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Ball-shaped Robots

Tomi Ylikorpi and Jussi Suomela
Helsinki University of Technology
Finland

1. Introduction

A sphere is "the set of all points in three-dimensional space lying the same distance (the radius) from a given point (the centre)" (Encyclopedia Britannica Online). In terms of robotics, a spherical structure can freely rotate in any direction and all positions are stable. The shape of a sphere provides complete symmetry and a soft, safe, and friendly look without any sharp corners or protrusions, which is advantageous when a robotic device is dealing with people.

The principle of mobility for a ball-shaped robot is usually based on the movement of the robot's centre of gravity (cog) inside the spherical shell. The further the cog is from the centre of the ball, the greater the driving torque. Naturally, the ball diameter defines the maximum distance and the total mass limits the unbalanced mass being moved inside the ball. Often the available torque is quite modest compared to the total weight of the robot. An alternative method to create torque is based on the inertia of a rotating mass; inside the ball a rotating mass is accelerated and generates a counter-torque that drives the ball in the opposite direction. As the torque is a result of acceleration, the speed limit of the rotating mass sets a time limit for the applied torque. Hence this method can be used only for short periods and it also requires a means to decelerate the rotating mass back to rest. Inertia can, however, be used for orienting the ball when selecting the desired rolling direction.

A large diameter for the robot helps to generate greater driving torque and, at the same time, resistive torque from environmental objects such as stones or doorsteps remains lower. Hence large size is a benefit, while the overall mass then tends to increase. Technological developments with robotic balls aim to maximise the driving torque while minimising the mass, providing steering capability, modifying sphere surface texture to achieve the desired terrain interaction, and generating autonomous functions through sensors and added intelligence. The greatest technical challenges are the robot's limited off-road capability and the challenge of controllability. Step-climbing capability is defined by the radius of the ball and the ratio of the masses of the cover and the unbalanced mass. Typically, the static step-climbing capability is less than 0.25 x R. The possibility of rotation in all directions makes the control of the ball challenging. Ball oscillation during movement is difficult to handle and the control system requires powerful actuators to compensate the oscillations.

While the propulsion system is located inside the ball it can be hermetically sealed to provide the best possible shield for the interior parts. The spherical shape maximises the internal volume with respect to surface area and provides optimal strength against internal

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overpressure or under-pressure, which is an important feature for underwater and space applications. Ball-shaped autonomously moving vehicles have a long history, and recent studies have described a variety of applications in different environments, including marine, indoors, outdoors, zero-gravity and planetary exploration.

1.1 Illustration Credits

All the patent drawings have been adopted from the website of the United States Patent and Trademark Office; Patent Full-Text and Full-Page Image Databases (http://www.uspto.gov/patft/) accessed during the period May 21st 2007 – May 25th 2007 (USPTO, 2007).

2. Mechanical Construction

This chapter presents some technical structures for spherical robots that have adopted different mechanical constructions. The study is limited here to robots moving over terrain with an internal power and traction system. Floating and flying robots, as well as wheeled robots with spherical or semi-spherical wheels, are omitted. Wind-propelled balls and human-carrying marine vessels are included as curiosities. The robots can be classified according to the following properties:

Power source
- internal spring or rubber band
- internal electrical/combustion motor
- internal human muscle power
- external wind thrust

Control and degrees of freedom (dof.)
- forward rolling only
- fixed manually pre-set off-balance (curved path)
- cyclic, mechanically disturbed balance (oscillating path)
- shell texture-activated randomly changing direction
- reactive change of rolling direction
- reactive activation of steering function
- controlled in one direction
- controlled in two dofs.

Steering method
- tilting of rolling axis
- internal movable rolling axis
- inertia steering
- several mobile masses

Control method
- mechanical reaction
- electrical reaction

- radio control
- computer control

Internal traction method
- uniaxial
- biaxial
- single-wheel
- bicycle
- tricycle or four-wheel
- wheel-track
- multiple mobile masses
- deformation of shell

Engineers are often advised not to reinvent the wheel. However, a quick search of the U.S. Patent office database immediately reveals more than 50 patents related to the autonomous mobility of a ball-shaped object. These patents date from 1889 to 2005 and all comprise a mobile counterweight that is used to generate ball motion. The examples presented in this chapter show several of the properties presented in the list above.

2.1 Early 1-dof Spring-driven Models

The 'Toy' by J.L. Tate, patented in the U.S. in 1893 (U.S. Patent 508,558), presents a spherical vehicle that carries an internal 1-dof. counter-mass driven by an elastic spring. Fig. 1 (left) shows a counter-mass (C) carried by a central axis (B), an elastic spring (E), and a drum (D) that winds the spring when the ball is first manually rotated. Upon the release of the ball the spring would unwind from the drum and make the ball rotate in a forward direction. There is no other steering except bouncing off external obstacles, which, however, is often enough to allow the ball to continue its motion successfully. This basic principle was later presented in several other patents in which the internal mechanical arrangement or construction of the spring was modified. The most complex designs utilise clock-springs and are accompanied by gearboxes.

In 1906, B. Shorthouse patented a design that offered the possibility of manually adjusting the position of the internal counterweight in order to make the ball roll along a desired curved trajectory instead of a straight path (U.S. Patent 819,609). Fig. 1 (right) shows how the counter-mass and its support (g) can be placed at an angle to the rolling axis (f), which then remains in a tilted position relative to the horizontal.

Ever since then, patents have presented mechanisms to produce more or less irregular rolling paths for self-propelled balls. The toy shown in Fig. 2 dates back to 1909 and shows how the counter-mass (16) is made to move in a circular path inside the sphere by means of a gear (18). The internal motion of the counter-mass makes the rolling axle change its attitude continuously and the ball proceeds along a wobbly 'zig-zag' path, as described by the inventor (U.S. Patent 933,623).

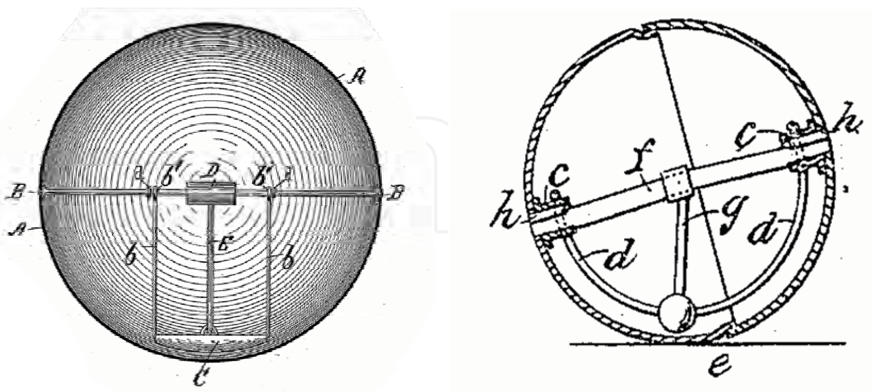

Fig. 1. (left) Toy by J.L. Tate (U.S. Patent 508,558); (right) Self-Propelling Device by B. Shorthouse (U.S. Patent 819,609)

