

Design of a Spherical Vehicle with Flywheel Momentum Storage  
for High Torque Capabilities

by

Gregory C. Schroll

Submitted to the Department of Mechanical Engineering  
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

June 2008

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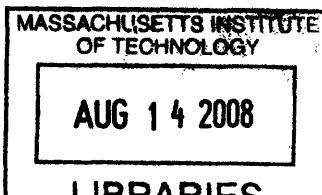
  
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## **Abstract**

A novel method for supplementing the propulsion of a spherical ground vehicle was conceived and developed. The addition of angular momentum storage via counter-rotating control moment gyroscopes is proposed in order to overcome significant limitations in the performance of earlier designs of spherical vehicles. Analysis and design of a fully functioning spherical vehicle incorporating such a mechanism is completed and indicates significantly increased torque capabilities for ascending steep inclines and stairs. A fully functional prototype is built and testing is ongoing to verify its capabilities.

Thesis Supervisor: Alexander H. Slocum  
Title: Professor of Mechanical Engineering

## **Acknowledgements**

For his tremendous enthusiasm and encouragement for creativity in design and engineering, and for supporting me during this project and other times during my life at MIT, I would like to thank my thesis advisor, Professor Alexander Slocum.

I would also like to thank Ken Stone and the MIT Hobby Shop for providing a wonderfully creative environment and community that has allowed me to explore my interests in design and engineering and given me a place to enjoy the thrill of realizing some of my ideas. I hope that I have been able to give back to the hobby shop at least part of what it has given me.

I would like to thank my good friend Ilan Moyer for always being there for me and helping me get through difficult times, and have no doubt our friendship will continue on.

I would like to thank my parents for supporting me and encouraging me.

I dedicate this thesis to my best friend and confidant, Georgia Hoyer, who has stuck by me even when I would not have stuck by myself. I greatly appreciate her diligence and patience, as it is her constant support that inspires me to do what I do. I look forward to what the future has in store.

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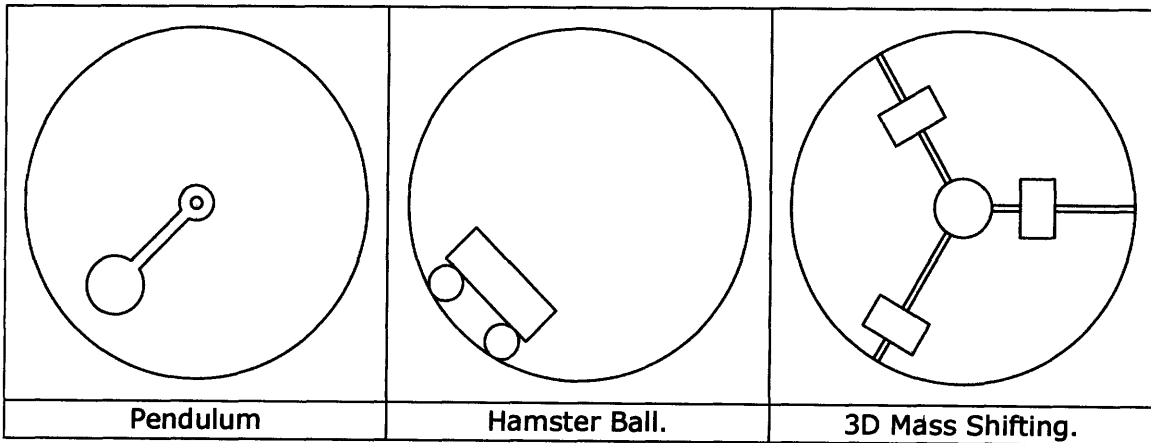
# 1 Introduction

A mobile land vehicle capable of traversing a wide variety of difficult terrain, while remaining near impossible to disable is an attractive concept for many applications including search and rescue, reconnaissance, sentry, and planetary exploration. Research in these fields has explored a large gamut of ideas and concepts that have yet to become very successful in practice. A spherical vehicle in which the outer surface is also the driving surface is quite appropriate in concept, because it is always right side up, and the outer shell protects all components safely inside. However this type of vehicle has not become much more than a curiosity due to significant limits to its acceleration and the maximum incline it can ascend based on the traditional propulsion method of shifting mass internally.

This project seeks to address these limitations by incorporating the ability to manipulate angular momentum internally as a supplement to propulsion. This concept is believed to be a novel approach and has the potential to provide a spherical vehicle with the capability of overcoming large obstacles, steep hills, and stairs. With these abilities, a spherical vehicle may be a viable and attractive solution for many mobile robotics applications. This project follows the conception, design, and implementation of a system for manipulating angular momentum inside a spherical vehicle, and verifying its capabilities in a fully functioning prototype.

## 2 Concepts

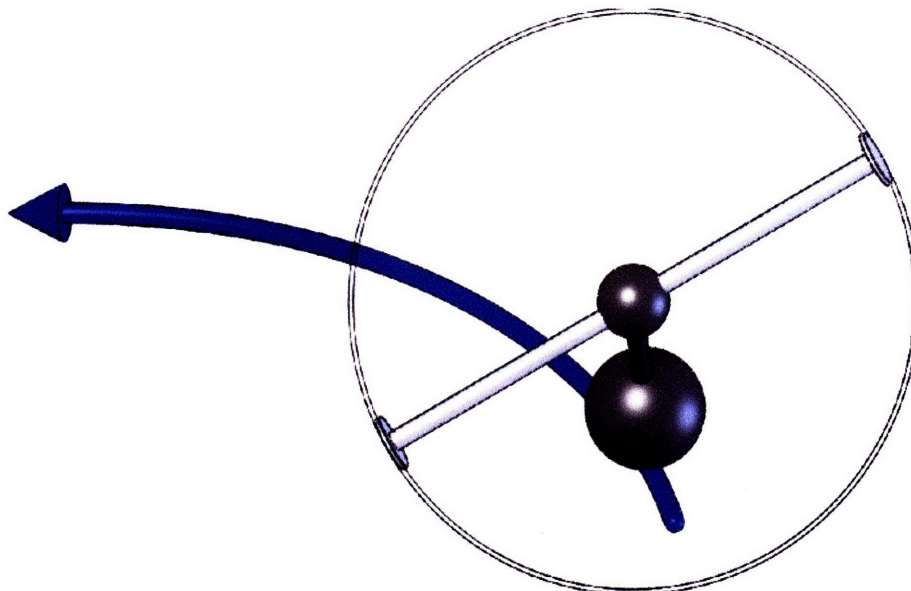
Different methods for propelling a spherical vehicle have been developed in the past and generally employ the principle whereby internally shifting the center of gravity (CG) of the vehicle causes it to roll in the desired direction. Based on my research, there appear to be three popular methods for achieving this behavior shown below in figure 2-1.



**Figure 2-1:** Sphere Propulsion Concepts. Three popular concepts for propelling a spherical vehicle are shown.

**2.1 Pendulum.** This design consists of a shaft fixed to the spherical shell across its diameter, with the remainder of the mechanics hanging down from this shaft. With the CG below center, torque can be applied to the main shaft to tilt the whole internal pendulum up in front, shifting the center of mass forward. On a level surface, this action moves the center of mass out in front of the sphere's contact point with the ground and gravity will cause it to roll forward. Continuously driving the pendulum up at an angle will provide thrust for the sphere to roll continuously,

