A Literature Review on the Design of Spherical Rolling Robots

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***Abstract*— There are many advantages to the use of spherical robot designs. The current status of the design of spherical rolling robots is reviewed.**

I. INTRODUCTION

There are many advantages to a spherical robot design. First of all, they are very maneuverable. They can be designed to be holonomic, so they can move in any direction. This increases the options for navigating around objects and prevents the robot from getting stuck in corners. Spherical robots also cannot be overturned. Traditional wheeled robots have the ability to be rendered useless if they land upside-down. This is not the case with a spherical robot. Stairs and ledges are also a problem for traditional robots, and a spherical robot can overcome these conditions very well. This feature also allows them to be thrown or dropped. They have a great capability to recover from collisions with obstacles. This would be useful in a swarm application, where many spheres could be traveling in close proximity, and because of the design they would not interfere with each other's motion. Since they can be designed to be totally sealed, they are ideal for hazardous environments. The sensors, electronics, and mechanisms are all protected. This makes them capable of functioning in snow, mud, and even water. Spherical robots be assisted or powered by winds. They can also be smaller than wheeled vehicle, and can be made cheaper with fewer parts, or they could even be disposable.

II. PROPULSION MECHANISMS

A. Wheel Based

The first spherical mobile robot was developed by Halme et al. in 1996 [2]. The propulsion was derived from a wheel in contact with the bottom of the sphere as shown in Fig. 1. Above the wheel is the Inside Drive Unit (IDU) with power and communications. The wheel and IDU are integrated into a single axis support. On the opposite end of the powered wheel is another stabilizing wheel. By steering the powered wheel, the sphere has the ability to turn.

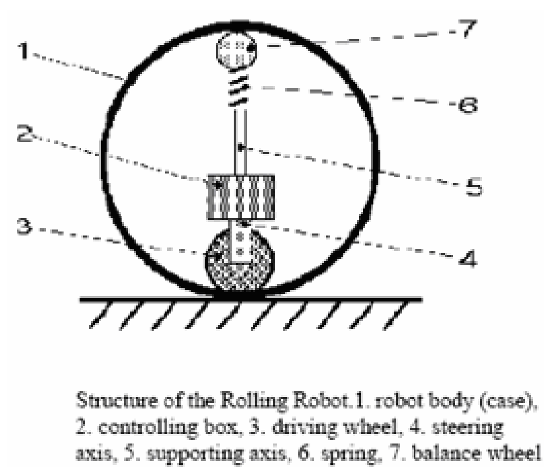


Fig. 1. Structure of the Rolling Robot.

This design was also configured with two wheels in contact with the bottom surface as shown by an implementation by K. Husoy shown in Fig. 2 [19].

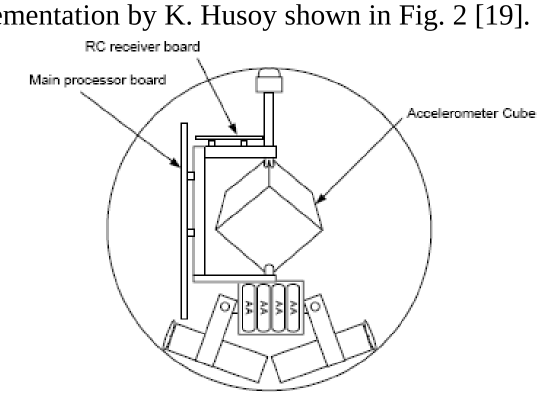


Fig. 2. Two wheeled design.

In 1997, A. Bicchi et al. proposed a design that was propelled by a small car resting at the bottom of the sphere illustrated in Fig. 3 [3]. The car could be steered to change the direction of the sphere. The robot was modeled using a combination of unicycle kinematics and ball-plate kinematics.

