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EXPERIMENTS TO VALIDATE THE USE OF A CONTROL MOMENT GYROSCOPE (CMG) TO TURN ROBOTS

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ABSTRACT

Turning a robot, particularly an under-actuated bipedal humanoid robot, is challenging. Several methods proposed in the literature for producing human-like motion in such robots are innovative but are limited in their range of motion. This paper presents an approach to control the orientation of a robot using a control moment gyroscope (CMG). A demonstration platform is developed to test this concept and physical experiments are conducted to determine the prototype's turning range and performance. This concept is then extended to a backpack mount where trials are conducted using human subjects to estimate the performance of the system that can potentially be used to turn bipedal humanoid robots.

Keywords: control moment gyroscope; human+oid robot; biped; human-like motion; gyroscope; gyroscopic torque

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INTRODUCTION

Bipedal robots are increasingly being investigated for tasks that demand human-like motion. As evidenced by DARPA's Robotics Challenge (2012), many researchers believe that bipedal robots are capable of traversing rough terrain and performing tasks in unstructured, hazardous environments. However, motion planning for bipedal locomotion is much more complex than for traditional mobile platforms that utilize wheels and/or added-points of contact with the ground surface for stabilization and navigation. One factor associated with bipedal locomotion that has proven to be a real challenge is the turning motion. Farrel and Herr [1] highlight the difficulties related to achieving reliable turns using robots, including the need for real-time stabilization. While there are several methods in the literature focusing on stability, our project is concerned with generating the turning motion itself. Several papers that address related topics include Aoi et al. [2] who analyze turning control schemes of a biped robot while Ott et al. [3] demonstrate the use of torque-controlled joints to produce a turning motion. Although these methods can be effective, they often require large numbers of actuators on both feet and therefore introduce additional single-point failures to the system. The intended locomotion (angle of turn or distance moved) can be improved by coupling methods based on path planning and imaging. However, they have a tendency to limit the system's ability to rapidly respond to challenging terrains due to their algorithmic complexities.

There are also methods based on the center of mass (COM) such as the one suggested by Ozawa and Ishizaki [4] and Meyer et al. [5]. Meyer coupled a COM approach with an active reaction wheel that yielded slower turns and concluded that large amounts of energy would be required to effect larger, faster turns. This was also confirmed in tests conducted by members of the HCR Laboratory at UT Austin who focused on using the reaction wheel approach for turning an experimental platform. There are also methods based on shifting the center of pressure (COP) of a humanoid's foot, and ones where the angular momentum of the arms or torso is changed. Both of these methods require a large number of actuators to successfully turn a robot and have the potential to limit maneuverability of the humanoid.

In the search for a simple and effective solution for turning a biped robot, our group investigated control moment gyroscopes (CMGs), a device that is primarily used for stabilization purposes. Of the different available schemes for stabilization using CMGs, Wong and Hung [6] investigate a gyroscope mounted on a walking bipedal robot for balancing by restricting movement in the coronal plane in addition to shifting the COM for walking. Spry and Girard [7] employ a similar technique using gyroscopes for the stabilization of monorail cars and unstable bicycles. They also present ideas based on single-gyro and double-gyro systems that have enormous potential in humanoid robots. Based on the available literature, we feel that a CMG may be superior to other methods for producing a quick and significant shift in angular momentum. This can be achieved by rotating a gimbal that houses a spinning mass, whereby a torque is generated perpendicular to the gyroscope's gimbal and rotation axis. This torque can be used to turn the robot as it walks.

The proposed concept is investigated by building a semi-autonomous structure that mimics a bipedal robot on which an off-the-shelf battery powered gyroscope is mounted to a gimbal. Experiments are conducted to determine the turning effectiveness of such a system. The idea will be described in the next section, where details regarding the design will be presented. In the following section, the experiments performed on the design will be discussed. The benefits and novel features of using a simple design such as the one proposed here will also be illustrated along with trials on a modular backpack-style mount for porting this concept on to an actual biped humanoid robot in the concluding sections.