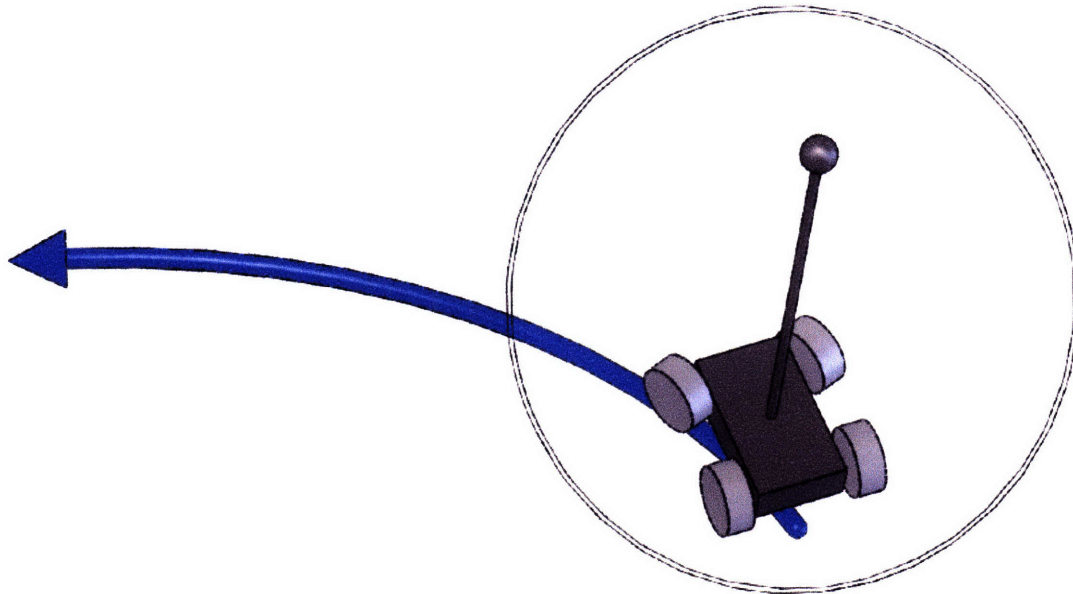
and tilting it up in back will cause the sphere to roll backwards. Tilting the mechanism to one side while the sphere is rolling forward or backward will cause the sphere to lean and travel in an arc to the left or right (see figure 2-2).



**Figure 2-2:** Pendulum Concept. Raised up in front and tilted to the side, the pendulum causes the sphere to roll in an arc.

The pendulum technique is straightforward in terms of design and the control scheme is analogous to a 4-wheeled vehicle with front wheel steering. The internal drive mechanism only interfaces with the shell at two poles; therefore, the internal and external surface of the shell is dimensionally non-critical. This characteristic is advantageous, because it allows the shell to be constructed in a variety of ways and be flexible for shock absorption. A major disadvantage of the pendulum design is that it is not truly omnidirectional. From a standstill, the sphere cannot roll in any direction; it must roll forward or in arcs.

**2.2 Hamster Ball.** This design consists of a wheeled vehicle that rides on the inside surface of the spherical shell (see figure 2-3). Many different wheel configurations can be used, but the principle is always similar to the pendulum design. In this case the internal car contains the majority of the overall mass of the sphere and by driving this car inside the shell, the CG can be shifted, causing the sphere to roll. Some variations include a tensioning mechanism which keeps the car pressed against the inside of the shell so that it can always apply force while not becoming inverted.

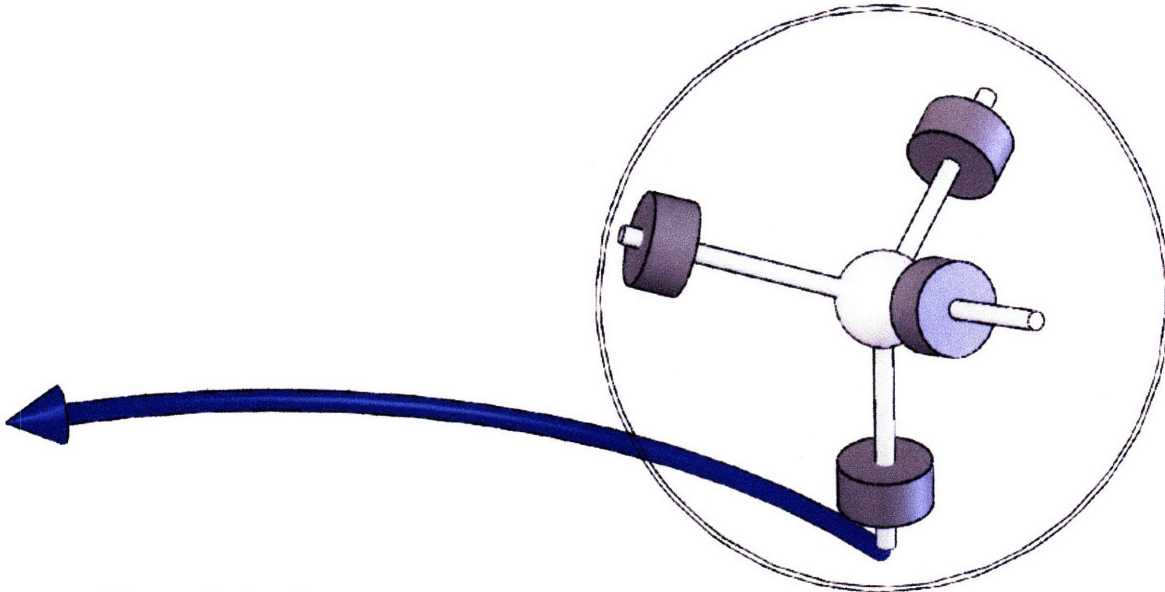


**Figure 2-3:** Hamster Ball Concept. A front-wheel-steering car inside, driving forward and to the left. A conceptualized tensioning arm is also shown.

With differential steering, the internal car can drive the sphere in any direction allowing it to be essentially omnidirectional. It too has the advantage of being relatively simple in design and simple to control. The major disadvantage to this design is that the inner surface of the shell is critical in specification. The internal vehicle and its tensioning mechanism require a relatively uniform surface to ride on and grip, which restricts how the shell can be made and how flexible it can be.

**2.3 3-Dimensional Mass Shifting.** This design is a relatively new concept patented by Ranjan Mukherjee consisting of a plurality of masses constrained along different radial axes of the sphere [1]. The masses can be driven in and out along these axes from a hub in the center of the sphere, and when coordinated properly the CG of the entire mechanism can be carefully controlled to cause the ball to roll in any desired direction.





**Figure 2-4:** 3-D Mass Shifting Concept. The mass positions are dynamically coordinated to maintain the overall center of mass out in front, causing the sphere to roll forward.

This approach is truly omnidirectional, but it is significantly more complicated than the previous two techniques in both design and control. Another disadvantage is the ineffective utilization of mass by having it distributed around a central hub which presumably houses the power source, electronics, and possibly other mechanics. The ability of this design to shift its CG is limited in comparison to the previous two techniques and its performance will be significantly lower.

**2.4 Limitations.** The principle of shifting the sphere's CG to cause it to roll, which these three different designs employ, places strict limits on the vehicle's ability to ascend inclines and overcome obstacles. This ability is dictated by how well the design can optimize its mass placement and how far the CG can be shifted internally. In practice, after incorporating all necessary components including motors, batteries, transmission components, and the shell itself, a spherical vehicle can ascend an incline of approximately 20-30 degrees maximum at constant speed (could probably cite some things here). This also translates to only being able to traverse an obstacle with a height less than about 1/10 the diameter of the sphere. A more detailed explanation is provided in later sections.

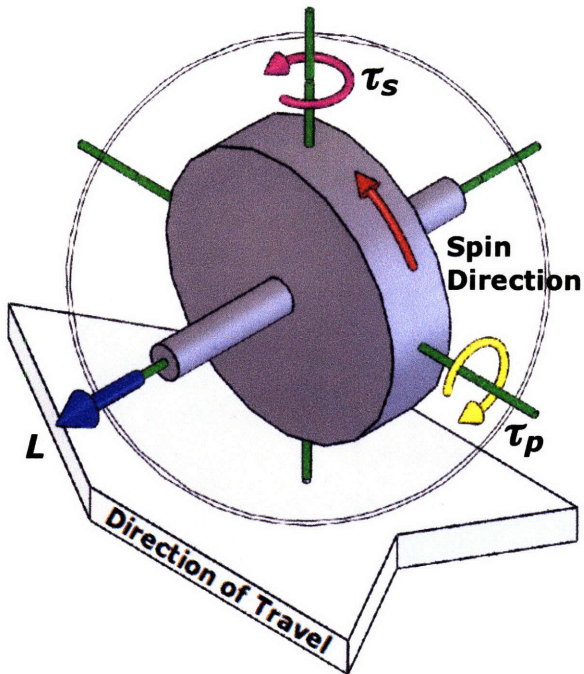
These significant limitations to a spherical vehicle's performance has prevented it from becoming a viable design for the applications it would otherwise be appropriate. Its advantage of being un-invertible appears negated by the likelihood of it getting stuck in a shallow valley, or easily stopped by small obstacles.