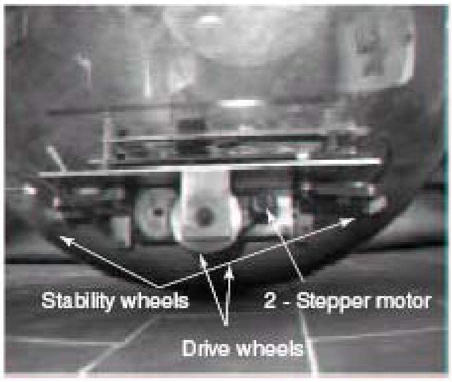


Fig. 3. Bicchi design.

The advantages of the wheeled design are that it is a simple mechanical structure and the motors can be smaller since they do not require much torque. The system can also be holonomic or non-holonomic depending on the wheel configuration. It is also helpful that the system can be modeled by well known mathematical models, making control easier.

B. *Two Independent Hemispheres*

S. Bhattacharya developed a design that involved a set of two mutually perpendicular rotors attached to the inside of the sphere [7]. The sphere is assembled in two halves, with each half containing a motor and rotor. The two halves can be seen in Figure.

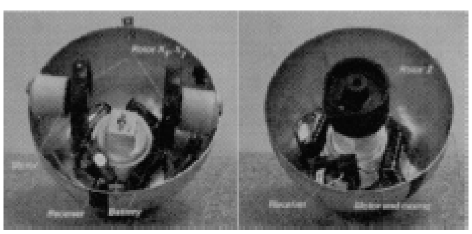


Fig. 4. Two halves of Bhattacharya design.

The sphere moves by using conservation of momentum in the rotors. Problems with this design are that it has a complex mechanical structure. It also requires high performance motors due to the high speed of the rotors, and is not very efficient since the rotors spin very fast compared to the movement of the sphere.

Another design involving two hemispheres being independently controlled is shown in Fig. 5. The motors are mounted low, and by adjusting their speeds the motion is achieved. The robot can turn by slowing one motor, or even reversing one to spin on the vertical axis. A gap between the hemispheres can be advantageous for sensor visibility, but does not seal the internal components from the environment.

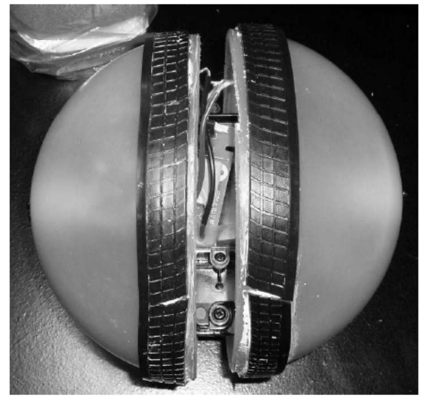


Fig. 5. Another two hemisphere design.

C. *Pendulum Based*

A simple spherical robot can be developed using a pendulum based design. Fig. 6 shows a schematic of the internals of a robot called Rotundus [11]. This design consists of a motor attached to the horizontal axis that goes through the sphere. In the center there is a pendulum that drops down. When the motor is activated, the sphere will move as long as the weight of the pendulum has enough inertia that it is easier for the casing to spin than the pendulum to go around. The pendulum can move to the left and right, causing the robot to turn.

