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# Self Locomotion of a Spherical Rolling Robot Using a Novel Deformable Pneumatic Method

Keith W. Wait, *Member, IEEE*, Philip J. Jackson, and Lanny S. Smoot, *Member, IEEE*

*Abstract*—**The authors have designed and constructed a new type of actuation for a spherical robot. The proposed actuation system consists of a large number of individually inflatable rubber bladders covering a sphere. Inflation of one or more of these bladders imparts a moment to the sphere and coordinated inflation results in a directed motion. Further, the authors introduce a scheme for steering the robot by correctly selecting the proper bladders to inflate so that motive force is developed in a specified direction. The control scheme utilizes a passively rolling inner vehicle with a directional, remotely positioned light source that causes valves housed within the sphere to inflate the designated bladders through optical commutation.**

*Index Terms*—**Pneumatic systems, mobile robots, spheres**

## I. Introduction

SPHERICAL rolling robots have a unique place within the pantheon of mobile robots in that they blend the efficiency over smooth and level substrates of a traditional wheeled vehicle with the maneuverability in the holonomic sense of a legged one. This combination of normally exclusive abilities is the greatest potential benefit of this kind of robot propulsion. An arbitrary path that contains discontinuities can be followed (unlike in the case of most wheeled vehicles) without the need for the complex balancing methods required of legged robots. However, spherical rolling robots have their own set of challenges, not the least of which is the fact that all of the propulsive force must somehow be generated by components all of whom are confined within a spherical shape.

This general class of robots has of late earned some notoriety as a promising platform for exploratory [1] missions and as an exoskeleton [2,3]. However, the history of this type of device reveals that they are most common as a toy or novelty. Indeed, the first documented device of this class appears to be a mechanical toy dating to 1909 [4] with many other toy applications following in later years [5-8].

Many efforts have been made to design and construct spherical rolling robots and have produced many methods of actuation to induce self-locomotion. With a few exceptions, most of these efforts can be categorized into two classes.

The first class consists of robots that encapsulate some other wheeled robot or vehicle within a spherical shell. The shell is then rolled by causing the inner device to exert force on the shell. Friction between the shell and its substrate propels the assembly in the same direction in which the inner device is driven. Early examples of this class of spherical robot had a captured assembly whose length was equal to the inner diameter of the spherical shell, such as Halme et al. [9] and Martin [6], while later iterations included what amounts to a small car that dwells at the bottom of the shell, such as Bicchi et al. [10,11], Sonesson [7], and Robinson [8].

The second major class of spherical robots includes those in which the motion of the sphere is an effect of the motion of an inner pendulum. The center of mass of the sphere is separated from its centroid by rotating the arm of the pendulum. This eccentricity of the center of mass induces a gravitational moment on the sphere, resulting in rolling locomotion. Examples of these efforts are those of Michaud and Caron [12], Jia et al. [13], Ming et al. [14], and Clark and Greene [15]. Javadi and Mojabi [16] as well as Mukherjee et al. [2] have devised systems that work using an eccentric center of mass, but each moves four masses on fixed slides within the spherical shell to achieve mass eccentricity instead of tilting an inner mass.

Little work has been done outside these two classes. Jearanaisilawong and Laksanacharoen [17] and Phipps and Minor [18] each devised a rendition of a spherical robot. These robots can achieve some rolling motions when spherical but are capable of opening to become a wheeled robot and a legged walking robot respectively. Sugiyama et al. [19] created a deformable spherical rolling robot using SMA actuators that achieves an eccentric center of mass by altering the shape of the shell. Finally, Bart and Wilkinson [5] and Bhattacharya and Agrawal [20] each developed spherical robots where the outer shell is split into two hemispheres, each of which may rotate relative to each other in order to effect locomotion.

The authors have developed a novel actuation method in which the outer spherical surface of the robot is composed of a large number of individually inflatable cells. Deforming the robot's surface close to its point of contact with the substrate provides the motive force.

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K. W. Wait is with Vanderbilt University, Nashville, TN 37212 USA (e-mail: keith.w.wait@vanderbilt.edu).
P. J. Jackson and L. S. Smoot are with Disney Research, Glendale, CA 91201 USA (e-mail: phil.jackson@email.disney.com; lanny.s.smoot@email.disney.com).