**2.5 Angular Momentum Usage.** To overcome these limitations, angular momentum can be generated and later dispensed, temporarily providing increased torque to overcome large obstacles or steep yet finite inclines. With enough power and momentum, this mechanism can even allow the sphere to ascend stairs. The technique is analogous to 'building up momentum' with a running start except that the momentum is generated internally and released at will without the need for the sphere to be moving.

To build up and store a significant amount of momentum, a large rotating mass is spun up to high speed such that its angular momentum is in the same direction as

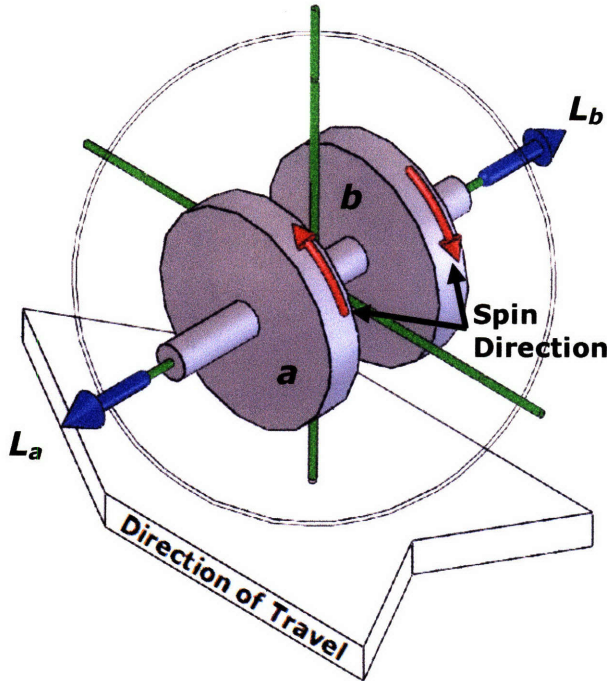
the axis of the sphere when it is rolling in the intended direction. To transfer the momentum to the sphere itself, the flywheel and shell are coupled together such that the flywheel can apply torque to the shell. This technique is suitable for 1-dimensional travel, but has limitations for 2-dimensional motion of the sphere.

Incorporating directional control for a sphere with a spinning flywheel introduces the undesirable effect of gyroscopic precession on the vehicle. As shown in the figure 2-5, when a torque is applied along an axis perpendicular to the spin axis of the flywheel, the flywheel will precess, or rotate, about the axis perpendicular to the first two axes because of a change in the direction of the angular momentum of the flywheel (a more detailed explanation follows in a later section) [2]. When the internal drive mechanism of the sphere is rotated to change the direction of travel, the axis of the flywheel must rotate along with it in order for the flywheel to be effective in helping drive the sphere in the new direction. This action causes the flywheel to precess and react along the third perpendicular axis, causing the sphere to roll or tilt in an undesirable fashion.



**Figure 2-5: Single Flywheel Momentum Storage.**  $L$  is the angular momentum of the flywheel in the direction necessary for supplementing forward motion,  $\tau_s$  is the torque on the flywheel due to turning the sphere (by some other means), and  $\tau_p$  is the precession torque induced.

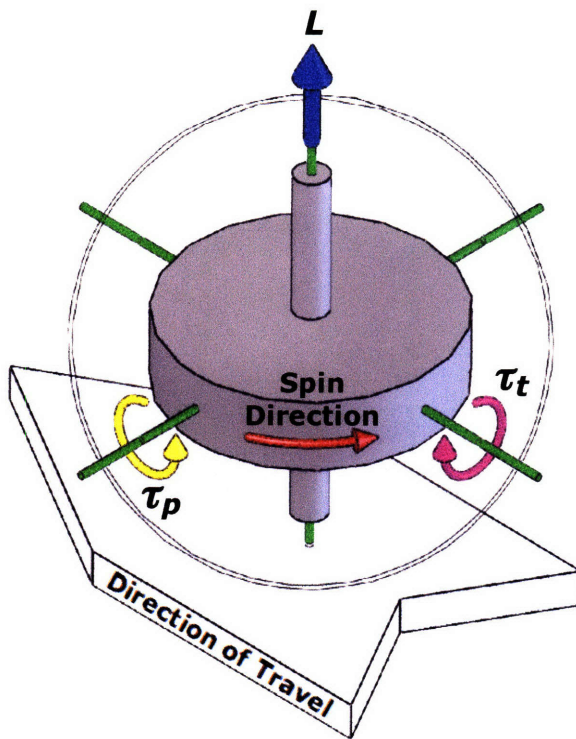
To address the issue of undesirable precession, two counter-rotating flywheels of equal but opposite momentum can be used (see figure 2-6). When spinning, the net angular momentum of the system is zero. Therefore, tilting the spin axis of the dual flywheel assembly, as is required when steering the sphere, induces no gyroscopic precession effect on the overall assembly. Inside the dual flywheel assembly, precession is experienced, but the precession torques generated by the flywheels are equal and opposite and cancel out. Besides addressing the issue of precession, however, the second flywheel in this configuration does not contribute to the forward motion performance of the sphere itself, since it is spinning in the opposite direction. When the momentum from the other flywheel is dispensed to help the sphere overcome obstacles, the two flywheels no longer cancel each other out and the counter-rotating benefit is compromised until they can be equalized again.



**Figure 2-6: Dual Flywheel Momentum Storage.** When added together, the opposite angular momentums  $L_a$  and  $L_b$  equal a net angular momentum of zero for the two flywheels. As a unit, they behave as if no mass is spinning, and therefore do not produce precession effects on the sphere itself.

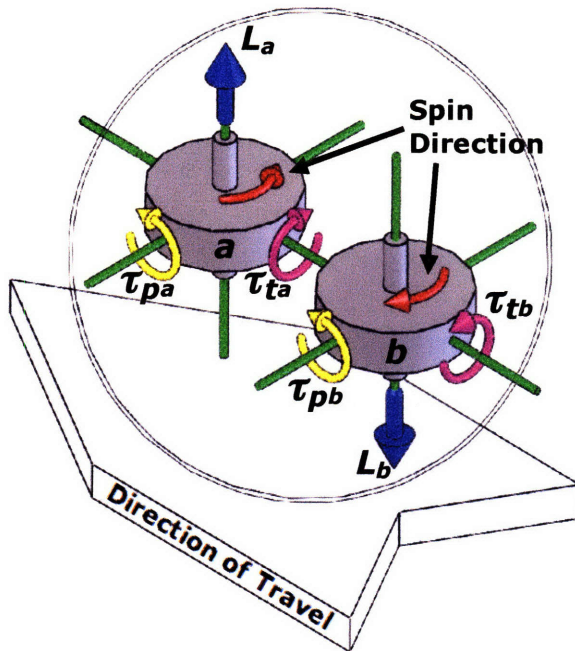
**2.6 Moment Control.** In the configuration described above, the momentum from the spinning flywheel is transferred to the spherical shell via torque along the spin axis of the flywheel. This torque not only transfers momentum, but also kinetic energy. When the flywheel is utilized in this manner, it is considered a momentum wheel. To equalize the two flywheels again the lost energy must be replenished. Since the flywheels are of very high momentum and energy already, a motor powerful enough to replenish this energy quickly would be prohibitively large, costly, and require large driver electronics. It is possible for a motor to be designed such that its rotor is essentially the flywheel itself, but this alternative is beyond the scope of the project.

With a slightly different configuration, it is possible to utilize the angular momentum of the flywheels while not significantly disturbing their kinetic energy. Taking advantage of the precession effect deemed unfavorable in the previous section, the precession torque can be generated along the desired axis for forward motion of the sphere by changing the direction of the angular momentum while leaving its magnitude unaffected. This technique is used in some spacecraft and satellites for attitude control, in which the flywheels are called control moment gyroscopes (CMGs). CMGs are useful for space applications and for the current project because they require far less power than momentum wheels to generate the desired output torque. While controls are complex for 3-dimensional attitude adjustments (roll, pitch, and yaw), the application of CMGs to a spherical vehicle necessitates only 1-dimensional control (for forward and backward motion).