DESIGN PROCEDURE

Our first exposure to a system to turn a robot was the reaction-wheel based experimental platform in Figure 1 below. That approach consists of two weights that are accelerated to create a reactive torque that turns the platform. The platform consists of a friction surface contact at the center and four castor wheels to balance the system. The amount of turn produced by this system is limited as the torque generated in this technique is not sufficient to produce a large turn of the platform.

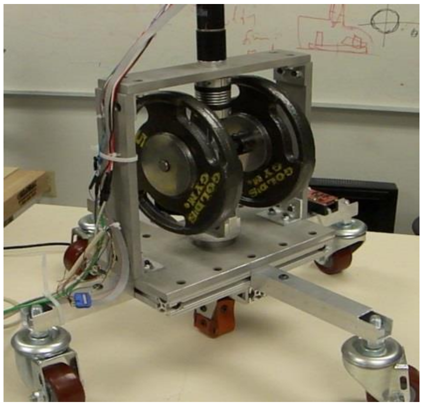

Figure 1. Platform for turning using reaction wheel

With the reaction wheel as an example, we decided to explore other alternatives for turning a biped humanoid robot. We conducted a conceptual design exercise with several graduate students working in design, manufacturing and robotics. The design concepts we obtained as a result of that exercise were consolidated and combined with the results of our literature survey and that lead us to try using a CMG for turning a robot.

The idea behind using the CMG is based on the following. Consider a gyroscope mounted on a gimbal as shown in Figure 2. The gyroscope is oriented along the x-axis and is rotating with an angular velocity of ω_{gyro}. This gyroscope is mounted on a gimbal, which is rotated with an angular velocity ω_{gimbal}, about y-axis. These two angular movements along mutually perpendicular axes result in a precessing motion, $\omega_{precession}$, about the z-axis, which is also the direction of the angular momentum about that axis. The angular momentum (A) can be found using:

$$A = J * \omega_{gyro} \qquad [1]$$

where J represents the polar moment of inertia of the gyroscope. The corresponding torque, T, generated is equal to:

$$T = A * \omega_{precession} \qquad [2]$$

Using these basic equations, a structure was designed and control schemes were developed for a semi-autonomous robot that is capable of turning using gyroscopic torque.

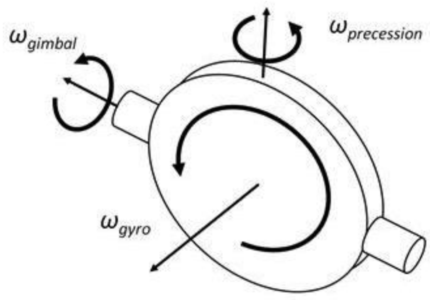

Figure 2. Schematic of a gimbal-mounted gyroscope

The structural design of the robotic platform was defined by the following criteria:

- Design a device that utilizes gyroscopic torque generated by a spinning mass to turn a large frame
- Maintain appropriate gyro-mass to total-mass ratio
- Slow and fast turning capabilities
- Maintain stability during gimbal reset
- Locate specific points on the design to determine angle turned
- Maintain a low experimental cost using off-the-shelf materials and electronics
- Start/stop precisely and ensure repeatability in producing the same turn for the same gimbal rotation

Using the above criteria, the design, fabrication and testing processes were divided into two broad phases. In the first phase, we constructed an experimental robotic platform similar to the reaction wheel approach shown in Figure 1 to test the feasibility of the CMG turning concept using open and closed loop control. In the second phase of the design, we extended this concept to the human to validate turning for full-scale bipedal robots. These two phases will be explained in detail in the next section. Three dimensional designs for both phases were developed using SolidWorks and the experimental setups were fabricated using several off-the-shelf components.

PHASE I: ROBOTIC PLATFORM

The first phase involved fabricating an experimental platform for testing our concept. The main components required were a gyroscope and a rotary actuator. We decided to procure an off-the-shelf gyroscope named "Gyrobike"[8] for use in our concept. This device is a commercial product used to stabilize bicycles for small children. The actuator we decided to use is a HS-805 BB servo motor coupled with a 5:1 gearbox shown in Figure 3 (marked as C). The gyroscope is mounted on a servo-actuated gimbal (indicated by letter B on the figure) capable of 180 degrees of rotation. This gimbal was made into a modular unit so that it could be switched between different test setups.