## II. Principle of Operation

The basic principle used in the device to effect locomotion is relatively straightforward. In a simplified two-dimensional example, shown below in Fig. 1, a pneumatic tire is partitioned into eight individually indexed segments. The device inflates the segment which is located near bottom dead center, but located counter to the desired forward direction along the axis of travel.

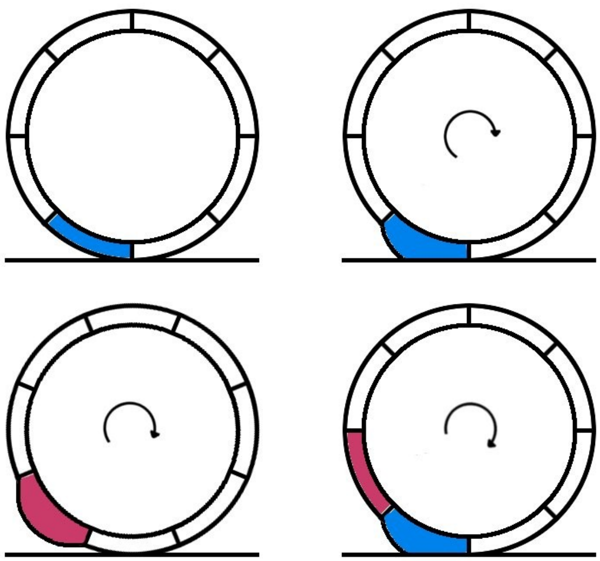

Fig. 1. Two-dimensional example. At top left, the highlighted segment is marked to be inflated. At top right, the pressure within the inflated segment applies a moment to the tire, which begins to roll. At bottom left, tire rotation has caused the inflated segment to release its contact with the ground and it begins to deflate. At bottom right, the previous segment has totally deflated and a new segment begins to inflate.

The partitioned tire is made from some elastomer that can sustain very high strain or expansion. Upon inflating, the segment deforms radially outward so that, in addition to touching the ground, it also exerts a moment about the instantaneous center of rotation of the device. This moment causes the tire to begin to rotate. As the tire segment that was inflated loses contact with the ground, it deflates and a new segment takes its place in the inertial frame of reference attached to the center of the tire. This new segment is inflated as it passes bottom dead center, providing the rotating device with additional motive force. Note that segments do not deform radially inward because the inner rim of the tire is rigid and resists this motion.

This principle is trivially expanded into the third dimension by replacing the segmented tire with some appropriately partitioned spheroidal solid. One can use, for example, a convex polyhedron whose normally planar polygonal faces are replaced by spherical polygons. A common example of such a solid is the truncated icosahedron, or the traditional soccer ball whose faces are 20 hexagons and 12 pentagons. While any arbitrary solid meeting the description above could be used, the authors choose the truncated icosahedron for the robot's morphology because the spatial resolution of actuators appears to be well matched to the desired scale of an approximately 30 cm diameter robot. Larger or smaller instances of the device described herein may require a different choice of solid in order to achieve the appropriate spatial resolution.

While in the two-dimensional example of Fig. 1, a single inflated segment was sufficient for both locomotion and stability, this is not true for the three-dimensional case. Inflation of a single face of the truncated icosahedron results in an indeterminate direction of motion because of the metastability of the resulting deformed geometry. To better control the direction of travel, a collection of the spherical shell segments semi-encircling bottom dead center is inflated. More specifically, the cells to inflate meet criteria (1) and (2):

$$\left(\vec{d}_{sc,i} - \vec{d}_{bdc}\right) \cdot \vec{v}_t \le 0 \tag{1}$$

$$\vec{d}_{sc,i} \cdot \vec{d}_{bdc} > 0 \tag{2}$$

Here, $d_{sc,i}$ is the displacement vector locating the center of the $i^{th}$ spherical segment relative to the sphere's centroid, $d_{bdc}$ is the displacement vector locating bottom dead center on the sphere's surface relative to the sphere's centroid, and $v_t$ is a unit vector pointing along the desired direction of travel. Fig. 2 illustrates how to apply these criteria to a sample situation.

