

A SINGLE-WHEEL, GYROSCOPICALLY STABILIZED ROBOT

H. Benjamin Brown, Jr. and Yangsheng Xu
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213, USA

Abstract

We are developing a novel concept for mobility, and studying fundamental research issues on dynamics and control of the mobile robot. The robot, called Gyrover, is a single-wheel vehicle with an internal gyroscope that provides mechanical stabilization and steering capability. This configuration conveys significant advantages over multi-wheel, statically stable vehicles, including good dynamic stability and insensitivity to attitude disturbances; high maneuverability; low rolling resistance; ability to recover from falls; and amphibious capability. In this paper we present the design, analysis and implementation of the robot, as well as the associated research issues and potential applications.

1 Introduction

Land locomotion can be broadly characterized as quasi-static or dynamic. Quasi-static equilibrium implies that inertial (acceleration-related) effects are small enough to ignore. That is, motions are slow enough that static equilibrium can be assumed. Stability of quasi-static systems depends on keeping the gravity vector through the center of mass within the vehicle's polygon of support determined by the ground-contact points of its wheels or feet. Energy input is utilized predominantly in reacting against static forces. Such systems typically have relatively rigid members, and can be controlled on the basis of kinematic considerations.

In dynamic locomotion, inertial forces are significant with respect to gravitational forces. Dynamic effects gain relative importance when speed is high, gravity is weak and dynamic disturbances (e.g. rough terrain) are high. Significant energy input is required in controlling system momentum, and in some cases, in controlling elastic energy storage in the system. As performance limits of mobile robots are pushed, dynamic effects will increasingly come into play. Further,

robotic systems that behave dynamically may be able to exploit momentum to enhance mobility, as is clearly demonstrated by numerous human-controlled systems: gymnasts, dancers and other athletes; stunt bicycles and motorcycles; motorcycles on rough terrain; cars that vault obstacles from ramps; etc.

It is paradoxical that those factors which produce static stability may contradict dynamic stability. For example, a four-wheel vehicle that is very low and wide has a broad polygon of support, is very stable statically, and can tolerate large slopes without roll-over. However, when this vehicle passes over bumps, dynamic disturbances at the wheels generate large torques, tending to upset the vehicle about the roll, pitch and yaw axes. In effect, the large polygon of support required for static stability provides a leverage mechanism for the generation of dynamic torque disturbances. Further, the support points must comply with the surface, statically as well as dynamically, by control of support points (e.g. suspension) and/or by vehicle attitude changes. Sophisticated vehicle suspensions have been developed to minimize dynamic disturbances, but passive-spring suspensions decrease static stability by allowing the center of mass to move toward the outside of the support polygon. Active suspensions may overcome this problem, but require additional complexity and energy expenditure.

As a second example, consider a bicycle or motorcycle which has two wheels in the fore-aft (tandem) configuration. Such a vehicle is statically unstable in the roll direction, but achieves dynamic stability at moderate speed through appropriate steering geometry and gyroscopic action of the steered front wheel. Steering stability generally increases with speed due to gyroscopic effects. Dynamic forces at the wheel-ground contact point act on or near the vehicle center (sagittal) plane, and thus produce minimal roll disturbances. Additionally, the bicycle can remain upright when traveling on side slopes. Thus, sacrificing *static* roll stability enhances the *dynamic* roll stability and permits the vehicle to automatically adjust to side

slopes.

As a logical extension of this argument, consider a wheel rolling down an incline. Under the influence of gravity, gyroscopic action causes the wheel to precess (the axis of wheel rotation turns) about the vertical axis—rather than simply falling sideways as it does when not rolling—and the wheel steers in the direction it is leaning. The resulting curved path of motion of the wheel on the ground produces radial (“centrifugal”) forces at the wheel-ground contact point, tending to right the wheel. Dynamic disturbances due to surface irregularities act through or near the wheel’s center of mass, producing minimal torques in roll, pitch and yaw. The angular momentum of the wheel, in addition to providing the natural gyroscopic steering mechanism, tends to stabilize the wheel with respect to roll and yaw. In terms of attitude control, the wheel is relatively insensitive to fore/aft and side slopes. The result is a highly stable rolling motion with minimal attitude disturbances and tolerance to fore/aft and vertical disturbances. One can readily observe this behavior by rolling an automobile tire down a bumpy hillside.