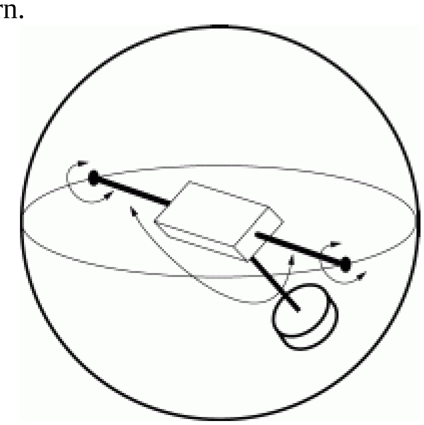


Fig. 6. Pendulum Design

D. *Relocation of Center of Gravity*

The idea behind this type of spherical robot propulsion is to redistribute masses in order to change the center of gravity. Continuously redistributing the masses in a certain way will allow the sphere to move in any direction. R. Mukherjee *et al.* in their Spherobot design, propose a central body with weights distributed radially along spokes fixed to the inside surface of the sphere [5]. The weights can actually be the pancake motors themselves, and move along the axes to change the center of mass. Fig. 7 also depicts other design features included telescopic limbs and a retractable camera. Another similar design seen in Fig. 8 is proposed by A. Javadi and P. Mojabi, in their robot called August [6]. This time four axes are mounted in a tetrahedral pattern. Stepper motors at the center of the robot advance the weight on the axes with a screw. This design is easier to model than the Spherobot since without weights, August has a mass center located at the geometrical center.

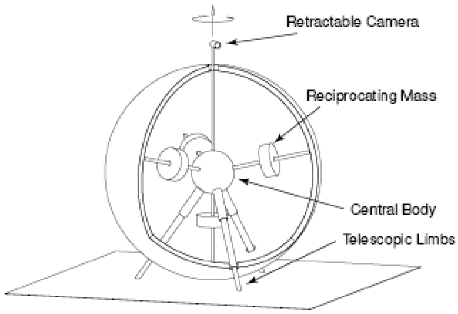


Fig. 7. The Spherobot Design

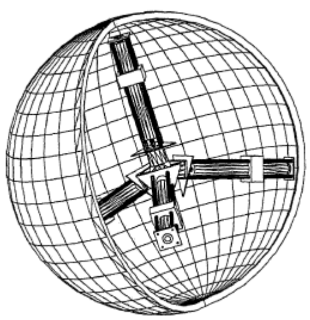
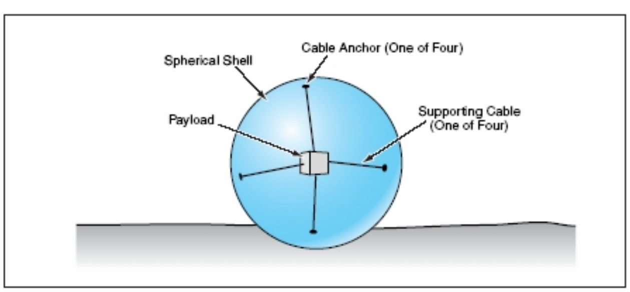


Fig. 8 August

An alternative to shifting masses on rigid rods was proposed by Lux and can be seen in Fig. 9. The payload is also the actuation and sensor unit. By using winches, the cables can be retracted and released to shift the mass. The number of winches can also be reduced by spring loading some of the cables so they return without needing winches. An advantage to these designs is that they can move the mass to the center and then just glide, saving energy when it is windy or they are descending a hill.



The Payload Would Contain Winches that would extend some cables while retracting others to move itself to a specified position within the spherical shell.

Fig. 9. Winch and cable design.

E. Wind Powered

There has been some work to design large wind-powered spherical robots. This is mostly due to NASA's effort to create wind powered Mars exploration rovers [10]. The high winds of Mars are a powerful natural resource, and could be harnessed. The biomimetic design is inspired by tumbleweeds. Some concepts are shown in Fig. 10.

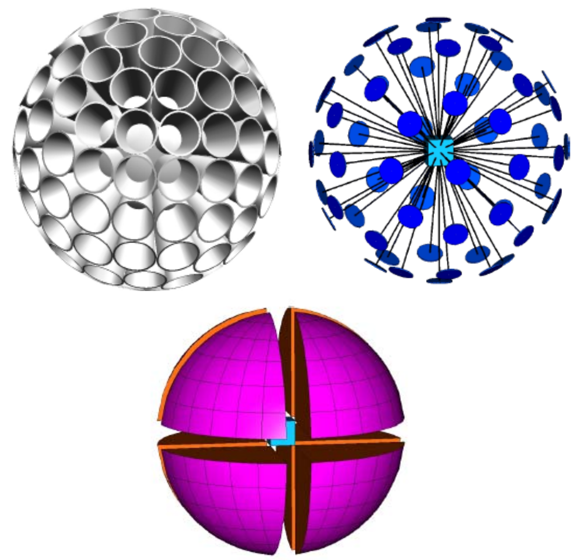


Fig. 10. Wind Spheres

The design would allow for a robot that can go over larger obstacles than a car-like rover of its size. Other designs have mixed the pendulum design with wind powered, allowing the robot to steer and stop by using a pendulum that can be retracted into the center of the sphere to "coast" [18].