Our experimental setup, named "*GyroBot"*, is comprised of six major components:

A. Commercial Gyroscope
B. Custom Gimbal
C. Servo / Gearbox
D. Support Leg
E. Caster Wheels
F. Platform Support Structure

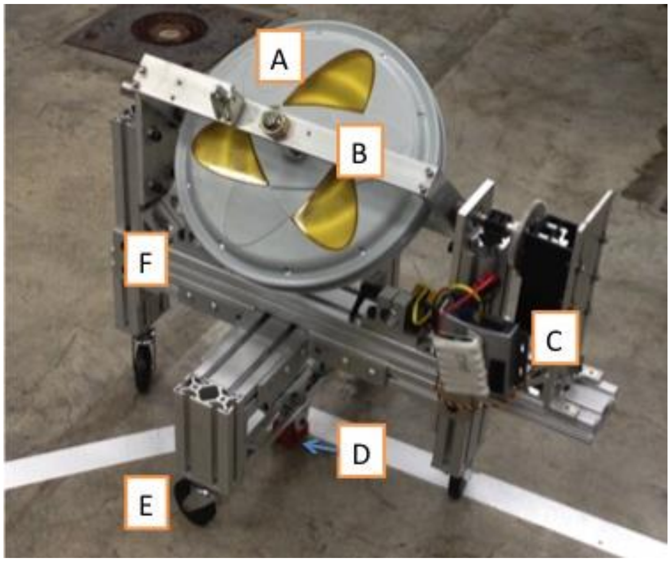

Figure 3. Platform for turning using CMG

To maximize the flexibility of the test bed for the CMG, extruded aluminum was used to build the *GyroBot*. Extruded aluminum and accompanying fasteners permitted quick and easy adjustments to important parameters of the robot that can significantly impact turning performance, including: height and width of robot, lateral position of leg, length of leg stroke, and the height of the gimbal. The angular rotation of the gimbal is provided using the aforementioned servo motor [C]. The "pivot" leg is located underneath the center of mass (COM) of the entire structure always remains in contact with the ground. This static leg represents the leg that a human or robot rotates about during a turning motion.

In addition to the leg, four caster wheels are attached to the base. The caster wheels are loosely mounted in the vertical direction to ensure that the majority of the platform's weight is transmitted through the leg of the structure. An offset of approximately 0.25" was also included in the design of the leg to guarantee that the leg accepts most of the structure's weight. The wheels are necessary for stability due to the constantly changing direction of the precessing angular moment of the gyroscope as the gimbal is rotated. The friction between the casters and the ground surface is kept to a minimum to preserve the fidelity of the turning motion of the robot about its static leg. Although the casters increase the points of contact between the robot and the ground, which slightly compromises testing and our results, they are necessary to prevent damage to the structure during testing.

In addition to the actuating the gimbal using the 5:1 servo driven gearbox, another configuration was assembled to rotate the gimbal faster using a pneumatic actuator. Equation 2 proves that higher torques can be achieved with faster rotation rates ($\omega_{precession}$), which results in a larger turn of the robotic platform. The arrow in Figure 4 shows the pneumatic actuator used to quickly re-orient the active gyroscope. The overall weight of the experimental platform in both cases is approximately 30 lbs.

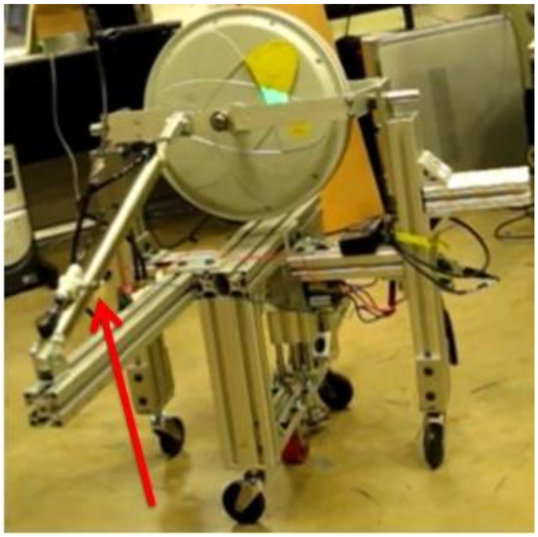

Figure 4. Experimental platform using a pneumatic actuator for gimbal rotation

OPEN LOOP CONTROL

An Arduino based Bluetooth controller was designed to operate the entire system using an Android phone. Figure 5 indicates the open loop operating procedure.