Note that, while the device has been described using pneumatic actuation and inflatable actuators, the design can be easily amended to instead use other linear actuators such as voice coils, electric DC motors with ball screw transmissions, or pneumatic cylinders.

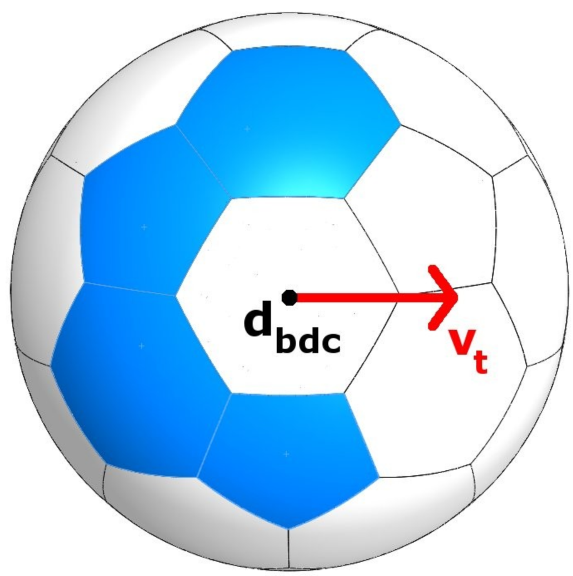


Fig. 2. Inflation scheme for 3D device. Highlighted shell segments are inflated when direction of travel and gravity are as shown.

## III. Mechanical Design

The robot's overall physical design stems from the design of a basic actuation unit. An individual actuation unit consists of a rubber bladder, an inner, stiffening structure, and a fill valve along with its associated electronics. A hexagonal elastomeric actuator is shown in Fig. 3. A pentagonal unit, while not shown in the figure, is analogous to the hexagonal unit.

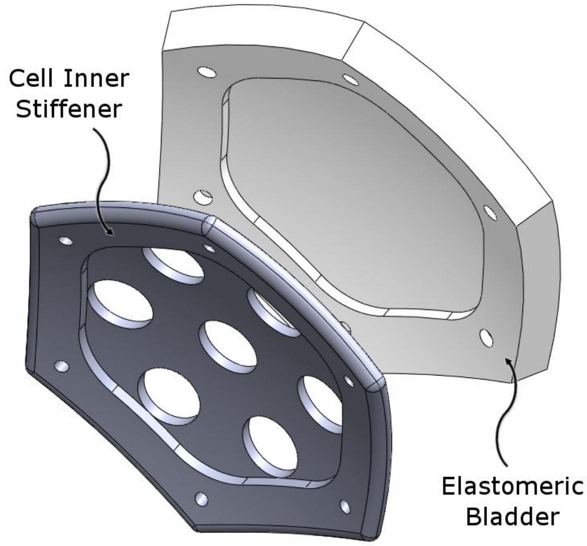


Fig. 3. A single elastomeric actuator. When assembled, the bladder is stretched over the inner stiffener. In this configuration, the stiffener provides rigidity to the bladder as well as a means of mounting it to the robot's superstructure.

The rubber bladder is custom formed with the desired tapered hexagonal shape as well as a convex spherical segment face. As mentioned above, the material from which the bladder is formed is an elastomer (Smooth-On Dragon Skin) that the manufacturer advertises as able to stretch by ~1000% before breaking. The bladders have a 3.2 mm wall thickness, a 178 mm external radius, and an overall thickness of 12.7 mm.

A stiff, ABS plastic component is inserted into the bladder. When deflated, this component fills the entire inner volume of the bladder. It provides shape to the normally highly flexible bladder so that the sphere is able to roll smoothly on a level substrate. In the absence of the stiffener, the flaccid bladders could be deformed inward, causing the sphere to develop flat spots that would hamper rolling. The stiffening member features tapped mounting holes that align with the holes in the proximal portion of the bladder. Additional large holes pass through the body of the component to allow for the inflation of the bladder.