**Figure 2-7:** Single CMG Momentum Storage.  $L$  is the angular momentum of the flywheel,  $\tau_t$  is the applied tilting torque on the flywheel, and  $\tau_p$  is the precession torque produced in the direction necessary for supplementing forward motion.

With a single CMG, shown above in figure 2-7, the applied flywheel tilting torque is perpendicular to the flywheel spin axis and to the desired output axis (along which the output precession torque helps drive the sphere forward). Unbalanced, this tilting torque causes the sphere to roll or tilt in an undesirable way. Two counter-rotating CMGs, however, tilted in opposite directions, will precess in the same direction and the resulting torque will be the sum of the precession torques from the two flywheels along the desired axis for propelling the sphere (see figure 2-8 below). Essentially, when spinning but not being utilized, the net angular momentum of the two CMGs is zero and the sphere can maneuver normally on relatively flat terrain. When the CMGs are tilted to utilize their momentum, they maintain speed (neglecting increased friction) since none of their kinetic energy is transferred to the outer shell. Therefore, tilting the flywheels requires little power and the motor(s) can be of manageable size without sacrificing performance.



**Figure 2-8: Dual CMG Momentum Storage.** When added together, the angular momentums  $L_a$  and  $L_b$  equal a net angular momentum of zero for the two flywheels. The tilting torques  $\tau_{ta}$  and  $\tau_{tb}$  are applied to the flywheels in opposite directions resulting in no net torque on the whole assembly. The precession torques  $\tau_{pa}$  and  $\tau_{pb}$  that are produced, however, add together in the direction necessary for supplementing forward motion.

**2.7 Design Focus.** After investigating prior research and patents, it was determined that utilizing two, counter-rotating control moment gyroscopes to supplement the propulsion of a ground vehicle is a unique idea, and it is believed that this type of mechanism is the missing link for bringing the spherical vehicle concept to practicality. For the spherical vehicle prototype, the pendulum drive system was chosen as the design to pursue due to its relative simplicity, and the limited restrictions on how the shell must be made. However, the dual flywheel mechanism is the main focus of this project and the purpose of the spherical vehicle platform is to demonstrate and verify its utility.

### 3 Performance Objectives

A spherical vehicle with enhanced torque capabilities is appropriate for a variety of applications including search and rescue, reconnaissance, sentry, and planetary exploration. These tasks present a variety of terrain from urban to rocky landscapes. A generalization of the most difficult obstacle that a spherical vehicle could be expected to negotiate using only drive torque and traction is a step whose height is equal to or less than the radius of the sphere. For the purposes of this project, obstacles of similar height such as rocks are considered to be of similar difficulty to overcome. Based on this generalization, the metric for satisfactory performance of the prototype was prescribed as the ability to ascend a standard step in a flight of stairs.

**3.1 Stairs.** According to the 2006 International Residential Code, a step can have a maximum rise (height) of 7.75" and minimum run (depth) of 10" [3]. Also, a stairway should have a minimum width of 36". While not all staircases fit these specifications, the vast majority of stairs do.

**3.2 Vehicle Scale.** The step and stairway parameters describe a minimum and maximum diameter for a spherical vehicle in order for it to navigate urban environments effectively. A realistic maximum diameter would be about 32" to allow for some maneuverability within the staircase width and account for some stairways potentially being under code. The minimum diameter of the sphere is about 16"

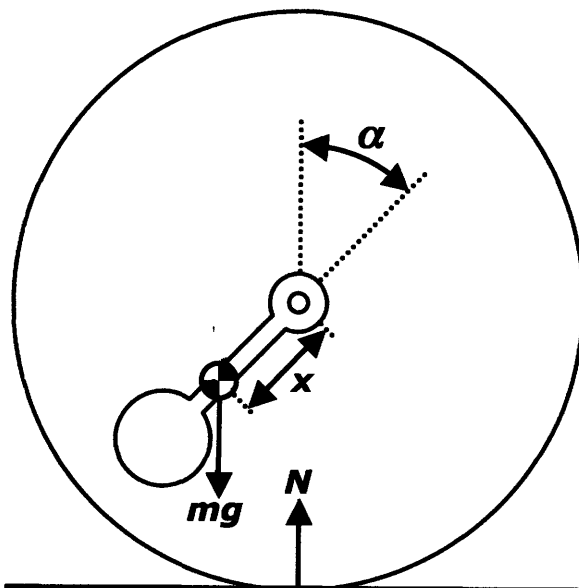
such that with an effective tread, it would be able to achieve enough traction to climb up the maximum step height. Interestingly, if the sphere is less than 20" it is able to rest unpowered on a step of minimum depth, and therefore could ascend a whole flight of stairs even if it requires climbing one step at a time. A target diameter of 18" was chosen to take advantage of this ability. The selected size is also appropriate in terms of cost of parts and manageability.

**3.3 Inclines.** While stairs were chosen as the metric for performance, the ability to ascend inclines is also important. Since the step height is close to the radius of the sphere, the torque that is required to ascend such a step is the same as the torque required to ascend an incline approaching 90 degrees from the horizontal. Therefore, a design satisfying the required torque for the primary step climbing metric also has enough torque to ascend any possible incline for a finite period of time. The largest distance up an incline that the sphere can ascend is determined by the slope and the maximum amount of angular momentum that can be built up inside the sphere. As will be described in a later section, the design must try to maximize the stored angular momentum in order to maximize performance.

## 4 Theory

In order to design the prototype, the basic concepts were explored mathematically to estimate performance when using a flywheel momentum storage system to perform the desired capabilities. Early approximations were made of the masses and center of masses of different components as well as the velocity and angular momentum of the flywheels in order to verify the feasibility of the project.

**4.1 Pendulum Drive Torque.** The pendulum drive concept described earlier operates by applying torque between the pendulum and the main drive shaft fixed to the outer shell. This torque attempts to swing the pendulum up, shifting the sphere's center of mass forward in front of its contact point with the ground. A moment is created due to the acceleration due to gravity of the center of mass of the sphere and the normal force pushing up, which causes the sphere to roll assuming there is no slip with the ground (see figure 4-1 and equation 1). The sphere accelerates when rolling until the point when frictional torque associated with the rolling and friction in the mechanism counteracts the drive torque equally.

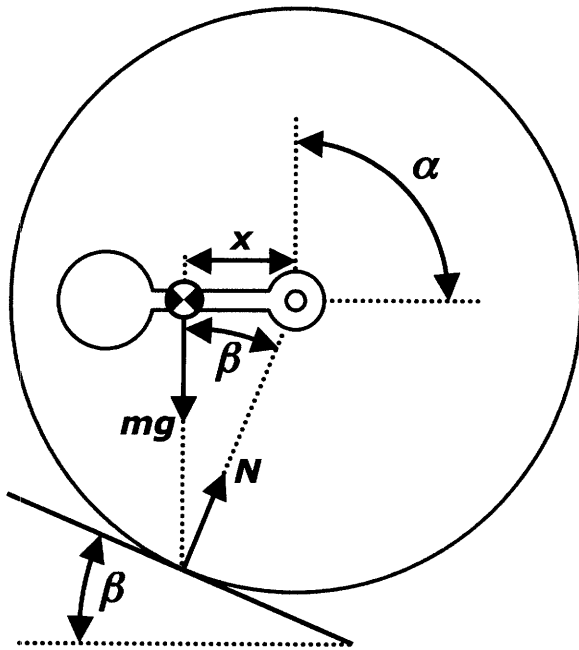


**Figure 4-1:** Pendulum Drive Torque. A sphere rolling on level ground with the pendulum raised at an angle  $\alpha$  w.r.t vertical.

$$t_{roll} = mgx \sin \alpha, \quad (1)$$

The greatest amount of torque for rolling is generated when the moment arm for gravity to act on the center of mass is maximized, which occurs when the pendulum is straight out in front (raised up 90 degrees). If greater drive torque is applied, the pendulum rotates further than 90 degrees thereby shortening the effective moment arm and decreasing the torque for rolling. This behavior is the limiting factor for the performance of a spherical vehicle that only shifts its center of mass to move.