There are precedents for single-wheel-like vehicles. In 1869, R.C. Hemmings [8] patented a “Velocipede,” a large wheel encircling the rider, powered by hand cranks. Palmer [19] describes several single-wheel vehicles with an operator riding inside. A 1935 publication [16] describes the *Gyroauto*, which carried the riders between a pair of large, side-by-side wheels, and was claimed capable of a speed of 116 mph (187 kph). Also in [16] is a description of the *Dyno-Wheel*, a concept having a bus-like chassis straddling a huge central wheel. The relatively large diameter of a single-wheel vehicle enhances its obstacle-crossing ability, smoothness of motion and rolling efficiency [3]. Further, a single-track vehicle can more easily find obstacle-free paths on the ground, and its narrow profile can improve maneuverability. However, problems with steering, low-speed stability and aerodynamics, have kept such vehicles from becoming commonplace.

2 Background

Traditionally, researchers have viewed mobile robots largely as quasi-static devices. Numerous robots with four, six or more wheels have been developed to maximize mobility on rough terrain. (See, for example, [4] [6] [10] [11] [12].) Likewise, legged robots, which may have potentially greater mobility, have been built and demonstrated, as described, for

example in [14], [25]. Generally these robots have featured low center-of-mass placement and broad base of support, along with intelligent control designed to keep the center-of-mass gravity vector within the support polygon (e.g. monitoring of slopes, coordination of legs). Many designs have attempted to maximize mobility with large wheels or legs, traction-enhancing tires or feet, multi-wheel drive, large body/ground clearance, articulated body configurations, etc. These robots were often limited by motion-planning constraints and hence designed for low-speed operation, typically 1 kph or less. Dynamic factors have little influence on such systems, and consequently, have been largely ignored.

A number of researchers have explored the possibilities of utilizing dynamic behavior in various robot linkages, legged locomotors and other dynamic systems. Examples include Fukuda’s *Brachiator* [21] and Spong’s robot acrobat [23], both of which utilized dynamic swinging motions. Koditschek [5] and Atkeson [22] and their students studied the dynamics of juggling. McGeer built a robot that walked down slopes without additional power or control input, utilizing the periodic swinging motion of the legs [15]. Raibert’s group built a series of dynamically balanced, hopping and running robots that jumped obstacles, climbed steps [9], and performed flips. Arai [1] and Xu’s group [2] developed underactuated robot systems by using the dynamic coupling between the passive and active joints. Dynamic motion in these systems allowed the emergence of behaviors that would not have been possible quasi-statically.

In parallel with the work on linkage dynamics, other researchers have focused on the dynamics and balance of wheeled robots. Vos [24] developed a self-contained unicycle that mimicked the behavior of a human cyclist in maintaining roll and pitch stability. Koshiyama and Yamafuji [13] developed a statically stable, single-wheel robot with internal mechanism that could move fore and aft and turn in place; their work emphasized control of the (non-inverted) pendulum carried on the wheel, utilizing momentum transfer in changing direction.

Traditional research on mobile robotics has placed heavy emphasis on perception, modeling of the environment and path planning. Consequently, vehicles have been designed to be compatible with these planning limitations, and the need for high speed has not been evident. Ultimately, as sensing and computation capabilities improve, robots will be limited less by planning and more by dynamic factors. Wheeled robots, capable of dynamic behavior – i.e. high-speed

motion on rough terrain – and of exploiting vehicle dynamics for mobility, represent an exciting and largely unexplored area.

The purpose of our present research is to exploit the natural steering behavior and stability of the rolling wheel in the development of a highly dynamic, single-wheel, mobile robot. We have built working models of such a vehicle, and demonstrated some of the potential capabilities.

3 Gyrover Concept

Gyrover is a novel, single-wheel, gyroscopically stabilized robot concept. The behavior of *Gyrover* is based on the principle of gyroscopic precession, as exhibited in the stability of a rolling wheel. (See Figure 1.) Because of its angular momentum, a spinning wheel tends to precess (its axis rotates) at right angles to an applied torque, according to the fundamental equation for gyroscopic precession:

$$T = J \times \omega \times \Omega \quad (1)$$

where ω is the wheel spin angular speed; Ω is the wheel precession rate, normal to spin axis; J is the wheel polar moment of inertia about spin axis; T is the applied torque, normal to spin and precession axes.