A commercially available miniature 3/2 valve (Clippard EV-3) is mounted so that its outlet port is coaxial with the central axis of the actuation unit. When provided with a pressure source and activated, a gaseous working fluid inflates the bladder and provides motive force to the robot as above. The valve along with fittings and associated electronics is shown in Fig. 4.

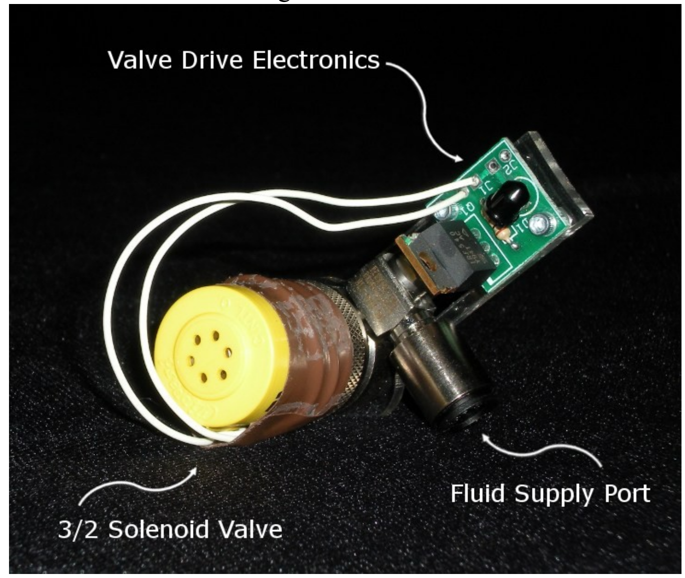


Fig. 4. Fill valve assembly for the elastomeric actuation unit.

Each actuation unit is mounted to one of two hemispherical rigid, acrylic parts. These two hemispheres are held together magnetically during operation.

As shown in Fig. 5, each hemisphere is drilled with holes to mount the valves on its inner surface, and the stiffened bladders to its outer surface. When the bladders are mounted to the hemisphere as shown, bolts passing through the hemisphere and flange of the bladder and threaded into the tapped holes of the inner cell stiffener serve to create the seal required for inflation of the cells and overall operation of the device.

The valve is secured to the hemisphere by a male to male pneumatic fitting (not shown in figure) that serves as the valve's outlet port and the conduit for gas to enter the actuator. The hole drilled into the hemisphere coaxial with the center of each actuator assembly receives this fitting.

A pressure supply energy source for the pneumatic actuators is not explicitly shown in the figures, as the present iteration is supplied with air through a tether. However, several options exist for a mobile supply. For example, small liquid CO2 cartridges can be positioned throughout the available space within the interior of the robot. In the future, the authors hope to improve the design so that it is compatible with hot gas [21], which will allow for much greater energy density and extended operation time relative to CO2. Further, it is possible to include a number of very small air compressors and use somewhat larger batteries to power both these compressors as well as the control valves.

## IV. Controlling the Robot

Probably the most conventional method of actually selecting the appropriate cells to inflate in practice (i.e., of implementing the algorithm described in section II) would involve employing a triaxial accelerometer and triaxial electronic compass to sense the direction of gravity and of the earth's magnetic field, respectively, both relative to a reference frame attached to the spherical robot's centroid.

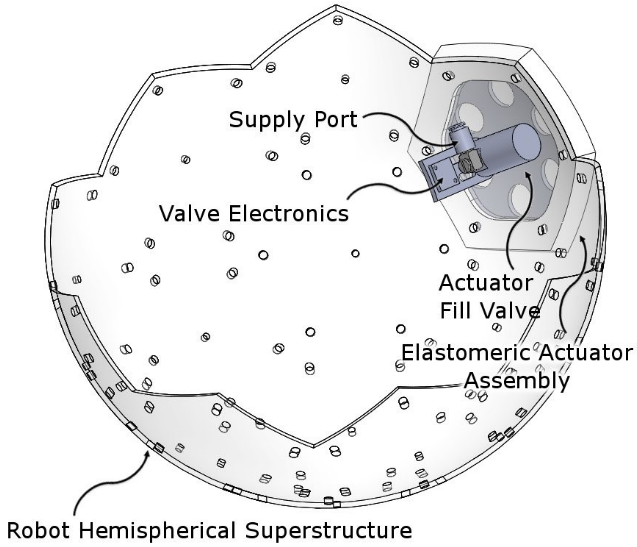


Fig. 5 Actuator assembly attached to the robot's superstructure. The hemispherical structure is shown as transparent with a representative elastomeric actuator shown attached to the distal face (relative to the viewer).