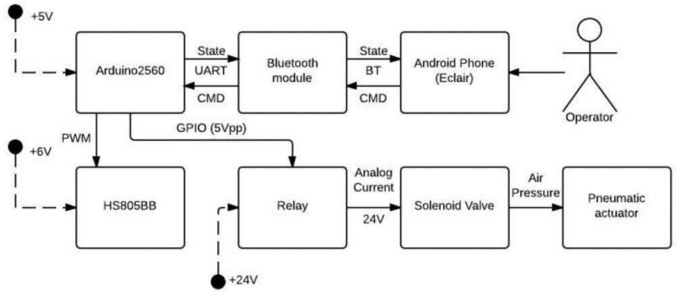

Figure 5. Open loop test procedure

Experiments were first conducted to determine the repeatability of the device using open loop control. Two different sets of trials were conducted. In the first trial, the rotation of the gimbal is achieved using the servo motor and in the second, the gimbal is actuated using the pneumatic setup in Figure 4 above. In each trial, the gimbal is turned to a commanded angle and the corresponding rotation angle of the platform is determined. To properly evaluate and control the system, the angular displacement of the robot must be calculated in real-time. Orientation feedback for the *GyroBot* was achieved using an externally mounted Microsoft Kinect [10] and a PhaseSpace motion capture system. Using the output from these devices, the “real-world” position and orientation of the robot could be obtained before, during, and after experimentation trials. An example of angle acquisition using the Kinect is shown in Figure 6. In addition to this data, angular displacements were also obtained using a digital compass available in a smartphone so as to ensure that the angles are accurately determined. A three-axis magnetometer integrated into a standard smartphone was also used to log real-time orientation data during testing. The smartphone was attached to the *GyroBot* such that the X and Y axes of the magnetometer were in same plane of rotation as the device. A data-logging program installed on the smartphone was used to log magnetic field strength data for all three axes at 100 Hz. The most accurate method for monitoring the orientation of the *GyroBot* proved to be the PhaseSpace motion capture system.

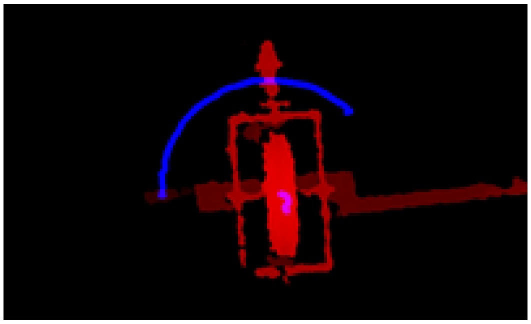

Figure 6. Orientation monitoring using Kinect

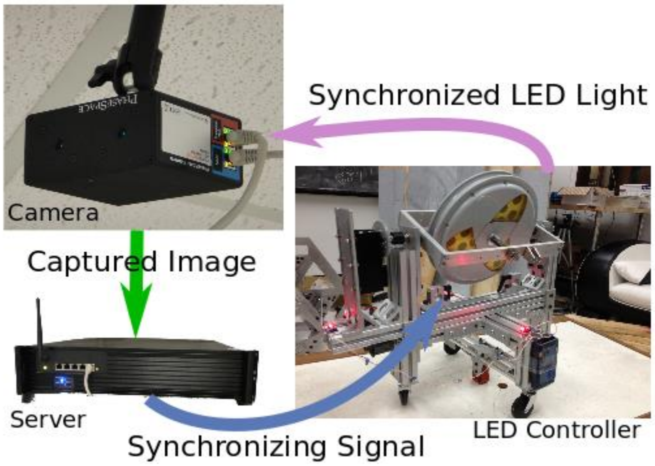

Figure 7. Orientation monitoring using motion capture

Since the PhaseSpace motion capture system provided the best results, we used it ultimately calculate the orientation of the system. The schematic for motion capture data acquisition is included in Figure 7. The motion capture server provides a synchronizing signal to the LED controller and has a sampling rate of 480 Hz. The LED controller lights the LED markers with the synchronized frequency. The cameras capture the image with the markers, and the server calculates the position of the markers. More than three markers are needed to define the position and orientation of a rigid body.