F. Deforming

Another type of spherical robot that is much different from the others is a deformable robot [17]. The design, proposed by Y. Sugiyama, consists of a four rings attached in the center by shape metal alloy (SMA) wire. Using pulse width modulation, the SMA wire contracts in a certain order to make the sphere move. Figure shows three states of the sphere.

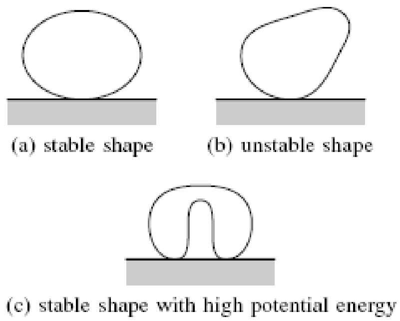


Fig. 11. Deformable sphere states.

The stable shape is used when the sphere is not to move. The unstable shape, when controlled correctly, will allow the sphere to move. And the stable shape with high potential energy, when released, will cause the sphere to jump into the air, as seen in Fig. 12.

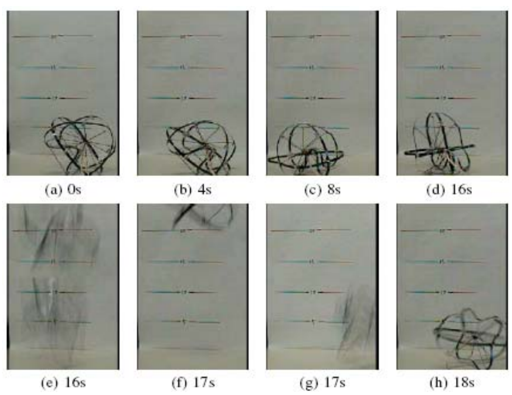


Fig. 12. Jumping sphere.

III. Dynamics

The dynamics for most spherical robot designs is quite complicated. However, for a simple wheel based mobile robot, it is pretty straight forward. A. Halme et al. analyzed the dynamics and motion control of the spherical mobile robot shown in Fig. 13 and 14 [14].

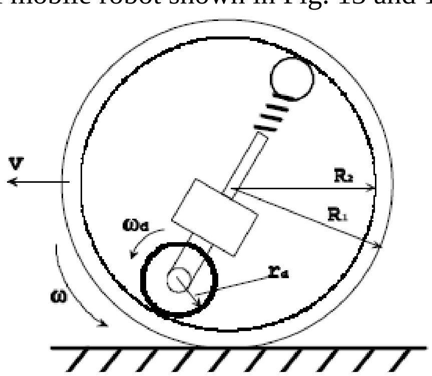


Fig. 13. Modeling of the Robot

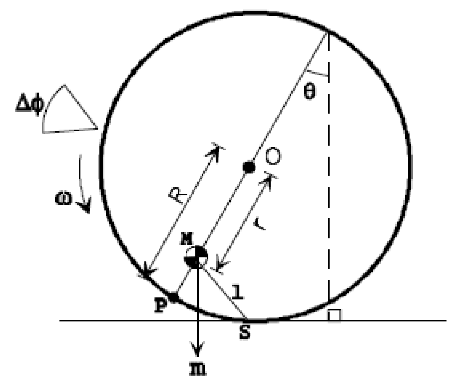


Fig. 14. A rolling disk.