A processor would then construct the kinematic transformation matrix between the reference frame attached to the robot and an inertial reference frame centered at the robot's centroid but aligned with local gravity and local north. Using this matrix along with the fixed locations of the elastomeric actuators relative to the robot's centroid and a user-commanded desired directional heading, the processor could identify those actuators that meet the criteria of (1) and (2), i.e., the actuators that surround ground on the side opposite the desired direction of motion.

However, the proposed robot requires that its control system need only sense the operator's desired direction of travel, the local direction of gravity, and some heading information of the robot. Further, while the computation required to implement the electronic method in real time is not severe relative to the capacity of modern processors, it is not trivial. Based on these two observations, the authors propose a computation-free method of controlling the spherical robot that draws inspiration from the robots of [7,8,10,11].

In the approach used here, a second, smaller spherical shell is located concentric to the structure constraining the elastomeric actuators. It houses a disc with a smaller diameter than its own. The disc features three ball (holonomic) casters that allow it to passively roll along the inner surface of this second sphere. Assuming the friction of these casters is low, gravity causes the disc to fall to the bottom of the inner sphere (with some disturbance due to acceleration of the robot). This phenomenon allows for sensing the direction of gravity. The disc is shown in Fig. 6.

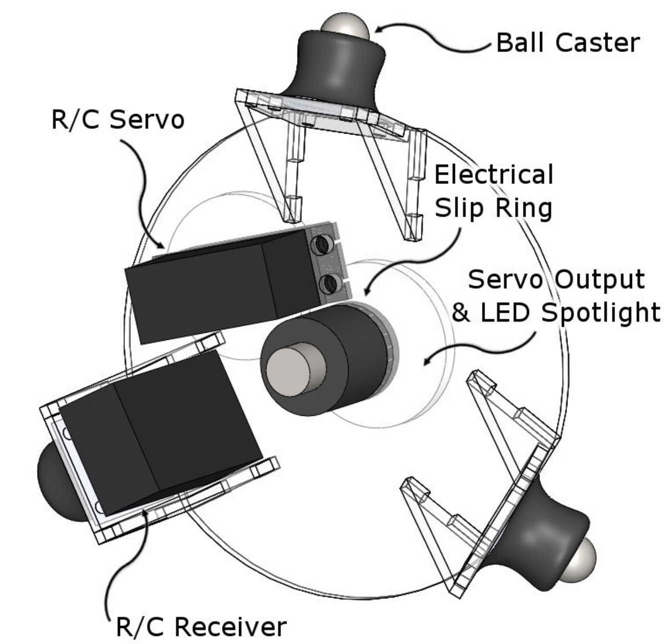


Fig. 6. Control disc as viewed from above. The disc structure is shown as transparent with the slip ring and servo extending through the disc body and the LED shown on the opposite side of the body from the viewer.

To sense the user's desired direction of travel, the control disc is fitted with an RC servo modified for continuous rotation as well as a matching RC receiver. Output velocity of the servo is directly controlled such that it holds direction when no command is applied but the operator is able to steer it clockwise and counter-clockwise as desired.

The servo acts as a rudder for the overall robot through the following mechanism. The output shaft of the RC servo steers an LED spotlight. The spotlight is apertured to illuminate the appropriate region of the sphere (i.e., the panels highlighted in Fig. 1). By turning the servo, the user selectively illuminates the portion of the sphere that corresponds to those actuators that are necessary to develop motive force in the desired direction of travel.

Each of the 32 valves used to inflate the elastomeric cells on the outer surface of the robot is driven by a power MOSFET with a Darlington phototransistor whose wavelength matches that of the phototransistor at its gate. When the phototransistor is made active because of light at the appropriate wavelength incident on its sensing element, the MOSFET is put in its active regime and the valve opens to allow compressed gas to flow from the pressure source through the valve and to inflate the actuator.