Thus, if a torque (T) is applied about the wheel's longitudinal axis as shown, rather than falling over, the wheel precesses about the vertical axis, causing it to follow a curved path. Therefore, if the wheel leans to one side, the gravitationally induced torque causes it to precess so that it turns in the direction it is leaning, tending to stabilize its upright position.

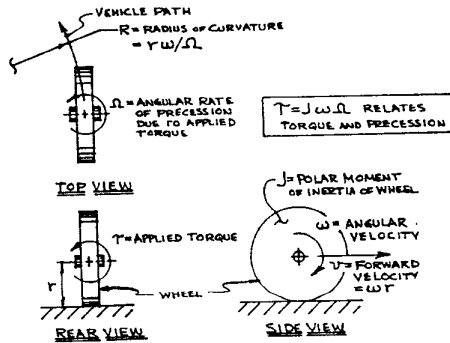


Figure 1: The fundamentals of gyroscopic precession, which stabilizes a rolling wheel, and is utilized for directional control of *Gyrover*.

Gyrover supplements this basic concept with the addition of an internal gyroscope nominally aligned

with the wheel and spinning in the direction of forward motion. (See Figure 2.) The gyro's angular momentum produces lateral stability when the wheel is stopped or moving slowly. A tilt mechanism enables tilting the gyro's axis about the fore/aft (roll) axis with respect to the wheel. Because the gyro acts as an inertial reference in attitude, the immediate effect of the tilt action is to cause the wheel to lean left or right, which in turn causes the wheel to steer (precess) in the direction of leaning. Torques generated by a drive motor—reacting against the internal mechanism which hangs as a *pendulum* from the wheel's axle—produce thrust for acceleration and braking.

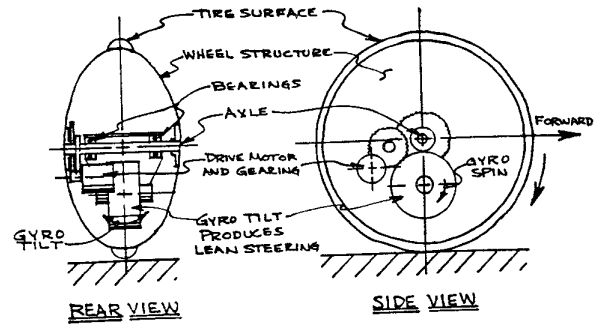


Figure 2: The basic *Gyrover* configuration, comprising a wheel: gyro and tilt mechanism for stability and steering; and drive mechanism.

In addition to those cited above, *Gyrover* has a number of potential advantages over multi-wheeled vehicles:

1. The entire system can be enclosed within the wheel to provide mechanical and environmental protection for equipment and mechanisms.
2. *Gyrover* is resistant to getting stuck on obstacles because it has no body to hang up, no exposed appendages, and the entire exposed surface is *live* (driven).
3. The tiltable flywheel can be used to right the vehicle from its statically stable, rest position (on its side). The wheel has no "backside" on which to get stuck.
4. *Gyrover* can turn in place by simply leaning and precessing in the desired direction, with no special steering mechanism, enhancing maneuverability.
5. Single-point contact with the ground eliminates the need to accommodate uneven surfaces and simplifies control.

6. Full drive traction is available because all the weight is on the single drive wheel.
7. A large pneumatic tire may have very low ground-contact pressure, resulting in minimal disturbance to the surface and minimum rolling resistance. The tire may be suitable for traveling on soft soils, sand, snow or ice; riding over brush or other vegetation; or, with adequate buoyancy, for traveling on water.

Potential applications for Gyrover are numerous. Because it can travel on both land and water, it may find amphibious use on beaches or swampy areas, for general transportation, exploration, rescue or recreation. Similarly, with appropriate tread, it should travel well over soft snow with good traction and minimal rolling resistance. As a surveillance robot, Gyrover could use its slim profile to pass through doorways and narrow passages, and its ability to turn in place to maneuver in tight quarters. Another potential application is as a high-speed lunar vehicle, where the absence of aerodynamic disturbances and low gravity would permit efficient, high-speed mobility. As the development progresses, we anticipate that other, more specific uses will become evident.