Some useful equations that were solved include the height of an obstacle that the sphere can climb that takes into account rolling friction, where k is the coefficient of friction.

$$h_{max} = R_1 - \sqrt{R_1 - \frac{mr - k(m + M_{ball})}{M_{ball} + m}} \quad (1)$$

Another equation is the relationship between the speed of the driving wheel and the speed of the ball, which is shown below.

$$\varpi = \frac{r_d}{R_1}\varpi_d \quad (2)$$

IV. Applications

A spherical robot design may be ideal for certain homeland security, homeland defense, military, and law enforcement applications [1]. With appropriate sensors they can be used for weapon detection, reconnaissance, surveillance, risk assessment, and situation awareness at safe distances. A robustly designed robot could be thrown through windows or into rooms and be controlled remotely, relaying back information to an operator station. The spherical design lends itself well to environments like ducts or dry pipes. The robots could also be stored in a holster and launched by hand. Or perhaps even by a gun such as a paintball gun.

There may also be demand for a spherical robot in the toy and entertainment industry. F. Michaud devised a robot called Roball with child-development studies in mind [9]. He chose a spherical robot since it is robust and safe, which is a concern with children’s toys. It has no external moving parts and is totally enclosed so it is very safe. It is also light, inexpensive, quiet, and washable. It encourages the child to move, crawl, manipulate, be visually stimulated, and to interact with it.

Spherical robots could be used for autonomous exploration. As mentioned earlier, a wind-powered large spherical robot has been proposed for Mars, and there are probably places on Earth that could be explored with a similar concept.

There is currently one spherical robot already being used commercially. It was designed by a Swedish company that was formed in December 2004 [11]. The robot is designed as a security robot that detects and reports intruders. It uses a pendulum-type propulsion mechanism which allows it to travel at 10-15 miles per hour. As visible in Fig. 15, sensor pods are mounted on the sides. Fig. 16 also shows its robustness by driving in snow.

Fig. 15. Security robot.

Fig. 16. Security robot in snow.

V. Future Research

The upward motion problem will likely have to be solved to make the spherical robots useful in more conditions. It is sometimes a disadvantage to not be able to go up steep inclines. Jumping would allow the robot to jump over holes or obstacles. The sphere design lends itself to jumping more so than most other mobile robot designs since it can be made lightweight and cannot land upside down. Deformable robots already have the capability to jump by deforming the surface in contact with the ground and releasing quickly to propel themselves upward. However, deformable robot design has not reached the level that traditional spherical rolling robots have; they are somewhat limited by their use of SMA wire, which requires high voltage and therefore tethered operation. One current design concept is to have the sphere split apart to deploy a leg mechanism like in Fig. 17 [2]. This leg can then be actuated to launch the robot.

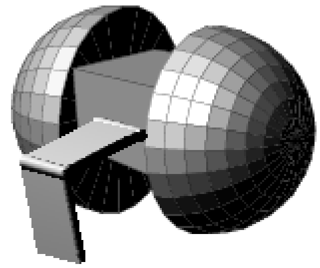


Fig. 17. Extendible leg concept.

This problem could be avoided in other ways. Perhaps there could be a hole at the bottom of the robot that allows a rod to be poked through quickly, coming into contact with the ground. Or maybe there could be a flap on the bottom of the sphere that can open quickly, launching the robot upwards. Another option is for an internal mass to be actuated quickly upward to use momentum to jump.

There are other aspects of spherical rolling robots that have not yet been fully explored. For example, it would be interesting to develop an amphibious robot that can travel long distances on water. Or perhaps develop a robot that is a combination of wind powered, current powered (while in water), and assisted by a motor and solar panel. A robust autonomous spherical robot like this could travel around the world.

It would also be interesting to learn how small a spherical robot can be made. Many of the types of spherical robots rely on inertia, which does not scale well as it gets smaller. A swarm of inexpensive jumping spherical robots could be quite powerful.