**4.2 Pendulum Drive on Inclines.** When ascending an incline, the contact point of the sphere with the ground is moved forward, thus shortening the maximum moment arm for gravity to act on, and decreasing the maximum torque causing the sphere to roll. The steepest ascendable slope is when the contact point between the sphere and the incline is directly below the furthest forward position of the center of mass of the sphere (see figure 4-2 below). Using estimated masses and component positions (including the flywheels), the steepest ascendable incline was found to be about 20 degrees for the prototype. Since the flywheels are large they must sit high up in the assembly which unfortunately raises the center of mass of the machine, hindering the incline climbing ability. However, the performance capabilities that the flywheels introduce outweigh this detraction. Future development may be able to optimize or eliminate this tradeoff.



**Figure 4-2:** Pendulum Drive on Maximum Incline. The contact point with the ground is directly below the CG of the sphere therefore no moment is generated. The maximum incline is indicated here by angle  $\beta$ .

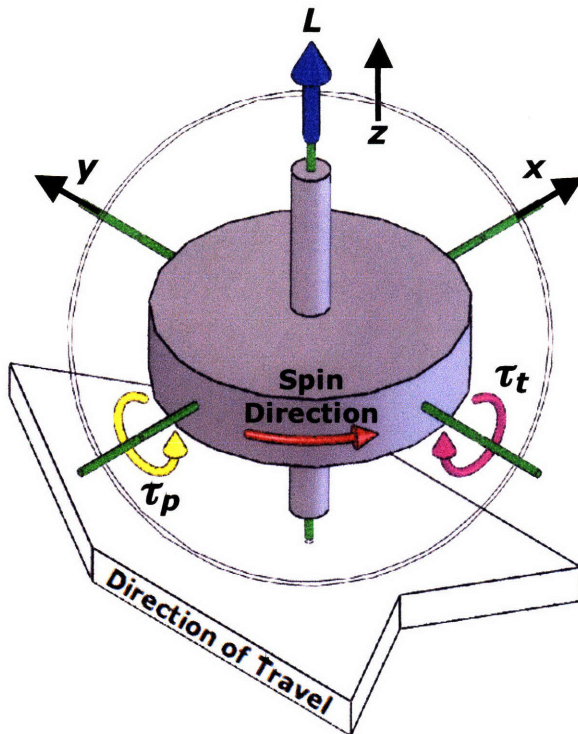
**4.3 Control Moment Gyros.** The principle behind the control moment gyro is gyroscopic precession which can be explained in terms of torque and angular momentum using the following equations

$$\tau = dL/dt, \quad (2)$$

$$L = I\omega, \quad (3)$$

$$E_{kinetic} = \frac{1}{2}I\omega^2, \quad (4)$$

where  $\tau$  is torque,  $L$  is angular momentum,  $I$  is moment of inertia,  $\omega$  is angular velocity, and  $E$  is kinetic energy. In equation 2, torque produces a change in angular momentum. The angular momentum of a flywheel is a vector (it has a magnitude and direction) and is a function of the moment of inertia of the flywheel and its angular velocity as shown in equation 3. In equation 4, the kinetic energy of the flywheel is a scalar and while also a function of moment of inertia and angular velocity, the direction of the angular velocity falls out of the equation when it is squared. This fact leads to the usefulness of the control moment gyro, where a torque can be applied to change the direction of the angular momentum of a flywheel, while not changing the rotational kinetic energy.

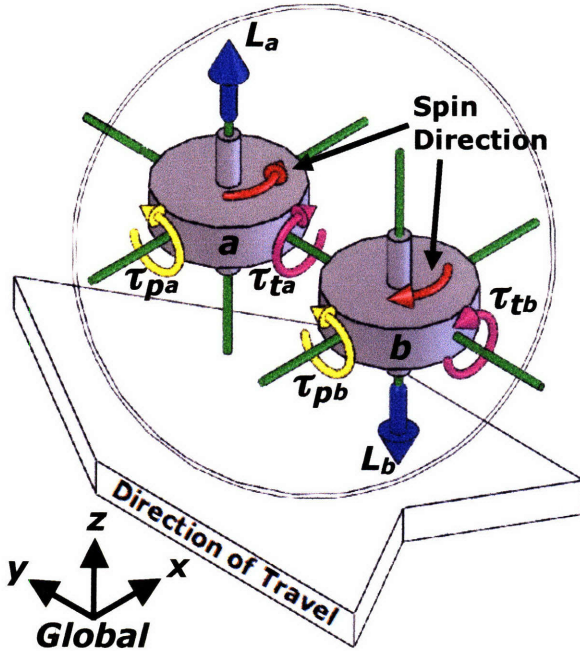


**Figure 2-7: Single CMG Momentum Storage.**  $L$  is the angular momentum of the flywheel,  $\tau_t$  is the applied tilting torque on the flywheel, and  $\tau_p$  is the precession torque produced in the direction necessary for supplementing forward motion.

In figure 2-7 reproduced above, the torque,  $\tau_t$ , is attempting to tilt the flywheel about the y-axis, which would try to point the momentum vector  $L$  more towards the positive x-axis, increasing the angular momentum in the positive x-direction. However, in order for there to be this increase along the x-axis, there must be a torque in that direction per equation 2 above. The gyroscope reacts in this case by producing a precession torque,  $\tau_p$ , in the negative x-direction, thereby canceling out the increase. Essentially, if the only torque that is applied to the flywheel is in the positive y-direction, then the angular momentum can only change in the y-direction; thus, the momentum vector tilts about the x-axis, towards the positive y-axis. It is this behavior that is referred to as gyroscopic precession.

Since there is no torque about the spin axis of the flywheel, the magnitude of the angular velocity remains unchanged and as a result the rotational kinetic energy stays the same. Therefore, the power put into the flywheel via the tilting torque is equal to the power coming out of the flywheel via the precession torque. The flywheel effectively converts a torque in one direction to a torque in a perpendicular direction at any particular instant. It is critical to note, however, that as the gyroscope precesses, the direction of the output torque constantly changes as well.





**Figure 2-8: Dual CMG Momentum Storage.** When added together, the angular momentums  $L_a$  and  $L_b$  equal a net angular momentum of zero for the two flywheels. The tilting torques  $\tau_{ta}$  and  $\tau_{tb}$  are applied to the flywheels in opposite directions resulting in no net torque on the whole assembly. The precession torques  $\tau_{pa}$  and  $\tau_{pb}$  that are produced, however, add together in the direction necessary for supplementing forward motion.

When two CMGs are configured as in figure 2-8 (reproduced above), the equal and opposite torques applied to tilt the flywheels result in no net torque on the sphere's internal assembly. Because the angular momentums of the two flywheels are in opposite directions, the tilting torques cause the CMGs to output precession torque in the same direction at the instant shown in the figure. As the flywheels tilt in opposite directions about their common y-axis, their angular momentums are no longer in parallel directions, but now have components along the global x- and z-axes. The components along the global z-axis remain equal and opposite and therefore cancel out. Importantly, the component of the output precession torque along the global x-axis (the direction useful for supplementing forward motion of the sphere) goes with the cosine of the tilt angle as shown in the equation

$$\tau_{px} = \tau_{tilt} \cos \theta_{tilt}, \quad (4)$$

where  $\tau_{px}$  is the component of the precession torque along the x-axis,  $\tau_{tilt}$  is the sum of the magnitudes of the opposite tilt torques, and  $\theta_{tilt}$  is the angle of tilt about the y-axis where the configuration shown in figure 2-8 is  $\theta_{tilt}=0$ . Therefore, the CMGs are able to produce the most useful torque when aligned as shown in the figure at zero tilt angle, and decrease with the cosine to zero useful output at 90 degrees tilt angle.