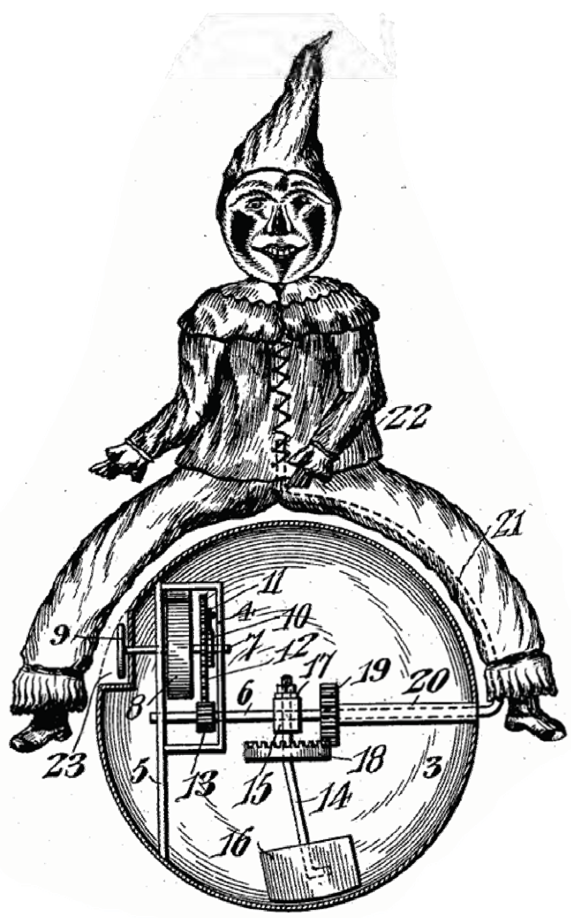

Fig. 2. Mechanical Toy by E.E. Cecil (U.S. Patent 933,623)

2.2 Man-carrying Models

Spherical vehicles to carry people were first developed for marine applications, such as that of W. Henry in 1889 (Fig. 3, left). This vehicle, floating in the water with its passenger, was balanced by the mass of the ballast and the weight of the passenger. The vehicle would move in a manner very similar to the toys described above, with a balanced mass inside and with its outer surface rolling. Steering would be achieved by tilting the axis of rotation by moving the passenger mass inside the vehicle, while the driving force comes from a hand-operated crank. (U.S. Patent 396,486) In 1941, J.E. Reilley patented a ball-shaped car (Fig. 3, right) (U.S. Patent 2,267,254).

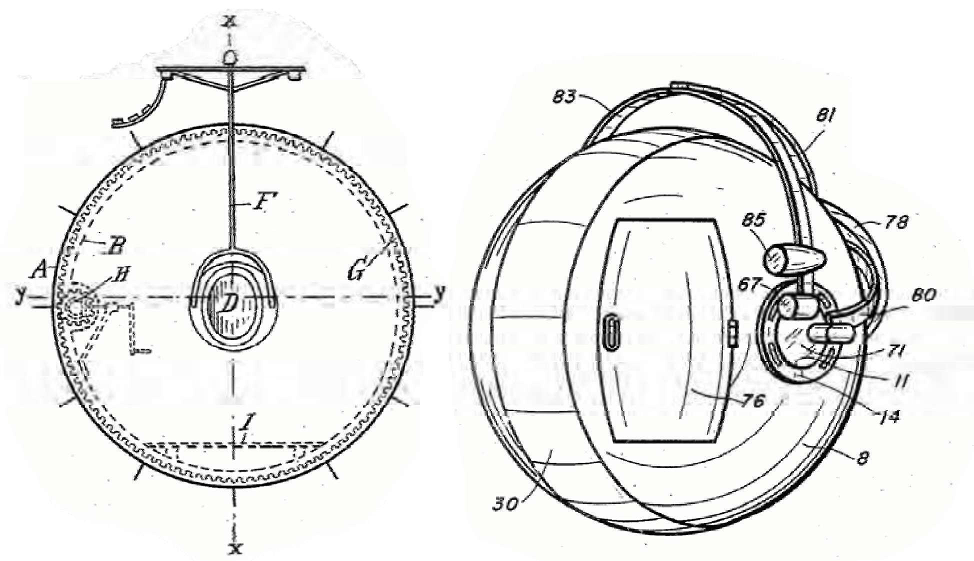

Fig. 3. (left) Marine vessel by W. Henry (U.S. Patent 396,486); (right) A spherical vehicle by J.E. Reilley (U.S. Patent 2,267,254)

In some cases, a person would enter a ball and operate it directly without any additional means, like a hamster inside a treadmill, as in Fig. 4 (left), dated 1958. (U.S. Patent 2,838,022) In 1969 S. E. Cloud patented a spherical structure that could accommodate a human being or even vehicles inside it (Fig. 4. right). The main objective was in inflatable/deflatable structure that could be easily stored and transported. He did not pay attention to the mobility of such a device. (U.S. Patent 3,428,015) In 1980 C. Maplethorpe and K. E. Kary patented a manned vehicle equipped with a seat and a pedal mechanism for use on land or water shown in Fig. 5 (left). (U.S. Patent 4,386,787) L. R. Clark Jr. and H. P. Greene Jr. patented yet another idea for a human-carrying spherical vehicle that could be steered by relocating the centre of gravity in a very similar manner to hang-gliders (Fig. 5 right). (U.S. Patent 4,501,569) In 1988 J. S. Sefton patented an open-mesh spherical structure for a man-carrying vehicle (Fig. 6 left). (U.S. Patent 4,729,446) Fig. 6 (right) presents a complex drive mechanism also intended for the transport of human beings. The design, patented by A. Ray in 1971, incorporates tracks composed of several wheels. Coordinated motion of the tracks and the wheels inside the spherical shell allow the ball’s rolling direction to be controlled.

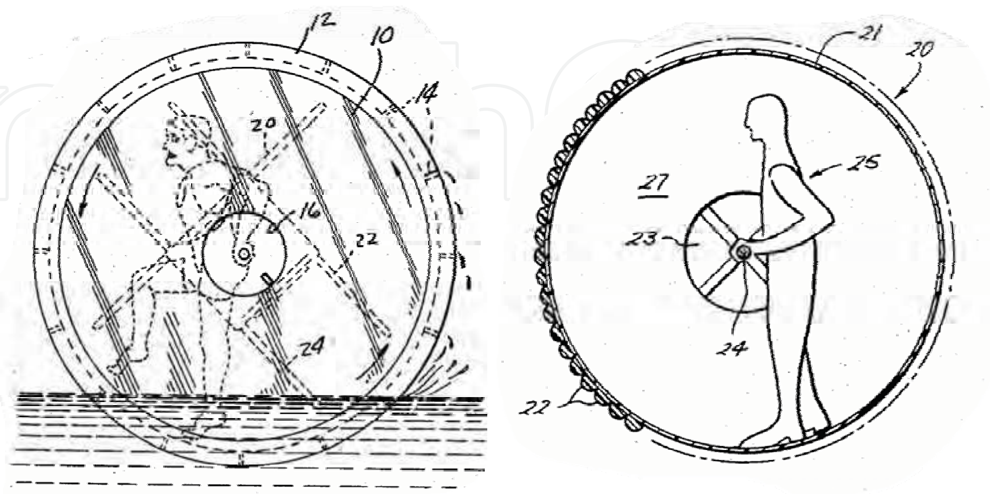

Fig. 4. (left) Spherical water craft by W. E. Wilson (U.S. Patent 2,838,022); (right) Spherical vehicle by S. E. Cloud (U.S. Patent 3,428,015)