VI. Conclusion

The literature review on the design of spherical rolling robots is presented. The advantages and disadvantages of a spherical robot are given and discussed. Several different designs are introduced. Also, a simple dynamic analysis, applications, and future prospects are presented in order to give a better understanding of the field of spherical rolling robots.

References

[1] S. H. Kenyon, D. Creary, D. Thi, and J. Maynard, "A small, cheap, and portable reconnaissance robot," in *Sensors and Command, Control, Communications, and*

Intelligence Technologies for Homeland Security and Homeland Defense IV, Proc. Of SPIE, Vol. 5778, 2005

[2] A. Halme, J. Suomela, T. Schonberg, and Y. Wang, "A spherical mobile micro-robot for scientific applications," ASTRA 96, ESTEC, Noordwijk, The Netherlands, 1996

[3] A. Bicci, A. Balluchi, D. Prattichizzo, and A. Gorelli, "Introducing the "SPHERICLE": an experimental testbed for research and teaching in nonholonomy," Proc. of the 1997 IEEE International Conference on Robotics and Automation, 1997

[4] J. Lux, "Alternative way of shifting mass to move a spherical robot," NASA Jet Propulsion Lab, Pasadena, California, June 2005

[5] R. Mukherjee, M. A. Minor, and J. T. Pukrushpan, "Simple motion planning strategies for Spherobot: a spherical mobile robot," *Proc. of The 38th Conference on Decision & Control*, Phoenix, AZ, December 1999

[6] A. H. Javadi and P. Mojabi, "Introducing August: a novel strategy for an omnidirectional spherical rolling robot," *Proc. of the 2002 IEE International Conference on Robotics & Automation*, Washington, DC, May 2002

[7] S. Bhattacharya and S. Agrawal, "Experiments and motion planning of a spherical rolling robot," Proc. of the 2000 IEEE International Conference on Robotics and Automation, April 2000

[8] S. Bhattacharya and S. Agrawal, "Spherical rolling robot: a design and motion planning studies," IEEE Transactions on Robotics and Automation, Vol. 16, No. 6, 2000

[9] F. Michaud, J. F. Laplante, H. Larouche, A. Duquette, S. Caron, D. Letourneau, and P. Masson, "Autonomous spherical mobile robot for child-development studies," IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, Vol.35, No. 4, July 2005

[10] J. Antol, R. Kolacinski, D. Minton, R. Owens, and J. Parker, "Low cost mars surface exploration: the mars tumbleweed," NASA Langley Research Center, August 2003

[11] www.rotundus.se

[12] F. Michaud, J. Lafontaine, and Serge Caron, "A spherical robot for planetary surface exploration," in Proc. 6th International Symposium on Artificial Intelligence, Robotis and Auomation in Space, 2001

[13] G. Hajos, J. Jones, A. Behar, M. Dodd, "An overview of wind-driven rovers for planetary exploration," NASA, Langley Research Center

[14] A. Halme, T. Schonberg, and Y. Wang, "Motion control of a spherical mobile robot," Proc. of 4th International Workshop on Advanced Motion Control, 1996

[15] R. Mukherjee, M. Minor, J. Pukrushpan, "Motion planning for a spherical mobile robot: revisiting the classical ball-plate problem," Transactions of the ASME, December 2002

[16] Y. Sugiyama and S. Hirai, "Crawling and jumping of deformable soft robot," Proc. of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, Sendai, Japan, 2004

[17] Y. Sugiyama, A. Shiotsu, M. Yamanaka, and S. Hirai, "Circular/spherical robots for crawling and jumping," Proc. of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, April 2005

[18] J. Jones, A. Yavrouian, "Lightweight 'beach-ball' robotic vehicles," NASA, Jet Propulsion Laboratory, Pasadena, California, July 98

[19] K. Husoy, "Instrumentation of a spherical mobile robot," NTNU, Department of Engineering Cybernetics, Trondheim, June 2003