The relationship between the tilting torque and the tilt rate is important since the CMGs need to produce a significant amount of torque for a useful duration of time to perform the intended maneuvers. The tilting torque and rate are related by the angular momentum of the flywheels as shown in the equation

$$\tau_{tilt} = L_{total} \frac{d\theta_{tilt}}{dt}, \quad (5)$$

where  $L_{total}$  is the sum of the magnitudes of the angular momentum of the two flywheels. Equation 5 indicates that the greater the angular momentum, the slower the flywheels will tilt for a given tilting torque, which ultimately allows them to be utilized for a longer period of time.

**4.4 Pendulum and Flywheels.** The torque produced by the acceleration due to gravity on the CG of the sphere is what causes the sphere to roll when the pendulum is driven up as described in section 4.1. When the CMG system is incorporated, the output torque from tilting the flywheels supplements the torque on the pendulum due to gravity. The drive motors inside are then able to apply greater torque to the main shaft (which is fixed to the shell) while keeping the pendulum at the most effective angle of 90 degrees.

The amount of time that the flywheels remain effective when utilized depends on how much momentum is stored and how quickly it is used. For instance, the sphere would be able to ascend a gentler incline for a longer period of time than a steeper incline. Also, ascending a step (which is essentially approaching a 90 degree incline) would utilize the flywheel momentum very quickly, since the torque required is likely the highest that the sphere will encounter. Based on estimated values for mass and momentum it was found that the prototype will be able to ascend one or perhaps two steps before the flywheels have tilted beyond their effective range. While the sphere rests on the new step, the flywheels can be tilted back in the opposite direction slowly to reset them without causing the sphere to roll down the stairs. This procedure can be repeated to ascend an entire staircase.

## 5 Design

**5.1 Design Goals.** Based on the performance objectives and theory, several goals were established in an effort to optimize the design. First, based on equation 1, a low center of gravity is desirable to maximize the possible moment arm for the pendulum drive. The placements of components, especially those of higher density such as motors, gearboxes, batteries, and the flywheels were prioritized to the bottom of the assembly to sink the CG as far as possible. Increasing the mass of the pendulum also improves its performance, but a compromise needs to be made to preserve a decent overall power to weight ratio. Also, it is important to minimize the mass of the spherical shell since it contributes to significantly raising the CG, and its high moment of inertia hinders the acceleration of the sphere, which also hinders the flywheel effectiveness.

In order to ascend a step, the drive torque needs to be quite high compared to the torque necessary for cruising on flat ground; therefore, much attention was paid to ensure all significant details were accounted for in selecting motors and gear ratios for the drive train and flywheel tilt mechanisms. The total drive torque needs to be equivalent to or higher than the sum of the torque required to drive the pendulum by itself plus the torque output from the flywheels.

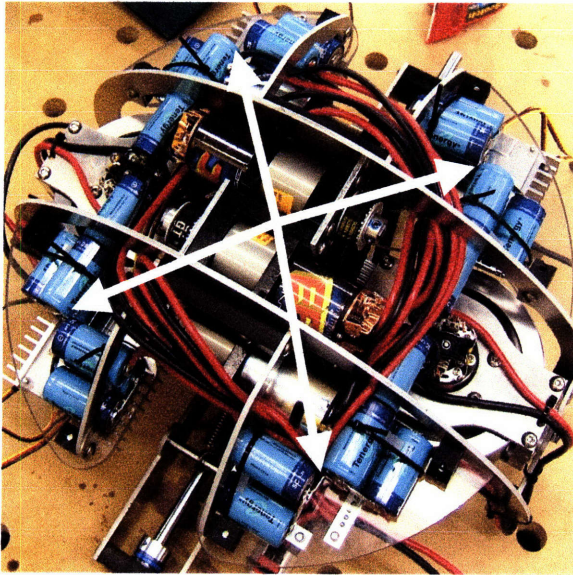
Equation 5 indicates that it is important to maximize the flywheel momentum in order to increase their performance. Conflictingly, it is beneficial to minimize the flywheel energy since it requires a significant amount of time and energy from the batteries to spin them up.

Simplicity and manufacturability were also considered paramount since the project was on a tight build schedule, and it would be helpful to minimize possible sources of error in the machining and assembling of the prototype. Part count was kept as low as possible and parts were combined when possible. Different kinds and shapes of material were kept to a minimum to eliminate waste and streamline machining operations. For instance, the majority of the structure was cut from a single sheet of aluminum on an abrasive waterjet machine. Also, the number of fastener types and sizes were minimized to eliminate confusion and tool count during assembly.

**5.2 Controls and Electronics.** The focus of this prototype was to test the mechanics of the flywheel system inside a fully functioning spherical vehicle. While

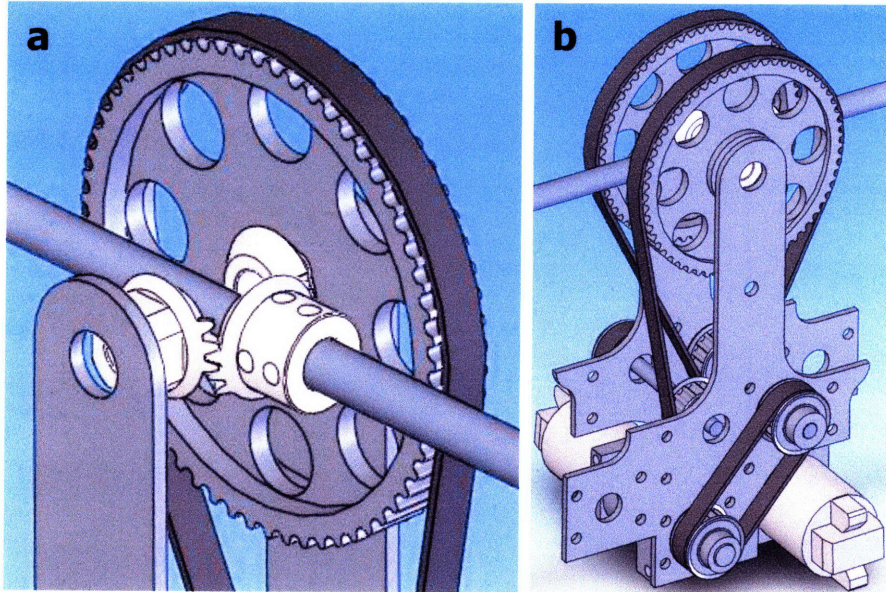
ultimately the various systems involved in this project ought to be coordinated with the help of sensors and computer control, it was deemed an unnecessary complication for testing the basic functionality of the first prototype. To enable human control, an R/C helicopter radio transmitter and receiver were utilized. Additional components such as standard 540 size motors and electronic speed controllers for R/C cars were used due to their high performance, relatively low cost, and simplicity of integration with the remote control system.

High capacity nickel metal hydride (nimh) batteries were selected for their high energy and power densities. Individual cells were purchased and assembled in custom packs in order to optimize the use of space and low the center of mass of the overall assembly (see figure 5-1 below).



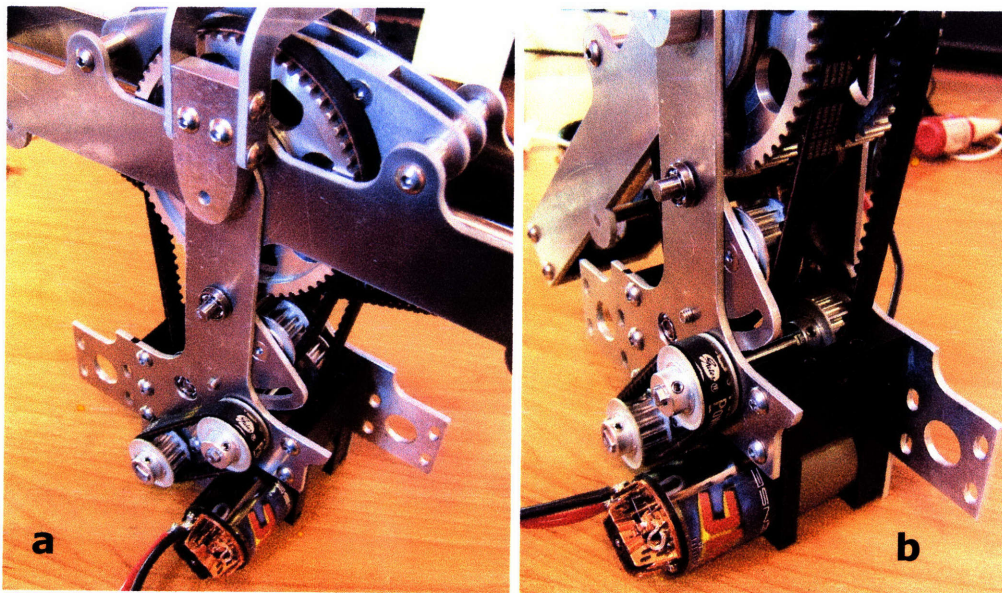
**Figure 5-1:** Battery Packs. Four battery packs of 7 cells each (indicated by the arrows) were designed to conform to the spherical shape of the shell to best utilize space and position their mass as low as possible. The underside of the pendulum assembly is shown here.