Table 1 and Figure 8 show the difference between the initial and final orientations of the robotic platform found using the motion capture system detailed above.

Table 1 Maximum robot turns produced for different angles of rotation of the gimbal

Angle of Gimbal Rotation (°)	Maximum Robot Turn Produced (°)
10	7.3
20	45.5
30	124.3
50	330.9
90	450.8

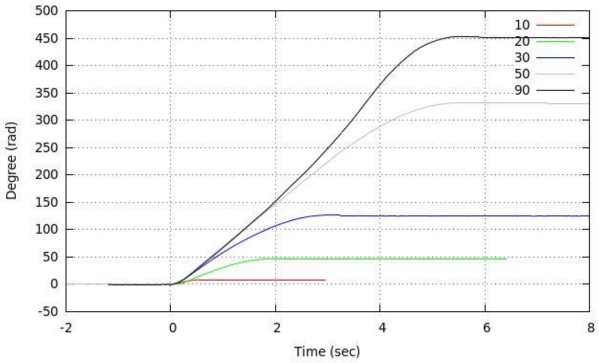

Figure 8. Open loop results using motion capture

Table 2 lists the maximum change in orientation of the robot produced by the pneumatic actuator detailed in Figure 4.

Table 2 Maximum turn produced for different angles of rotation of the gimbal using pneumatic actuation

Angle of Gimbal Rotation (°)	Maximum Robot Turn Produced (°)
25	65
45	180
90	765
100	850

As discussed above, the servo used limited the maximum turning angle due to its slow speed. This is because the amount of torque generated due to precession is dependent on the rate of gimbal rotation. Thus, the pneumatic cylinder was implemented to achieve rapid turning rates and larger angles of rotation. These effects are evident in Table 2.

The video link in [11] highlights all of the aforementioned features of this experimental platform. It should be noted that in former revisions of the platform, a pneumatic brake was included to force the robot to stop at a given orientation. This was a crude implementation that did not yield acceptable results and was thus omitted from this paper.

CLOSED LOOP CONTROL

To precisely control the orientation of the *GyroBot*, we implemented a simple feedback controller.

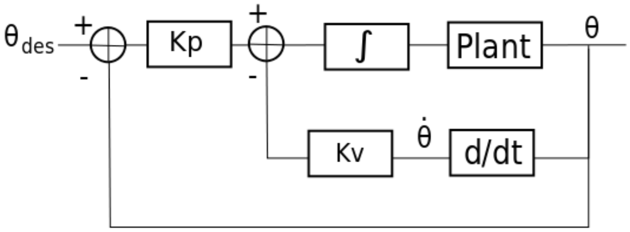

Figure 9. Closed Loop PD Control Diagram

Figure 9 shows the feedback control loop diagram. The desired angle of rotation for the robot is represented as θ_{des}. The actual orientation of *GyroBot*, θ, is obtained from the motion capture system in Figure 7. To achieve a rotation equal to θ_{des}, a torque is applied to the gimbal using the servo motor. The only input currently controlled is the angle of rotation of the motor-gearbox unit. Therefore, we assume the change of θ to be the result of the applied servo torque to the gimbal. For closed loop control of the system, the PD control scheme with respect to the orientation was implemented. The control input is integrated and then applied to the servo motor to achieve the desired rotation of the robot.

PHASE II: BACKPACK

In Phase II, our group evaluated several designs to extend the validation of turning a humanoid robot with a CMG. One such design that was prototyped in hardware is a backpack-style mounting of the gyroscope as shown in a blue rectangular box attached to the robot in Figure 10.