4 Dynamics and Control

Gyrover provides an interesting and challenging basis for development of dynamic models and controls. While apparently tractable, the system contains the complexity of two rotational masses whose axes of rotation are, in general, misaligned in 3-dimensional space. There are significant coupling effects between the steering (gyro-tilt) and propulsion (pendulum swinging). Environmental disturbances, from surface friction, vertical bumps, lateral forces, etc., further complicate the behavior.

We have studied the dynamics of the vehicle and established a first-order dynamic model to determine the relationship between the lean angle and the gyro tilt angle; and between the curvature of the path along the ground, and the wheel speed and lean angle. Based on small angles and other simplifying assumptions, the lean angle is related to the gyro-tilt angle by

$$\begin{aligned} \sin\phi_w &= \frac{\sin\phi_g \times H_g}{H_w} \\ &= \frac{\sin\phi_g \times H_g \times r_w}{J_w \times v} \end{aligned} \quad (2)$$

where ϕ_w is the wheel-lean angle; ϕ_g is the gyro-tilt angle (with respect to horizontal); H_w is the wheel an-

gular momentum; H_g is the gyro angular momentum; J_w is the wheel polar moment of inertia; r_w is wheel radius; v is the forward speed.

The normalized lateral acceleration of the wheel is related to the speed and path curvature by

$$v^2/(Rg) = \frac{\tan\phi_w}{1 + \frac{J_w}{mar_w} + \frac{H_g}{mav}} \quad (3)$$

where R is radius of curvature of path; g is gravitational acceleration; m is vehicle mass; a is height of center of mass from wheel periphery.

As wheel speed increases, gyro tilt *effort* needed for turning increases rapidly, due to both the increased angular momentum of the wheel and the radial acceleration ("centrifugal force") tending to right the wheel. Thus, we have an important design tradeoff: for good low-speed/static stability, we would like a gyro with large angular momentum: but for responsiveness, especially at high speed, we want a small total angular momentum (gyro plus wheel). So, for optimal performance, we may want a gyro whose angular momentum can be varied (e.g. by varying flywheel speed), or possibly a pair of gyros that can be tilted relative to each other to produce the desired angular momentum vector.

Forward/rearward thrust is needed for acceleration/deceleration of the vehicle, and for hill climbing/descending. Thrust is produced by pitch torques applied to the wheel by a drive motor reacting against the suspended internal mass (pendulum). The maximum torque occurs when the pendulum is horizontal: for this condition, the slope-climbing ability is given by

$$\sin\theta = \frac{m_p r_p}{mr_w} \quad (4)$$

where θ is slope angle; m_p is pendulum mass; r_p is pendulum center-of-mass radius; m is vehicle mass; r_w is wheel radius.

Rough calculations for typical vehicle parameters suggest such thrust will be limited to perhaps 25% of the vehicle weight, which would permit quasi-static climbing a grade of 25%, and would allow reasonable acceleration and braking capabilities. Steeper grades can be climbed dynamically, using the vehicle's kinetic energy.

5 Design and Implementation

Gyrover has grown from an improbable yet intriguing concept for mobility, to the reality of working vehicles. We have studied the feasibility through

basic analysis and simple experiments, and designed and built two, radio-controlled (RC) working models. These have proven the concept workable, and have verified many of the expected advantages.

Given a basic understanding of the gyroscopic principle and wheel dynamic stability, our first task was to find a mechanism for steering the wheel along a desired path. Turning (steering) of the wheel is the result of gyroscopic precession about the yaw axis, caused by roll torques as explained above. We considered two mechanisms for producing this torque: lateral shifting of weight within the vehicle; and leaning of the wheel. With regard to the first approach, the need to provide adequate internal space for shifting large masses within the vehicle is a significant drawback. Moving the mass outside the wheel's envelope is unappealing because of the effective broadening of the vehicle and potential for the movable mass to contact the ground or other obstacles. Allowing the entire wheel to lean employs the complete weight of the wheel to shift laterally – not just a relatively small, movable mass – to generate the needed roll torque. Leaning of the wheel, can be effected by the use of internal reaction wheels or masses, but these tend to acquire kinetic energy, become velocity-saturated, and generate angular momentum that can corrupt vehicle behavior. Another way is to react against an internal gyroscope as described above; this mechanism has been implemented and operated successfully.