**5.3 Drive Train.** The pendulum assembly needs to be able drive the main shaft to swing itself forward and backward, but also tilt side to side in order to steer. To enable this functionality a differential drive system was implemented shown in figure 5-2 below. The differential is composed of three miter gears, where the two opposing gears are each independently driven and controlled by a motor. When the opposing miter gears are driven in opposite directions, they apply a torque to the main drive shaft, to swing the pendulum assembly. When they are driven in the same direction they cause the pendulum to tilt to the side enabling the sphere to steer. The drive motor outputs are continuously variable in between these two cases allowing full proportional control of the sphere's forward and steering motion. Stiff springs create a restoring force to re-center the side to side tilt of the pendulum.



**Figure 5-2:** Differential Drive System. (a) The three miter gears are shown with one pulley hidden for visibility. (b) The bare pendulum assembly showing all of the main components of the drive train.

**5.4 Gear Ratios and Arrangement.** Since the outer sphere is basically a large diameter drive wheel, and R/C car motors tend to spin at high rpm, large gear reductions of about 150:1 were necessary to bring the drive torque and speed into an appropriate range. 48:1 planetary gearboxes made by Banebots designed specifically for 540 size motors were used since they were inexpensive and compact, and the remainder of the gear reduction was implemented with timing belts (see figures 5-2b above and 5-3 below) [4].



**Figure 5-3:** Drive Train Gear Reduction. (a) The assembled differential drive system and pendulum. (b) One of two drive motors face mounted to a Banebots planetary gearbox.

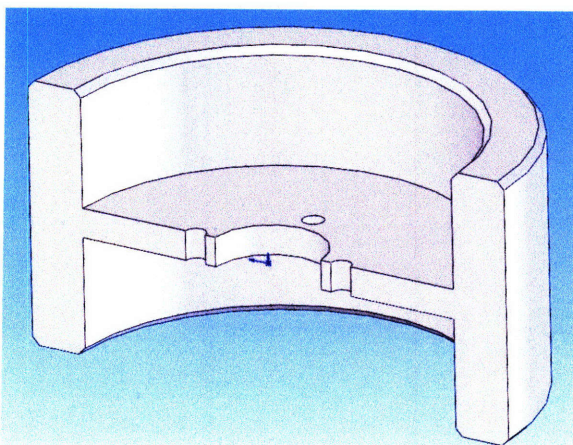
**5.5 Other Drive Train Considerations.** In designing the drive train, other details were worked out to ensure proper safety factors were in place. The miter gear teeth were analyzed for shear, and extra precautions were taken to ensure they were rigidly supported and properly meshed to minimize wear. The main shaft was studied in regard to torsional and bending stiffness. Due to concerns of bending, extra bearing supports were added on the far ends of the shaft. While technically overconstrained, machining tolerances plus tolerances in the bearings and shaft allowed for proper alignment to be possible.

Synchronous timing belts were utilized throughout the machine due to their potential for low backlash, and efficient operation. *PowerGrip GT2 series* belts with curvilinear tooth geometry were chosen for their high power transmission capability. Belts and pulleys were purchased from Stock Drive Products/Sterling Instrument, whose thorough technical documentation was referenced in determining proper belt sizes and pulley diameters for power transmission within an appropriate safety factor [5]. Belt tensioning was accommodated with adjustable idler pulleys for the main drive belts, and slotted holes for the gearbox mounts for the other belts. The slotted holes turned out to be quite difficult to adjust and a finer screw adjustment design would be much more effective in a later prototype.

**5.6 Flywheel Design.** The flywheel design focus was on maximizing the angular momentum. As shown in equation 3 in the theory section above, angular momentum is a function of moment of inertia. The moment of inertia of a spinning mass can be maximized by distributing the mass in a thin ring around the spin axis; the equation for this geometry is

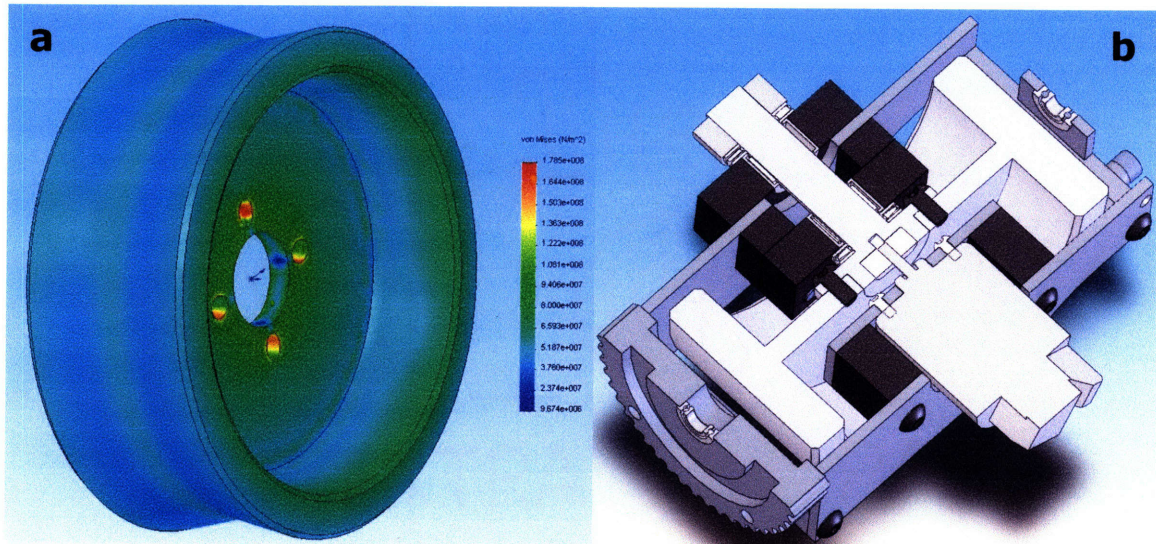
$$I = \frac{1}{2} \pi \rho h (r_2^4 - r_1^4), \quad (6)$$

where  $\rho$  is density,  $h$  is the thickness of the ring,  $r_1$  is the inside radius and  $r_2$  is the outside radius. It is clear that maximizing the radius is very important, and also using a dense material. Within the constrained space of the sphere, the flywheels were designed to be as large in radius as possible while still providing clearance for their cage structure to tilt. Also, the flywheels were designed to be machined from steel since it is relatively dense, machinable, high in strength, and low in cost when compared to other alternatives. A section view of the flywheel is shown in figure 5-4 below.



**Figure 5-4:** Flywheel Design. The majority of the mass is distributed around the outside perimeter to enhance its angular momentum. Bolt holes in the web are for mounting the flywheel shaft with integrated hub.

To aid in the design, and maximize the angular velocity within a large safety factor for yielding, finite element analysis was employed. For the particular alloy of steel to be used, it was found that the flywheels could be spun at 15,000 rpm with a safety factor of 3 for yielding (see figure 5-5a below). Since these flywheels are to be tilted forcefully, the radial load on their support shafts would be quite high. To accommodate this load, dual needle roller bearings were used to support the flywheel shafts and dual needle thrust bearings keep the flywheels located properly with low friction (see figure 5-5b below).