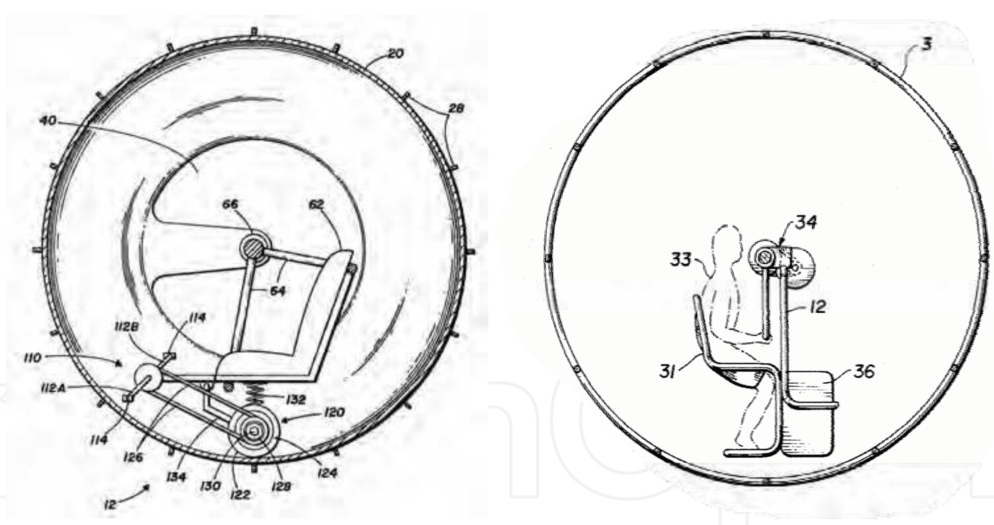

Fig. 5. (left) Spherical vehicle by C. Maplethorpe and K. E. Kary (U.S. Patent 4,386,787); (right) Yet another spherical vehicle by L. R. Clark Jr. and H. P. Greene Jr. (U.S. Patent 4,501,569)

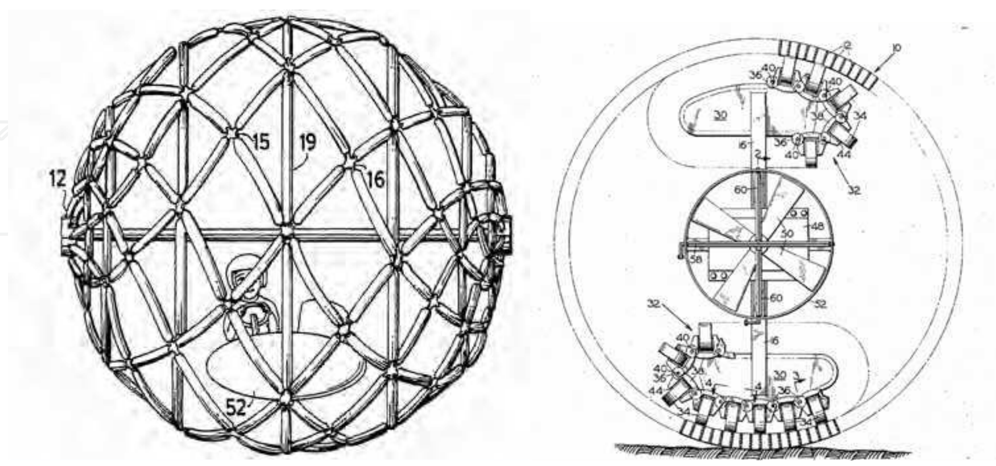

Fig. 6. (left) Mobile sphere by J. S. Sefton (U.S. Patent 4,729,446); (right) Spherical vehicle by A. Ray (U.S. Patent 3,746,117)

2.3 Electrical 1 and 2-dof. Models

A mechanical spring as a power source was displaced by a battery and an electric motor in two almost parallel patents; one by E. A. Glos (U.S. Patent 2,939,246, filed 1958) and another by J.M. Easterling (U.S. Patent 2,949,696, filed 1957). The design by Glos also included a gravity-operated switch that activated and de-activated the motor in desired positions. Easterling notes that upon contact with objects the motor is capable of driving the counter mass over the upper dead centre, which makes the ball autonomously reverse for a half-revolution. At the same time, as Easterling notes, the ball may also change its rolling direction. This property makes the ball move almost endlessly; this was referred to in several later patents and also modern-day toys such as the 'Squiggleball', 'Weaselball', and 'Robomaid', as well as the 'Thistle' concept of Helsinki University of Technology (to be presented later). Fig. 8 presents a 'Squiggleball' opened to show the battery compartment and electric motor and gears enclosed inside a plastic housing. The design is not very different from that of Easterling. One specific property of the 'Squiggleball' is a thick rubber band (not shown in the figure) that is placed along the rolling circumference on the outer surface. The thick band adds friction to the floor, but also makes the rolling axis tilt slightly to one side or the other. This makes the ball run along slightly curved paths and upon collision and autonomous reversing it always changes the rolling direction. Thus it can also get out of dead ends. Consequently, electric motors were introduced with several different mechanical solutions that were already at least partly familiar from earlier spring-driven inventions. Further development introduced shock and attitude sensing with mercury switches that would control the motor operation and rolling direction, as well as adding light and sound effects.

An active second freedom for a motorised ball was introduced by McKeehan in 1974 (U.S. Patent 3,798,835), as shown in Fig. 9 (left). This ball's structure is also different from the previous designs. Instead of the rolling axis extending across the complete ball, there is a support post that carries the rotating mass in the centre. Thus the rolling axis is perpendicular to the post, and the post itself rotates along with the shell so that its ends – or poles - are on the rolling circumference. Since the post is rotating in the middle of the ball the counter-mass must be divided into two halves, one on each side of the post. McKeehan's design shows two pendulums driven by a single motor. These provide one degree of freedom that also utilises an inertial switch to change the rolling direction in the event of a collision. Another dof. is provided by another motor that spins the post – and the rolling axis - around the longitudinal axis of the post. Should the post be in a vertical position while spinning, then the rolling axis would adopt a new rolling direction. Should the post be in a horizontal position spinning would cause the ball to roll sideways in the direction the actual rolling axis is pointing in. Any other position of the post and combined motion of the post and pendulum rolling would produce quite a complex motion. The post-driving motors can also be activated with an inertial switch in the event of a collision.

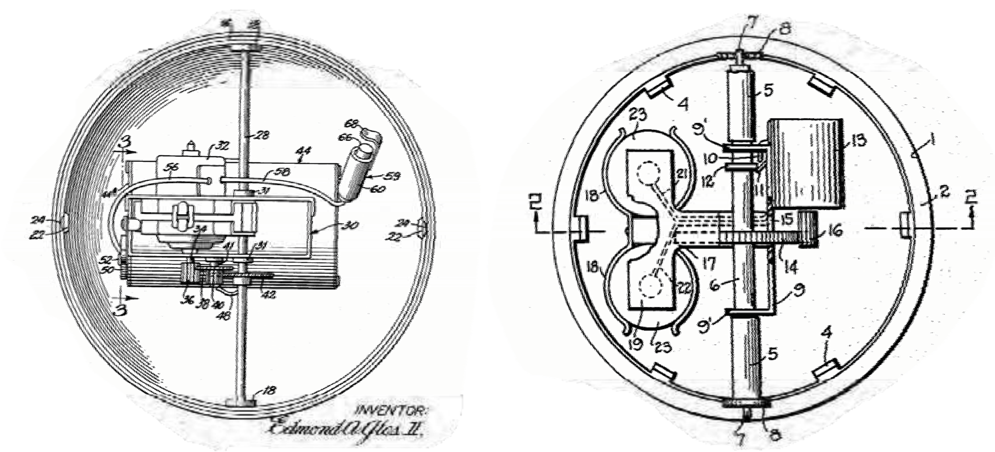

Fig. 7. (left) Toy ball by E. A. Glos (U.S. Patent 2,939,246); (right) Toy by J. M. Easterling in 1957 (U.S. Patent 2,949,696)