Several alternative vehicle configurations were considered. A spherical shape, which can be statically stable, does not exhibit the natural steering behavior resulting from the interaction of the gravitational (overturning) torque and the gyroscopic effect. In fact, a narrow tire-contact area is desirable for steering responsiveness (dependent on the gravitational torque for a given lean angle). Two wheels, side-by-side provide static stability, but are sensitive to roll disturbances, do not exhibit the same natural steering behavior, and will not roll stably on two wheels above a critical speed. (Observe the behavior of a short cylinder, such as a roll of tape, rolled along the floor.) Outboard wheels, either on the sides or front/back, were considered for static stability and steering effects, as well as acceleration and braking enhancement; but in addition to mechanical complexity, these defeat the basic elegance and control simplicity of the concept. Actually, the robot has the potential to be statically stable to provide a solid base of support for sensors, instruments or small manipulators, etc., simply by resting on its side. The present concept, totally enclosed in the single wheel, provides a simple, reliable, rugged

vehicle.

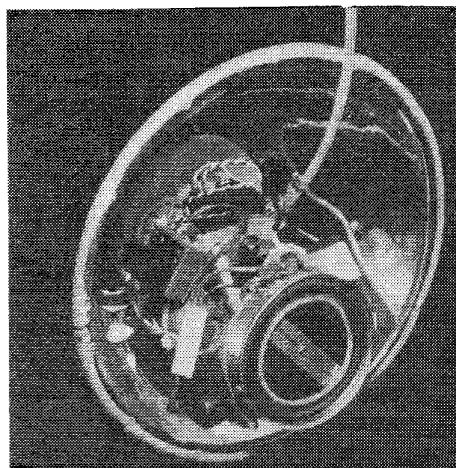


Figure 3: Photograph of Gyrover I. Gyro is in foreground, radio antenna extending upward.

Experimental work to date includes several simple experiments to verify the stability and steering principle, and two working vehicles. The first vehicle, Gyrover I, shown in Figure 3, was assembled from available RC model airplane/car components, and quickly confirmed the concept. The vehicle has a diameter of 29 cm and mass of 2.0 kg. It can be easily driven and steered by remote control; has good high-speed stability on smooth or rough terrain; and can be kept standing in place. This vehicle has traveled at over 10 kph, negotiated relatively rough terrain (a small gravel pile), and traversed a 45-degree ramp 75% its height diameter. Recovery from falls (resting on the round side of the wheel) has been achieved with a strategy using both the wheel forward drive and gyro-tilt control. The main shortcomings to this robot are its lack of resilience and vulnerability to wheel damage; excessive battery drain due to drag on the gyro (bearing and aerodynamic); inadequate torque in the tilt servo; and incomplete enclosure of the wheel.

A second vehicle, Gyrover II, (Figure 4) was designed to address these problems. It is slightly larger than Gyrover I (34 cm diameter, 2.0 kg), and also utilizes many RC model parts. Tilt-servo torque and travel were both approximately doubled. Gyrover II uses a gyro housed in a vacuum chamber to cut power consumption by 80%, which increases battery life from about 10 minutes to 50 minutes. The entire robot is housed inside a specially designed pneumatic tire which protects the mechanism from mechanical and environmental abuse, and provides an enclosure that is

resilient, although less rugged than hoped. The robot contains a variety of sensors to monitor motor currents, positions and speeds, tire and vacuum pressure, wheel/body orientation, and gyro temperature. Gyrover II has been assembled and driven by manual remote control on a smooth floor, and has shown the ability to float and be controllable on water.

Gyrover provides a unique concept of dynamically stable robots for locomotion on rough terrain, and a rich array of research issues on sensing, control, and dynamics. We are currently working on these issues in improving its control performance and demonstrating its feasibility in a variety of applications.

Acknowledgements

We are grateful for the partial financial support from the Space System Division of Shimizu Corporation in Japan.