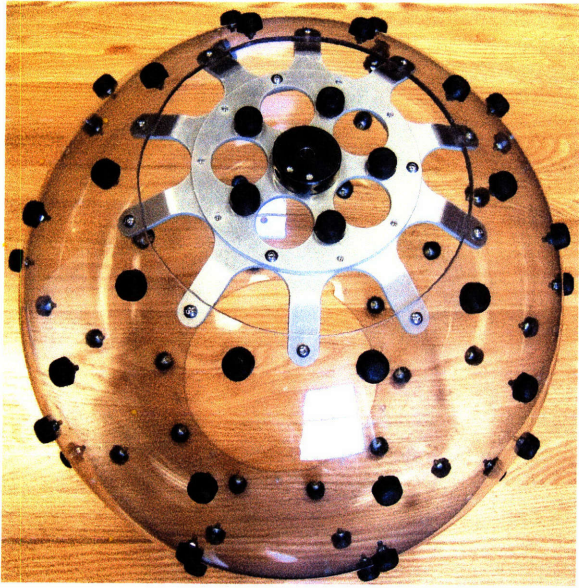


**Figure 5-5:** Flywheel F.E.A. and Bearings. (a) Stress in the flywheel at 15000 rpm. (b) A section view of the flywheel assembly showing the bearing support.

**5.7 Spherical Shell.** The shell of the sphere is a critical part of this prototype since it is the only means of shock absorption and must provide adequate traction to be able to climb over obstacle effectively. It also has to be strong and have a torsionally rigid mount to the drive shaft in order to transmit high torque. Many designs were brainstormed including a woven design similar to the system of latitude and longitude with the shaft mounting at the poles, as well as a geodesic framework. These designs are complicated and would likely take several prototypes to effectively implement. An inexpensive and cheaper alternative was found in the form of a polycarbonate dome from the top of a large gumball machine.

The polycarbonate is highly impact resistant, and was an appropriate thickness providing the strength and flexibility desired. Also, the transparent nature of the plastic turns out to be very useful for testing since the mechanics inside are clearly visible. Rubber nubs were mounted on the sphere to provide increased traction (see figure 5-6 below).

For this prototype, large holes were cut in the shell at the poles and metal hubs were mounted in their place. These large holes allow the major assemblies of the machine to be inserted into the sphere and bolted together. Unfortunately much of the wiring and final assembly had to be completed piece by piece inside the shell which proved to be difficult and tedious. Future designs would be far easier to assemble if the shell can be separated into hemispheres.



**Figure 5-6: Spherical Shell.** The polycarbonate globe is shown with the rubber nubs and one hub mounted.

**5.8 Potential for Design Improvements.** While much analysis was done during the design of the prototype, there are several topics that were not covered in detail. For instance, studying the frictional losses experienced by the flywheels from resistance in the air and in the bearing could lead to a much more power efficient design. Also, optimizing the flywheel radius alongside the vertical position of the flywheels would be worthwhile. Looking into composite materials for the structure and flywheels could lead to significant improvements in lowering the center of gravity and increasing the stored angular momentum. Performance improvements could also be had by optimizing the battery weight with respect to the battery capacity that is required.

## 6 Testing

Testing of the spherical vehicle prototype is ongoing. Results to date are generally qualitative as experience is gained learning how to control the machine manually. In time more controlled experiments are to be carried out to test the machine's capabilities for ascending inclines and stairs, and overcoming obstacles. A testing method being explored is frame by frame video analysis for estimating velocities and distances, as well as the positions of the internal structure and flywheels which cannot be directly measured externally. With proper setup this technique can provide reasonably accurate estimates of the sphere's performance (see figure A-1 in the appendix for a video capture of the sphere ascending a hill).

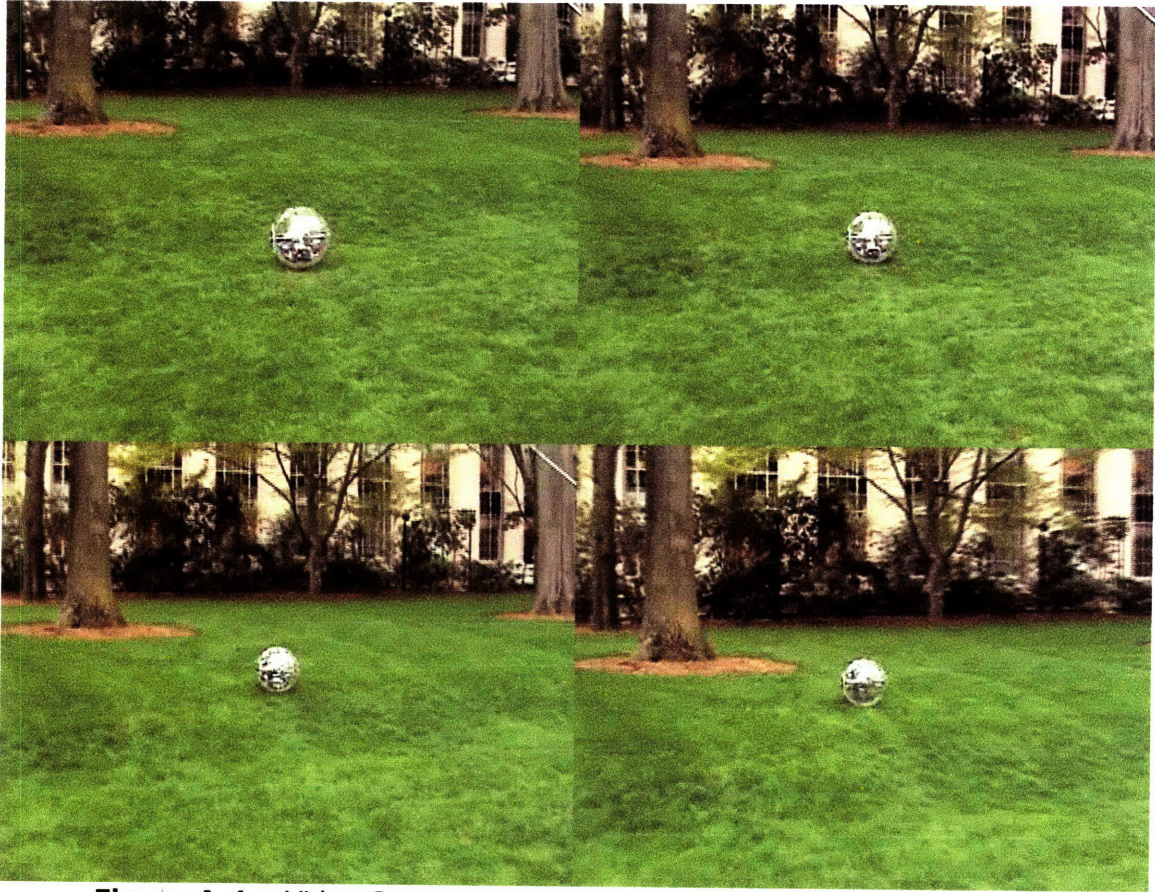
While eliminating the steps of configuring, programming, and debugging computer controls for the sphere has allowed the vehicle to be test driven far sooner, it is becoming apparent that computer control is necessary for more effective testing of the flywheel angular momentum storage system. With the implementation of feedback control for steering and fine coordination of the flywheels, the sphere would perform much better and more research could be done on utilizing the unique capabilities of the flywheels.

## **7 Further Research**

This prototype is solely meant to verify the capability of the flywheel system, however this research is only the beginning of the topics that could be explored. A current topic of interest is evaluating the potential capabilities of the sphere at different scales. In particular, an understanding is sought for how momentum storage scales with sphere diameter in terms of flywheel radius and maximum safe angular velocity. For future prototypes, closed loop control of the various systems is to be implemented and autonomous control and navigation will be added. Also, it is believed that investigation into control laws for mixing and manipulating the sphere's momentum will lead to far more complex behaviors and stability enhancements. With this theoretical understanding, the sphere would have the potential to evaluate its complex dynamics in real time and navigate smoothly and successfully over very jagged terrain. Ultimately, further research should be done into other applications of flywheel momentum storage, in particular control moment gyros for supplementary control of other dynamic/robotic systems.



## Appendix



**Figure A-1:** Video Captures. The sphere is ascending a short hill utilizing the flywheel momentum storage system.

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