Fig. 8. 'Squiggleball' opened to show the interior parts (Image: TKK)

The spherical vehicle control system of L. R. Clark Jr. et al. in 1985 (U.S. Patent 4,501,569) resembles a motorised version of B. Shorthouse's Self-Propelling Device of 1906. In addition to two degrees of freedom, Clark's design also provides full controllability of both by means of two servo motors. One motor (No. 8 in Fig. 9 right) drives the ball forward and the other (15) moves the pendulum and adjusts the position of rolling axis. Continuous control is realised with radio control equipment

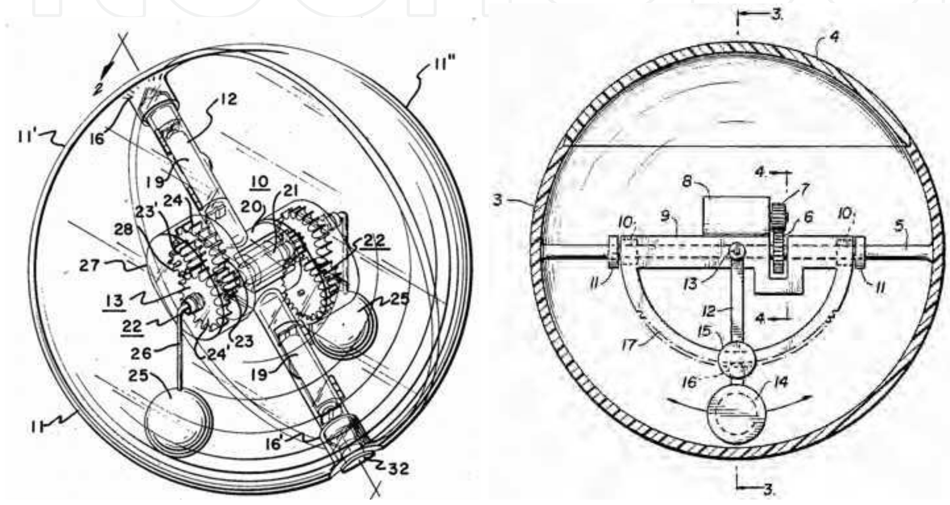

Fig. 9. (left) Motor driven ball toy by McKeehan (U.S. Patent 3,798,835); (right) Steerable ball toy by L. R. Clark Jr. et al. (U.S. Patent 4,501,569)

2.4 Hamster-wheel Models

The counterweight was usually constructed with a lever rotating around the ball's axis of rotation. Mobility was provided by generating torque directly to the lever. The amount of torque needed from the power system was directly proportional to the mass of the counterweight and length of the lever arm. During the development of the 'Thistle' at TKK it was soon realised that this approach sets high requirements for the motor torque and in fact the actual driving torque for the ball may be much less than the torque applied by the motor. In 1918, A. D. McFaul patented a spring-driven hamster-ball design (a derivative of a hamster treadmill), where the counterweight was moved by friction between the ball's inner surface and traction wheels mounted on the counterweight (Fig. 10). In this construction, the length of the lever arm no longer affects the required power-system torque (but the diameter of the friction wheels does), and similar mobility can be achieved with less internal torque. This is of great benefit in low-torque spring-driven toys and balls with a large diameter.

In McFaul's design a single axis with two traction wheels was supported from the ball rolling axis. C. E. Merril et al. placed a three-wheeled vehicle freely inside the ball in 1973 (U.S. Patent 3,722,134). Subsequently several patents placed a three- or four-wheeled vehicle inside the ball. Some vehicles are completely free inside, while others have some additional support from structures inside the ball; see Fig. 12. Advanced radio-controlled cars with full steerability placed inside also provide full steerability for the ball.

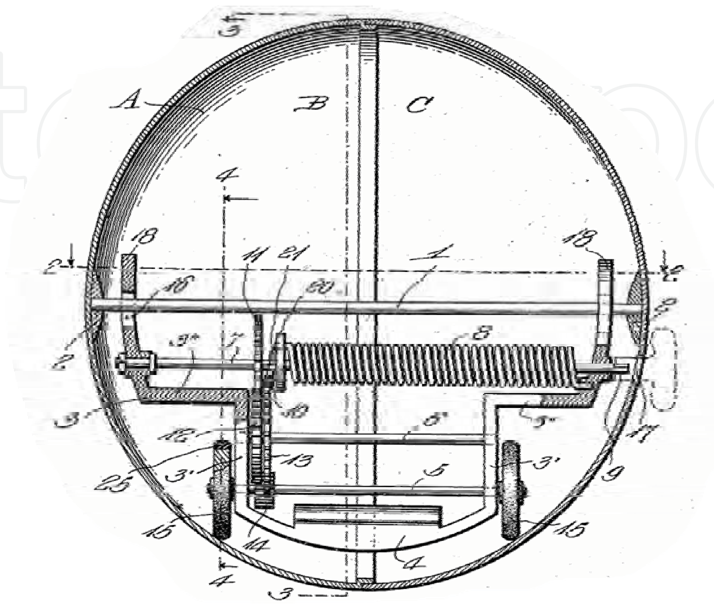

Fig. 10. Early hamster-ball by A.D. McFaul (U.S. Patent 1,263,262)

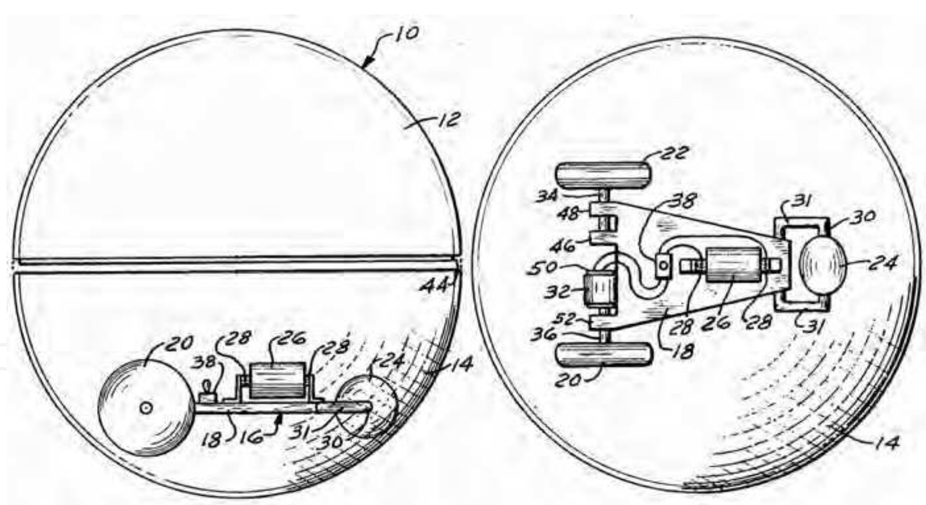

Fig. 11. A three-wheeler hamster-ball by C. E. Merril et al. (U.S. Patent 3,722,134)