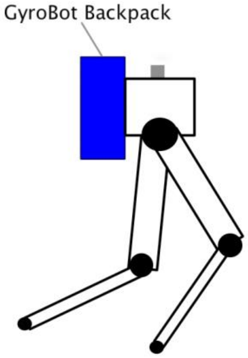

Figure 10. Mounting gyroscope on a biped-robot

Since we did not have access to a working biped robot, we decided to test our backpack design on human subjects. Therefore, the backpack was designed to be safe, modular, and relatively lightweight. The SolidWorks design in Figure 11 includes the gimbal, gyroscope, servo motor, and the accompanying aluminum structure.

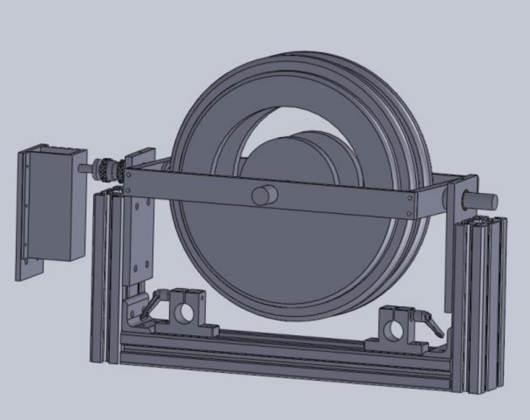

Figure 11. Modular gyroscope-gimbal unit design

The gimbal mechanism used in Phase I was modified to make it more modular such that it could easily be transferred between the two different test setups. The modular gimbal unit mounts to the backpack frame with adjustable tube connectors. The gimbal was arranged such that the gimbal axis was parallel to the ground. Therefore, when the gyroscope is actuated from a vertical position, a torque would be generated about the vertical axis.

Once assembled, the gyroscopic backpack unit was used to change the direction of a walking person. This was tested by having user follow a particular path and manually controlling the gimbal actuator. This modular design allows the system to be integrated into existing humanoid robots. Figure 11 shows the custom backpack mounted on human subjects for testing.

Figure 12. Backpack mounting of the gyroscope on two human-subjects

The demonstration of the backpack concept can be viewed in the link included in [11]. The video clearly demonstrates the potential of this technique in turning a biped robot for human-like locomotion.

VALIDATION OF EXPERIMENTAL RESULTS

A simple one-degree of freedom model of the system was constructed in MATLAB Simulink (shown in Figure 13) to determine the maximum angle turned for a particular gimbal rotation. In the model, the gimbal starts out at zero degrees (the gyroscope is in the vertical position) and moves until it is at the specified gimbal rotation angle. The model assumes that the servo starts out at its stall torque and its behavior can be approximated as a brushed DC motor (speed does not ramp down as it approaches the desired angle) and that the servo immediately stops when it reaches the desired gimbal angle. This is done with the saturation term in the Simulink model. There are several inputs to the system namely the required angle, moment of inertia of the frame about the z-axis, moment of inertia of the gyroscope and the gimbal about the gimbal axis, the angular momentum of the gyroscope rotor, motor stall torque and motor free-load speed.

The motor applies a torque to the gimbal proportional to its speed which increases the speed of the gimbal. The gimbal moves until it hits the desired angle (the saturation term). The gimbal rotating creates a torque on the frame proportional to the gimbal's angle and rate of rotation. This torque is counteracted by a constant frictional damping torque (block denoted 'frictional torque'). The output angle produced is measured in degrees and an example is shown in Figure14.