References

- [1] Arai, H. and Tachi, S., "Position control of a manipulator with passive joints using dynamic coupling", *IEEE Trans on Robotics and Automation*, Vol.7, No.4, pp.528-534, 1991.
- [2] Bergerman, M. and Xu, Y., "Dynamic coupling Index for underactuated manipulators", *Journal of Robotic Systems*, Vol.12, No.10, pp.693-707, 1995.
- [3] Bekker, M.G., *Theory of land locomotion*, University of Michigan Press, pp.213-217, 1956.
- [4] Bekker, M.G., "Accomplishments and future tasks in off-road transportation", *Journal of Terramechanics*, Vol.11, No.2, pp.11-30, Pergamon Press, Ltd., 1974.
- [5] Buhler, M., Koditschek, D.E., and Kindlmann, P.J., "A simple juggling robot: theory and experimentation", *Experimental Robotics*, edited by V. Hayward and O. Khatib, pp.35-73, Springer-Verlag, 1989.
- [6] Freitag, D.R., "History of wheels for off-road transport", *Journal of Terramechanics*, Vol. 16, No. 2, pp.49-68, Pergamon Press, Ltd., 1979.
- [7] Hautier, C., "Gyroscopic device for stabilization of laterally unstable vehicles", U.S. Patent, #3,787,066, 1974.
- [8] Hemmings, R.C., "Improvement in velocipede", U.S. Patent, #92,528, 1869.
- [9] Hodgins, J.K. and Raibert, M.H., "Adjusting step length for rough terrain locomotion", *IEEE Transactions on Robotics and Automation*, 7(3), pp.289-298, 1991.
- [10] Holm, I.C., "Articulated, wheeled off-road vehicles", *Journal of Terramechanics*, Vol.7, No.1, pp.19-54, Pergamon Press, Ltd., 1970.
- [11] Kemurdjian, A., Gromov, V., et al, "Small Marsokhod configuration", *Proceedings of IEEE International Conference on Robotics and Automation*, Nice, France, May, 1992.
- [12] Klarer, P.R., "Recent developments in the robotics all terrain lunar explorer rover (RATLER) program", *ASCE Specialty Conference on Robotics for Challenging Environments*, Albuquerque, NM, 1994.
- [13] Kosushi, A. and Yamafuji, K., "Development and motion control of the all direction steering-type robot (1st report: a concept of spherical shaped robot, roll and runing control)", *Proceedings of 9th Japanese Robotics Conference*, 1991, in Japanese.
- [14] Krotkov, E.P., Simmons, R.G., and Whittaker, W.L., "Ambler: Performance of A Six-legged Planetary Rover", *Acta Astronautica*, Vol.35, No.1, 1995.
- [15] McGeer, T., "Passive dynamic walking", *International Journal on Robotics Research*, 1989.
- [16] *Modern Mechanix and Inventions*, June, 1935.
- [17] Oliver, S.H., and Berkebile, D.H., *Wheels and wheeling*, Smithsonian Institution Press, 1974.
- [18] Palmer, A., *Riding high: the story of the bicycle*, Dutton, NY, 1956.
- [19] Patrin, R., "Gyrocycle", U.S. Patent, #4,712,806, 1987.
- [20] Saito, F., Fukuda, T., and Arai, F., "Swing and locomotion control for two-link brachiation robot", *IEEE Control Systems Magazine*, Vol.14, no.1, pp. 5-12, Feb. 1994.
- [21] Schael, S., and Atkeson, C.G., "Robot juggling: implementation of memory-based learning", *IEEE Control Systems Magazine*, Vol.14, no.1, pp.57-71, Feb. 1994.
- [22] Spong, M.W., "The swing up control problem for the acrobot", *IEEE Control Systems Magazine*, Vol.15, no.1, pp.49-55, Feb. 1995.
- [23] Vos, D.W. and Von Flotow, A.H., "Dynamics and nonlinear adaptive control of an autonomous unicycle: theory and experiment", *Proceedings of the 29th IEEE Conference on Decision and Control*, 1990.
- [24] Waldron, K., "The adaptive suspension vehicle", MIT Press, 1989.

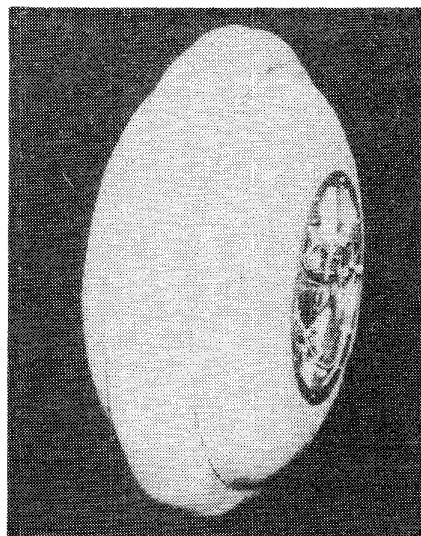


Figure 4: Photograph of Gyrover II enclosed in pneumatic tire.