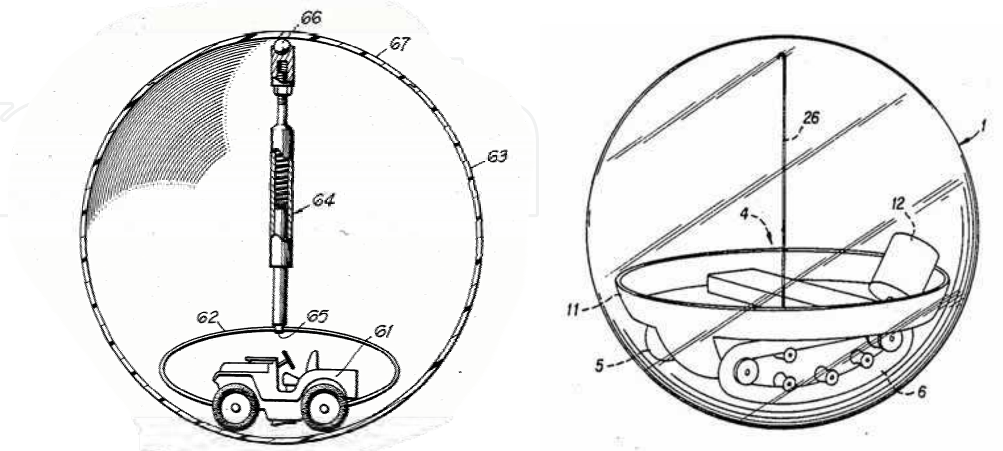

Fig. 12. (left) Mechanised toy ball by D. E. Robinson (U.S. Patent 4,601,675); (right) Radio controllable spherical toy by H.V. Sonesson (U.S. Patent 4,927,401)

2.5 Steerable Models

The above-mentioned radio controlled vehicles inside the ball provided full steerability. Apart from four–wheelers, radio-controlled single-/two-wheelers have also been presented, as shown in Fig. 13. This approach was also briefly adopted in the course of the development of the 'Rollo' robot at Helsinki University of Technology (to be presented later). Ku's design is a single wheel without a support post that would extend over the complete ball diameter. Instead, the wheel (525) gets support from a horizontal plane (2), which is supported on the inner surface of the ball with rollers (22). A servo motor (3) is used to freely control the wheel rolling direction. The driving and controllability of this kind of vehicle is very simple and straightforward, as has also been learned at TKK in the Rollo project.

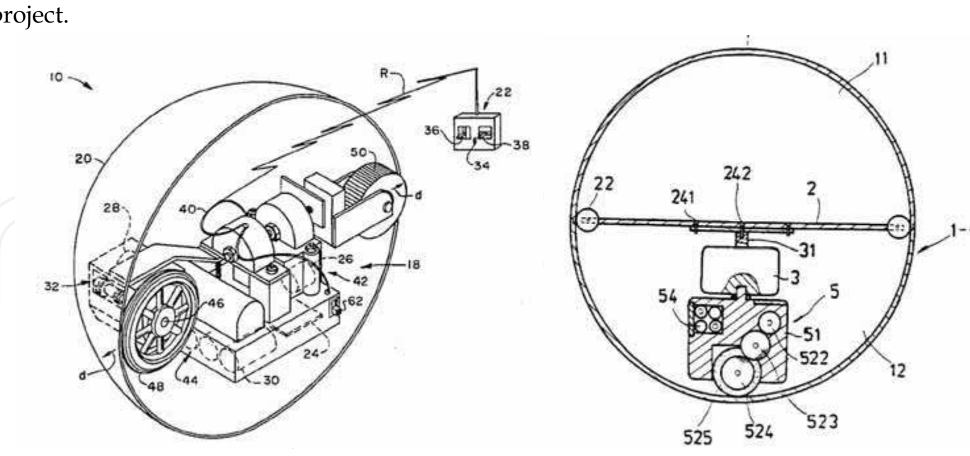

Fig. 13. (left) Radio-controlled vehicle within a sphere by J. E. Martin (U.S. Patent 4,541,814); (right) Spherical steering toy by W-M Ku (U.S. Patent 5,692,946)

In addition to the 'Vehicle inside the sphere' composition, steerability has also been introduced in older two-axis mechanisms, as already presented by Clark Jr., who patented a design with a controlled pendulum in 1985. A similar approach was also adopted by M. Kobayashi in 1985 (U.S. Patent 4,726,800) and by Michaud et al. in 2001 (U.S. Patent 6,227,933). Michaud also equipped the central rolling axis with an instrument platform for an on-board computer and electronics.

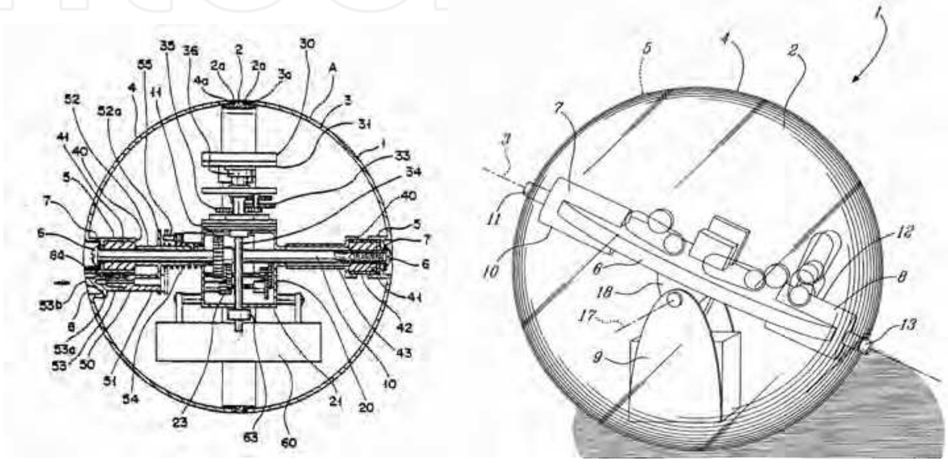

Fig. 14. (left) Radio-controllable toy vehicle Robot ball by M. Kobayashi (U.S. Patent 4,726,800); (right) Robot ball by F. Michaud et al. (U.S. Patent 6,227,933)

2.7 Rollo Robot

The Automation Technology Laboratory of Helsinki University of Technology developed ball-shaped robots to act as home assistants as early as in 1995. Rollo can act as a real mobile telephone, event reminder, and safety guard. The first-generation mechanics were similar to those of Martin, while the second generation was a radio-controlled four-wheeler slightly resembling that of Merril et al. To operate properly, both designs required a strong, accurate, and expensive cover. The early stages of the development of Rollo are described in Halme et al. (1996a), Halme et al. (1996b), and Wang & Halme (1996). The third-generation design is quite different from any of those presented before. It does carry a rolling axis extending through the ball, like most of the older designs. However, the rolling axis is not fixed to the ball surface, but it can rotate along the circumference on a rim gear; see Fig. 15. The rolling direction is selected by turning the rolling axis along the rim gear, which must then lie in the horizontal position. However, during rolling, the rim gear also rotates around the axis and there are only two positions where the robot can select the rolling direction (i.e. when the rim gear lies horizontally). In these two cases a similar motor rotation yields to opposite directions of rotation along the rim gear. The robot always has to advance a full number of half-revolutions, after which it needs to determine which direction along the rim gear is the correct one. The revolutions of the rim gear are counted by means of an inductive sensor. Continuous steering of the robot is also possible in theory, but in practice it would be a very demanding task.


