to adapt to both vertical and lateral environmental disturbances.

In summary, FRESE III and FRESE IV are, to the best of our knowledge, the first whegs-based robots with continuum body elements. Overall, the highly successful combination of whegs and continuum body elements in the FRESE III and IV series of robots allow the system to exploit the efficient “wheel-like” aspect of the whegs on relatively smooth ground, while also providing “snake-like” behavior when negotiating uneven terrain (Fig.12 and Fig.16) and cluttered obstacle fields (Fig.17). The continuum body allows the robot to navigate areas in which whegged robots with solid bodies would become snagged by obstacles. Although the body shape/compliance in the FRESE series of robots was not autonomously controlled, such control of continuum bodies has been successfully demonstrated previously [35]. At the cost of increasing complexity, it is quite feasible to autonomously control the shape trajectory for these robots using the models developed herein.

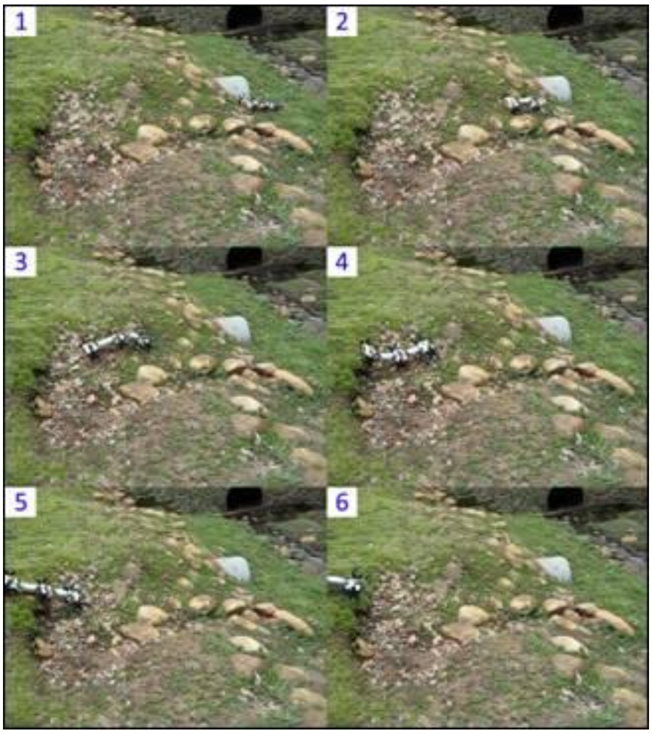

Fig.16 FRESE IV navigating hilly ground.

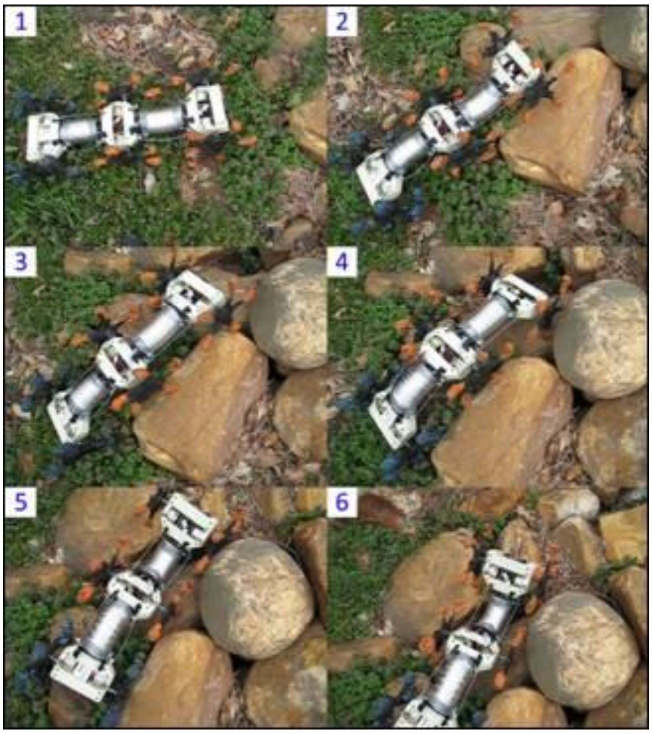

Fig.17 The FRESE IV mobile robot undulating its continuum body to negotiate rocky terrain.

4 Conclusion

We have discussed the potential for deployment of continuous backbone “continuum” robot elements in novel mobile robot application tasks. We considered several alternative cases of mobility using continuum bodies and legs. We have also discussed examples of use of continuum limbs deployed on conventional rovers as novel “tunable hooks” to enhance the mission capabilities of the overall system. We illustrated and supported the case studies using results from laboratory and field experiments using several types of continuum robots developed recently by our team.

In particular, this paper introduces the first whegs-based mobile robots featuring continuum body elements (FRESE III and IV). The infinite degrees of freedom present in the continuum elements provide superior maneuverability than in previous whegs-based robots featuring rigid bodies or finite body-joint elements. The presented experiments using the robots demonstrate how the use of continuum bodies enables novel and effective locomotion over a range of challenging terrains. The results suggest that the incorporation of continuum bodies – particularly if their shape can be actively controlled – in mobile robots can significantly enhance their performance and capabilities.

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