It is required, then, that the inner sphere housing the control disc must be optically transparent at the wavelengths of the components used, that the sphere be divided into two hemispheres to allow for assembly of the overall device, and that the phototransistors are very nearly aligned with their respective valves. The alignment is accomplished by affixing the phototransistors to the valve using a bracket that also serves as the support for the inner sphere (Fig. 4). An exploded view of the overall device (excluding gas supply, batteries, and power distribution) is shown in Fig. 7.

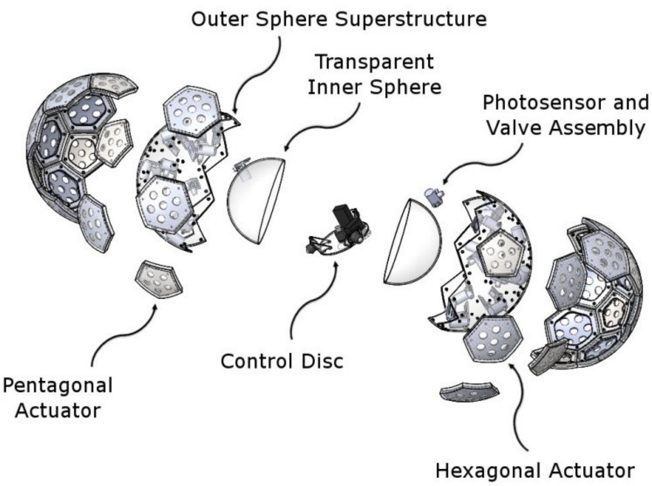


Fig. 7. Exploded view of rolling robot.

## V. RESULTS

The fully assembled robot including batteries for powering the valves and steering disc, (but omitting fluid power sources as the present work deals only with a tethered version of the robot) has a diameter of 35.6 cm, has a mass of 9.1 kg, and is shown below in Fig. 8.

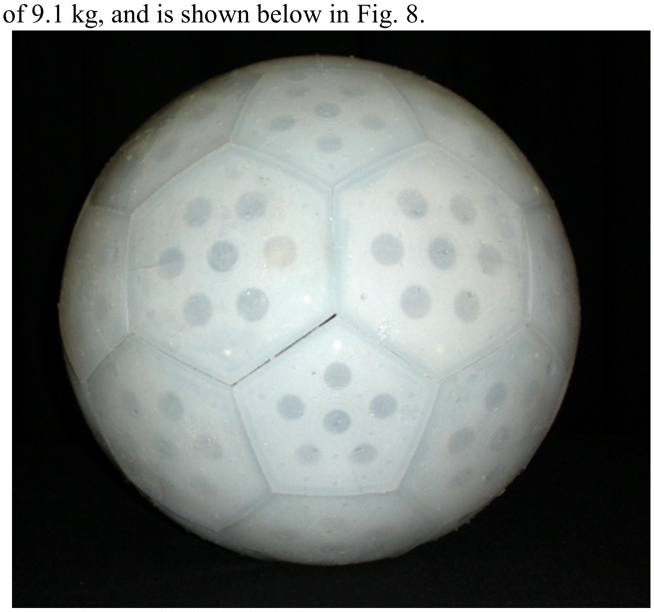

Fig. 8. The assembled spherical robot.

A video attachment to this paper demonstrates the operation of the robot. The first portion of the video shows inflation and deflation of the bladder actuators. In this illustration, the actuators are supplied with compressed air at a pressure of 2.1 bar. At this pressure, the actuators are slow to inflate and extremely slow to deflate. The authors believe this limitation is not fundamental, but rather is due to the restricted flow rates allowed by the small orifices of the selected valves. These valves were chosen for their immediate availability, low cost, and small size. They were not discovered to be serious flow-rate limiters until very late in the robot's development.

Subsequent experimentation with the actuators was conducted and established that the selected valves allowed an actuator to expand radially at a rate of 2.3 cm/s with a 2.1 bar supply and 1.2 cm/s with a .7 bar supply. In comparison, a manually operated valve with an orifice size 6.6 times that of the selected valves allowed the same actuator to expand radially at a rate of 17.8 cm/s with a 2.1 bar supply and 9.2 cm/s with a .7 bar supply.