Fig. 15. 2nd, 1st, and 3rd generations of the Rollo (Image: TKK)

The large instrument board along the rolling axis carries an on-board computer and advanced communication and interactivity tools, such as a camera, microphone, and a video link. Communication with the control station is achieved using a radio modem. The robot is equipped with a Phytec MiniModul-167 micro-controller board using a Siemens SAB C167 CR-LM micro-controller. The robot has sensors for temperature, pan, tilt, and heading of the inner mechanics and pulse encoders for motor rotation measurement. The local server transmits controls to the robot using commands that are kinematics-invariant (i.e., they use the work environment variables only). The commands include heading, speed, and running time/distance. Coded graphical signs mounted on the ceiling are utilised by means of the on-board camera to determine the absolute location of the robot when necessary. The system has an automatic localisation command, which causes the robot to stop, wait for some time to smooth out oscillations, turn the camera to the vertical position, find the visible beacons and automatically calculate the position, which is then returned to the control station.

The robot can be programmed as an autonomous device or it can be teleoperated via the internet. The user interface contains a virtual model of the remote environment where the video input and virtual models are overlaid to produce the augmented reality for robot guidance. Augmented reality provides an efficient medium for communication between a remote user and a local system. The user can navigate in the virtual model and subsequently use it as an operator interface.

As one application, an educational system has been developed for virtual laboratory exercises which university students can do over the internet. The overall experimentation system includes versatile possibilities to set up interactive laboratory exercises, from an elementary level to more advanced levels. Topics include mechatronics, robot kinematics and dynamics, localisation and navigation, augmented VR techniques, communication systems, and internet-based control of devices.

A second application, the Home Helper system, provides a mobile multimedia platform for communications between people at home and assistants working outside. The system is connected to various networked devices at home. The devices provide potential for remote security surveillance, teleoperation of the devices, and interactive assistance to people living at home.

2.7 Other Methods of Mobility

The most recent inventions have introduced novel solutions to alter the position of the ball's centre of gravity. One example is the Spherical Mobile Robot by R. Mukherjee, patented in 2001, which uses several separate weights that are moved with the aid of linear feed systems (U.S. Patent 6,289,263); see Fig. 14 (left). Abas Kangi has presented a spherical rover for the exploration of the planet Mars (Kangi, 2004). The shell of this rover consists of several small cells that can be inflated and deflated upon command. The deflation of certain cells around the support area in the lower part of the sphere causes instability and makes the ball rotate in a controlled manner. The rover would be used to search for water on the surface of Mars.

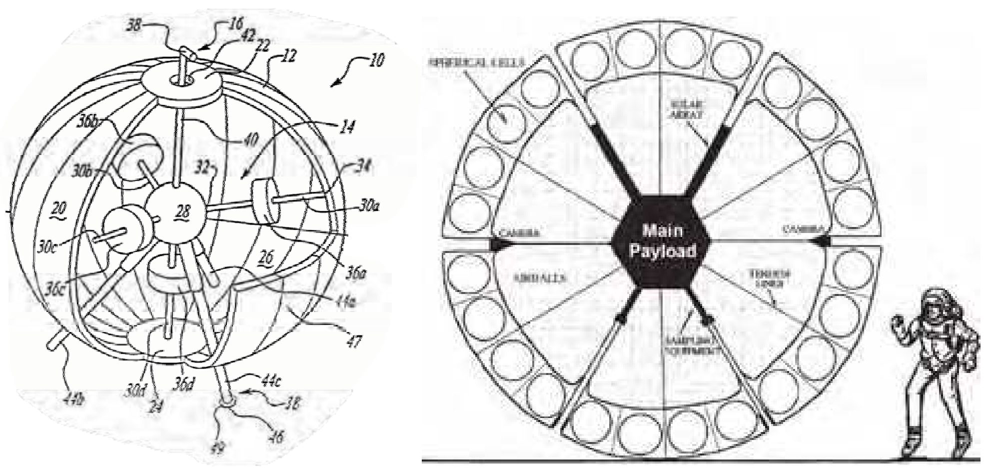

Fig. 14. (left) Spherical Mobile Robot by R. Mukherjee (U.S. Patent 6,289,263); (right) Wormsphere rover by A. Kangi (Kangi, 2004)

3. Wind-driven Balls

After Viking landers landed on the surface of Mars, confirming the presence of a CO_2 atmosphere and varying wind conditions, the potential for wind-driven exploration rovers on Mars, Titan, and Venus was recognised. The wind would provide a cheap and unlimited power source for long-range and lengthy exploration missions. Jacques Blamont of NASA Jet Propulsion Laboratory (JPL) and the University of Paris conceived the first documented wind-blown Mars ball in 1977. Such a ball, carrying some low-mass scientific instruments for measuring atmospheric conditions or suchlike, would be driven freely by the winds on the surface of Mars. (Hajos et al., 2005)

3.1 The Tumbleweed

The Tumbleweed rover derives its name from the dead sagebrush balls that blow across the deserts of the American southwest. A Tumbleweed 6 metres in diameter must have a mass of less than 20 kg for the thin Martian air to provide sufficient aerodynamic force for sustained motion though a Martian rock field. Travelling at speeds up to 10 m/s in the 20-m/s wind of a typical Martian afternoon, the ball is expected to climb 20° slopes with ease. Fig. 15 shows a 1.5-m small-scale model of the Tumbleweed by NASA/JPL under testing.

The motorised motion of such a ball equipped with a steerable pendulum was also studied earlier. However, the motorised concept was abandoned when it was realised that the mass increase did not justify the achievable driving torque and that relatively small rocks could easily trap the ball. (Hajos et al., 2005)
There are several organisations exploring Mars Tumbleweed concepts, including the NASA Jet Propulsion Laboratory (JPL), NASA Langley Research Center (LaRC), Texas Technical University (TTU), and the Swiss Federal Institute of Technology. The parties have adopted different approaches towards the construction of the ball shape and structure in order to maximise wind thrust force and cross-terrain mobility. (Antol et al., 2003)

Fig. 15. Tumbleweed concept under testing (Antol et al., 2003)

3.2 The Thistle

The Thistle is a large low-mass wind-propelled ball inspired by the Russian Thistle plant. A 1.3-metre ball represents a model of a larger 6-metre version that was proposed for operation on the surface of Mars for autonomous surface exploration. In order not to be fully dependent on occasional wind energy, the Thistle was equipped with a 2-dof. drive system that provided full steerability and motorised locomotion. (Ylikorpi et al., 2004)
This study, funded by the European Space Agency under the ARIADNA programme, focused on new innovations derived from nature to develop a novel system to provide a robust and efficient locomotion system to be used for exploring other planets. The Automation Technology Laboratory of Helsinki University of Technology explored the cross-terrain capabilities of both wind-driven rovers and unbalance-driven rovers and performed a comparison between those. As a consequence it is possible to identify different

operational scenarios. One scenario would be a large and light purely wind-driven ball, like the Tumbleweed. Another scenario would be a large but slightly heavier ball equipped with a limited capability to move with the aid of a motor. The cross-terrain capability of this rover with wind propulsion would be slightly more limited than that of the Tumbleweed, but the motor would allow the ball to get around the largest obstacles and could be used to orient the ball for scientific purposes. A third alternative would be completely motor-driven, much smaller but also much heavier than the other two. It would be able to carry a large amount of heavy instrumentation and the ball shape would protect it against the danger of tipping over. The problem of available energy would be the same as with conventional rovers. (Ylikorpi et al., 2006)

3.3 Mobility of Unbalanced Mass-driven Balls and Wind-driven Balls

As the ball hits an obstacle, it adopts a new point of contact. If we wish to surmount the obstacle the torque needed must be calculated according to this new point of contact between the ball and the object. As the contact point moves from the ground to the obstacle, the torque caused by the vertical ballast force or horizontal wind-load changes too.

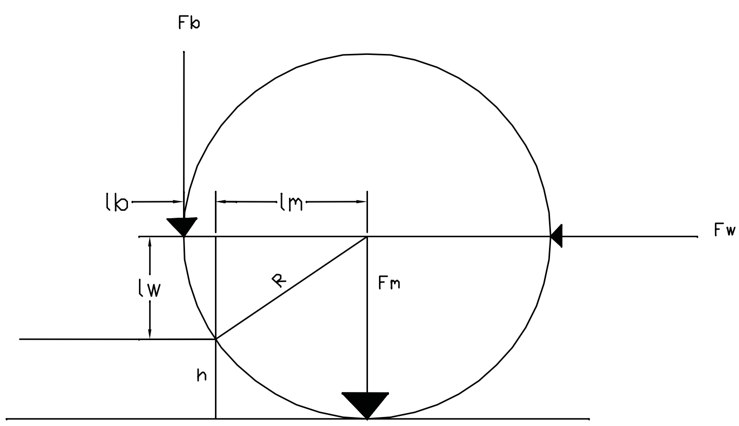

Fig. 16. Loads acting on a sphere surmounting an obstacle

Consider Fig. 16. The ball shell, with a radius R, has a weight F_m. F_b is the weight of the driving unbalanced mass and l_b is the distance between the mass and the contact point with the obstacle. L_m is the distance from the contact point to the ball shell centre of gravity. L_w is the vertical distance from the obstacle to the centre of the ball, and F_w is the thrust force from the wind. The figure assumes that the driving unbalanced mass is located at the outer surface of the ball shell. In practice this is not true; the mass will be located inside the ball, at a distance that is smaller than the ball radius R. The difference is taken into account in the calculations.

If the rolling ball meets an obstacle of height h, the mass load of the shell F_m generates a resistive torque T_m with a moment arm l_m.

$$T_m = F_m \cdot l_m \tag{1}$$

by geometry :

$$T_m = m \cdot g \cdot \sqrt{2 \cdot R \cdot h - h^2} \tag{2}$$

where :

g = gravity, m = ball mass

If wind load F_w is used for locomotion, the resulting torque T_w with a wind-load arm of moment l_w must overcome the resisting torque. We make an assumption that the wind load centre goes through the centre of the sphere.

$$Tw = F_w \cdot l_w \tag{3}$$

by geometry :

$$T_w = Fw \cdot (R - h) \tag{4}$$

The wind force F_w needed to surmount an obstacle can be calculated by setting $T_w = T_m$, from which follows:

$$F_w = m \cdot g \cdot \sqrt{\frac{2 \cdot R \cdot h - h^2}{(R - h)^2}} \tag{5}$$

Drag means a force on an object subjected to a fluid flow. Granger (1995) presents two formulae to define friction drag and pressure drag. From these the pressure drag is dominant for a blunt and smooth object, while friction drag increases as the surface gets rougher. In the case of the ball pressure drag can be used;

$$D_p = C_{Dp}(\tfrac{1}{2}\delta U^2 A_p) \tag{6}$$

where :

D_p = drag force
C_{Dp} = drag coefficient
δ = fluid density
U = flow velocity
A_p = cross – sectional area

The drag coefficient depends greatly on the geometry, surface properties, wind velocity, and air density. Heimendahl et al. (2004) and Hajos et al. (2005) present some experimental results for the C_D of different ball-shaped structures. It is reasonable to assume that a smooth ball on Mars would have a drag coefficient of 0.4, while with some added structural complexity it can be increased to 0.8. Making $C_D > 1$ would require the accurate design and

testing of a structure consisting of plate-like structures. The air density is 0.02 kg/m^3 for Mars and 1.29 kg/m^3 for the air on Earth.
The formulae presented now make it possible to calculate the force generated on the ball by the prevailing wind, or the other way around; the wind velocity needed to surmount a defined obstacle. The results will be presented and compared to unbalanced drive later in this chapter.
Study Fig. 16 again; if using unbalanced ballast mass for locomotion, the sphere mass must be divided into two portions: an evenly distributed structural mass acting through the shell centre and resulting in resistive torque, and the ballast mass causing F_b and having a moment of arm l_b. The figure shows the ballast mass to be located exactly on the outer surface, i.e. $l_b+l_m = R$. In reality this would not be the case. The length of moment arm l_b depends on the mechanical structure and ball size. For small spheres the ratio $(l_b+l_m)/R$ could be roughly 0.5, while the ratio approaches 1 as the sphere diameter increases. For a 6-m ball $(l_b+l_m)/R$ could have an estimated value of 2 m/3 m or 0.66. In the following calculations the value 0.66 is used for $(l_b+l_m)/R$. Now the resulting driving torque T_b can be calculated;

$$T_b = F_b * (0.66 * R - l_m) \tag{7}$$

Fig. 17 collects the calculation results for a given obstacle size with total ball mass, wind velocity, and driving unbalanced ballast mass as variables. It shows how a 6-m and 80-kg Thistle could be driven over 40-cm obstacles by a 30-m/s Martian wind. The same weight and size ball with an internal 60-kg motorised ballast mass would also surmount the same obstacle using the motor for propulsion. Hence in this scenario both methods of mobility could be used. However, the wind propulsion would be effective only during the strongest Martian storms. The mass reserved for the 6-m spherical shell remains 20 kg.
Reducing the total mass accommodates more modest wind speeds but also requires a lighter shell structure. Mass reserved for the shell structure is quite low and so inflatable structures are very interesting.
Similar comparison can be done with differing obstacle sizes. Mobility requirement can be set different for different locomotion methods. In order to utilise Martian wind more effectively total system mass can be reduced. As a consequence the ball would surmount the obstacles with less wind, or surmount even larger obstacles when driven by the wind. Motor drive would then have smaller unbalanced mass and motor-driven mobility would be reduced. The motor would be then used merely to get around the obstacles instead of getting over them.

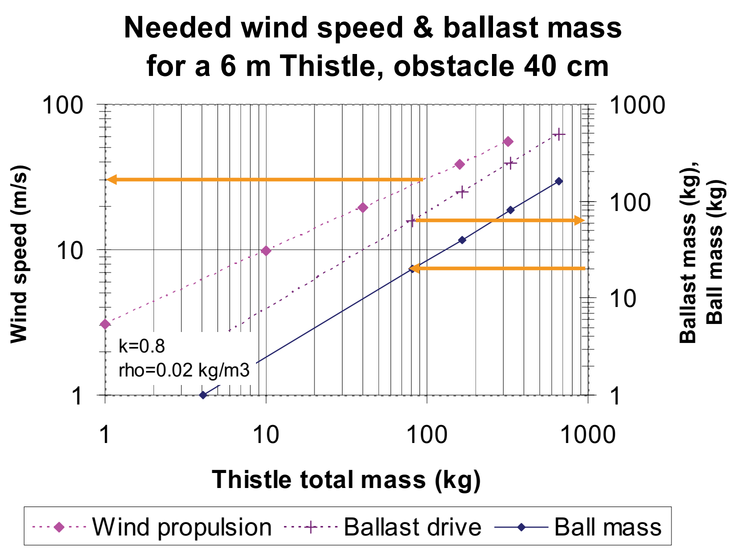

Fig. 17. Comparison of wind and ballast propulsion for the 6-m Thistle (Ylikorpi, 2005)