The second portion of the video demonstrates remote directional control of the internal infrared spotlight mounted on the control disc. It is shown that the spotlight's output beam is empirically shaped with a baffle to illuminate a number of valves as described in section II. Spotlight illumination is made visible through the use of an infrared camera in the video.

The final portion of the video shows the robot in operation. In this segment, a 6.4 mm diameter umbilical hose provides compressed air (again at 2.1 bar) to the inner workings of the sphere. Current operation is limited to a speed of approximately 7.6 cm/s. While the authors would prefer dynamic rolling, the device is currently limited to kinematic operation [22] due to the actuator speed, which is again suboptimal due to poor valve performance. The video clearly shows that the optical commutation and inflatable actuators are functional in generating controlled locomotion, although there are certainly improvements to be made.

## VI. FUTURE WORK AND ADVANCED CAPABILITIES

It is worth noting that the purely electronic approach outlined early in section IV is certainly straightforward and likely to be advantageous relative to the approach chosen by the authors especially with regard to weight and internal volume occupied. The optically commutated approach adopted by the authors is selected because it is superior in certain applications of the proposed holonomic drive and because it is somewhat easier to develop than alternatives; however, the authors believe that, with a sufficiently versatile electronic controller, the proposed actuation system has several advantages and abilities beyond those demonstrated by currently documented spherical robots and precluded by the present control system.

First, the robot is able to hold a static position without exerting effort. When the segment that is in contact with the substrate is totally encircled by inflated segments, all valves can be closed to reduce energy consumption to zero. In this configuration, the device remains stationary in the absence of perturbing forces because of the intrinsic stability of the deformed geometry. Admittedly, the number of possible orientations in which the device can perform this feat is finite. However, all of the previously demonstrated devices enumerated in section I (in their rolling, rather than legged modes) require active stabilization to maintain position.

Second, the device can potentially perform hopping motions (i.e., the actuation does not preclude it). In early tests of an incomplete prototype version of the present design, a single actuator was shown to cause such a motion. This would, of course, require the actuators to generate an output force in excess of the robot's weight. However, with sufficiently high supply pressure and with low enough losses in the pneumatic system, the experiments show that the elastic actuators could deliver such an impulse. The only currently documented spherical robots that advertise the capability of a hopping mode of locomotion seem to be those of [19,23].

Finally, the output force from the present robot is likely to be far in excess of that achievable by previous designs. In any situation where a payload will need to be transported (i.e., almost any practical case), having superior force capabilities is a significant advantage. Conventional pneumatic actuators have been shown to have force density superior to that of electric actuation [24], and the inflatable actuators of this design retain this attribute. In the non-deformable spherical robots that use mass-distribution eccentricities to achieve locomotion [2,12-16], the output forces are limited by the moments that can be generated by the offset mass (i.e., by the robot's weight and diameter). The robots that contain an internal vehicle to impart a frictional force on the spherical shell [6-10] are similarly limited by the maximum frictional force (i.e., by the internal vehicle's weight and the coefficient of friction of the interface). The present, inflatable, robot suffers from neither of these drawbacks and achieves greater output force because, when inflated, the actuators' contact area with the substrate is large. Because of this large area, a small pressure inside the inflated cells results in a great force.

## VII. CONCLUSION

The authors have introduced an inflatable pneumatic actuator and have used an array of these actuators to design a new type of spherical, self-rolling robot that is superior to previous designs both in potential capabilities as well as in maximum output force. The described and constructed robot is a first of its kind. As such, opportunities exist for the improvement of the device in both mechanical design and in control methods. However, the general concept is sound and has advantages and applications left to be explored.

Future investigations into the capabilities and operation of the new system include the replacement of the steering system described in section IV by a purely electronic substitute to ascertain what, if any, advantage is gained by this change. Also, the authors hope to introduce mobile power supplies such as hydrogen peroxide monopropellant fuel, liquid carbon dioxide cartridges, and electric compressors to determine how such supplies affect the operation and the working lifetime of the robot.

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