4. Thistle Prototype

Fig. 18 presents a small-scale prototype of the Thistle ball built at the TKK Automation Technology laboratory. Without internal driving mechanisms and assuming a low drag coefficient as a consequence of the open structure of the ball, a terrestrial 5-m/s wind is supposed to propel the roughly 4-kg and 1.3-m prototype shell over obstacles 10 cm high. When actively driven by a motorised 5-kg ballast mass, the prototype rolls over 4-cm obstacles. Driving tests with the Thistle show that locomotion is quite clumsy and somewhat chaotic. Its structural flexibility and sectional circumference make the ball advance in short bursts. If a tilt angle is introduced by means of the steering system, the Thistle follows a spiral-like path while rolling in which the radius of curvature decreases towards the end of the motion. The torque margin of the drive system allows the ballast mass to be rotated a complete revolution around the axis of rotation. This means that when the Thistle stops at an obstacle, the ballast mass finally travels over the upper dead centre and, in consequence, the Thistle autonomously backs off by half revolutions. Because of its instability the Thistle also simultaneously turns slightly. This behaviour enables the Thistle to circumvent obstacles autonomously and without any active steering. The Thistle was also tested on a snow bed during Finnish winter conditions. The soft structure of the snow effectively damped out the structural vibrations of the Thistle, while driving and steering were clearly easier and overall behaviour was more predictable. Fig. 18 (left) presents the driving and steering mechanism of the Thistle. The battery and two motors are mounted on a pivoted lever that hangs from bearings on the central rolling axis. The drive motor rotates the lever via a tooth belt and a large sprocket wheel. The tilting motor adjusts the angle of the lever with the aid of a lead screw. The motors are controlled with a radio control system and motor controllers familiar from toy cars. (Ylikorpi et al., 2004)

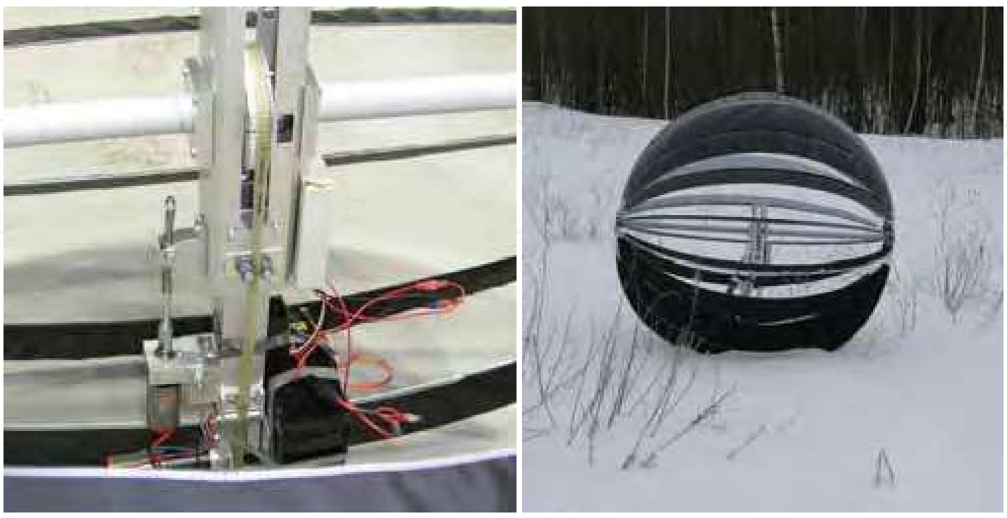

Fig. 18. (left) Thistle mechanism; (right), 1.3-m Thistle rolling on snow bed (TKK)

5. Other Recent and Related Development

In addition to the robots presented, there are several other similar devices, mostly intended for demonstration or simply for toys. The 1.5-metre-diameter scale models of the Tumbleweed Rover (Matthews, 2003) and Windball (Heimendahl et al., 2004) are intended for Mars exploration. Both of them are purely wind-driven, the only mobility-related actuation being re-shaping the structure by inflation/deflation (Tumbleweed) or with the aid of shape memory alloys (Windball). On Mars, 6-metre versions of these models would be used to carry out scientific tasks such as surface mapping and atmospheric measurements. The 15-cm Roball (Michaud & Caron, 2001) performed an important role in a study of interaction between the robot and small babies. It is anticipated that the 15-cm Cyclops (Chemel et al., 1999) and 50-cm Rotundus will be used to inspect and guard industrial plants (Knight, 2005). The Sphericle is used as an educational tool for learning the dynamics and control of a ball-shaped robot (Bicchi et al., 1997).

6. Control of Ball-shaped Robots

This chapter has shown a large variety of mechanical constructions of ball-shaped robots. As the operating principles of different models are different, so the kinematic and dynamic equations describing ball behaviour are different. Thus control algorithms for different robots become different. The possibility of rotation in all directions makes the control of the ball challenging. In addition, a hard-surfaced unbalanced ball on a smooth floor behaves like a pendulum; any change in motor torque or disturbance from its surroundings easily generates oscillation that attenuates very slowly. Oscillation around the rolling axis is controlled in TKK's Rollo by means of a closed-loop system that controls the drive motor torque. The control loop is equipped with attitude sensors and gyroscopes that measure the forward and backward motion of the payload mass. Controlling the sideways oscillation is a more difficult task, since we do not posses any actuators in this direction. So far, no active instrumentation has been included for this, but, in future, passive dampers or an active closed-loop controlled movable counter-weight or pendulum may be considered. The kinematics and control of the early versions of Rollo are discussed in Halme et al. (1996a). Apart from the development of Rollo at TKK, Bicchi et al. (1997) also describe the kinematics, dynamics, and motion planning of the single-wheel ball robot Sphericle. Laplante (2004) discusses the kinematics and dynamics of ball robots in great detail and develops a control scheme to steer a pendulum-driven Roball along curved paths. Regarding the same ball robot, Michaud & Caron (2001) write more about higher-level behaviours and interaction with people.

7. Conclusion

Throughout history, ball-shaped toys have been quite popular and they still exist. Developments in computer technology, wireless data transfer, and digital cameras have given them many advanced operational capabilities. Autonomous ball-shaped robots are being introduced back into modern homes, this time not only as toys, but also as serving and guarding robots. Future work in this field will concentrate on analysing and developing the dynamics and control of the ball, as well as on applications and interaction with the environment and people.
The utilisation of large wind-propelled balls for Mars exploration has been widely studied in many separate institutions. The main advantages are large size, low mass, and autonomous mobility, accompanied by the disadvantage of limited steerability. Only the future will tell if the current expensive Mars exploration missions will be followed by low-cost autonomous missions utilising the Windball, Tumbleweed, or Thistle carrying instruments in the search for life on Mars or other extraterrestrial bodies.

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Climbing and Walking Robots: towards New Applications
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With the advancement of technology, new exciting approaches enable us to render mobile robotic systems more versatile, robust and cost-efficient. Some researchers combine climbing and walking techniques with a modular approach, a reconfigurable approach, or a swarm approach to realize novel prototypes as flexible mobile robotic platforms featuring all necessary locomotion capabilities. The purpose of this book is to provide an overview of the latest wide-range achievements in climbing and walking robotic technology to researchers, scientists, and engineers throughout the world. Different aspects including control simulation, locomotion realization, methodology, and system integration are presented from the scientific and from the technical point of view. This book consists of two main parts, one dealing with walking robots, the second with climbing robots. The content is also grouped by theoretical research and applicative realization. Every chapter offers a considerable amount of interesting and useful information.

InTech Europe
University Campus STeP Ri
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51000 Rijeka, Croatia
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