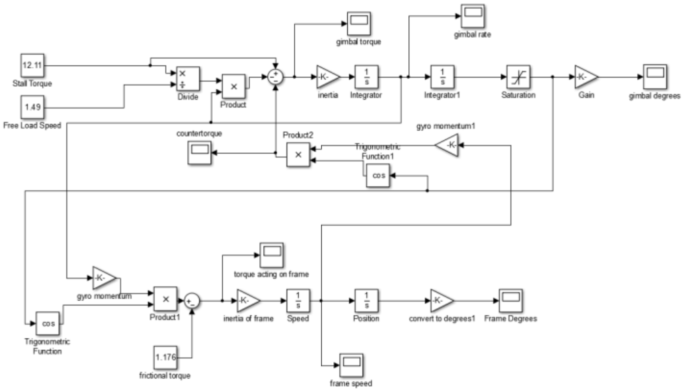

Figure 13. MATLAB-Simulink model used to estimate the behavior of the system

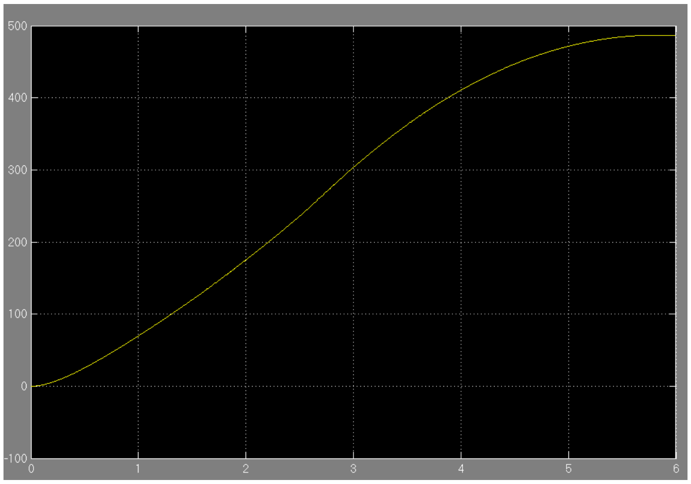

Figure 14. Degrees of frame rotation vs. time

DISCUSSION

Changing angular momentum to turn a humanoid robot is not a new idea[1]. However, doing so using a control moment gyroscope has not been investigated. Changing angular moment to turn other types of robots that are not humanoid has been investigated. For instance, reaction wheels have been used to steer unicycle robots. A one-wheeled robot was also turned using a gyroscope [12] but then that was a one wheeled robotic system and not a humanoid robot. Reaction wheels have been proposed for turning, but are less efficient due the need to be sped up and slowed down. Moment gyroscopes have been extensively used for attitude control of satellites and stabilization of various systems; however, they have not been used to turn humanoid robots. Satellites are quite different than human robots, especially since they operate in the absence of dissipative forces like friction. The IKURA autonomous underwater vehicle used control moment gyroscopes for attitude modification [13] in the presence of viscous dissipative forces; again this is a very different situation from a humanoid robot.

In this paper, a potential method for turning a humanoid robot using a control moment gyroscope is demonstrated. Two forms of actuation have been used namely a servo powered actuation and a pneumatic actuation of the gimbal on which a commercially sourced gyroscope is mounted. Different tests for obtaining the maximum turn angle achieved are conducted. During our open loop experiments, we also found out the repeatability of turning was not extremely consistent. This may be due to the existence of large amount of friction in the system and on the testing floor and the use of imprecise caster wheels to support the structure. Similar effects were noted in the pneumatic actuation too. Despite the friction and the total mass of the system being close to 30 lbs., the precessing torque generated by the CMG is able to easily turn the entire structure. This is significantly higher than the performance of the reaction wheels. Also the orientation determination and control of the pneumatic leg are all manual processes since our main intention was to demonstrate this system's capability to turn.

While the proposed extension to humanoid robot is under active research, we have demonstrated a backpack-style mounting with impressive results. We have demonstrated slow and fast turning using the servo and pneumatic actuation. We also feel that the following idea may present an interesting opportunity in biped robot research. For turning an actual humanoid robot, the gyroscope can be rotated while only one of the humanoid's feet is on the ground, causing the humanoid to rotate about the foot. When the turn is completed, the humanoid puts down the other leg to stop the turn and while both feet are on the ground the gyroscope is moved back to its original position. While this single configuration is advantageous in that it saves space, the obvious limitation in that the robot will be unstable due to the constant directional changes of the precessing torque as the gimbal on which the gyroscope is mounted is tilted. In order to counteract the directional changes and robot instability, another gyroscope can be introduced such that the off axis torque produced by the second gyroscope counteracts the off axis torque of the first. One could possibly change the control of a humanoid robot to account for this off axis torque, for example, one could compensate for the off axis torque by shifting the center of gravity. Though this may seem simple, there are several tests and experiments that are required to be performed in order to formalize the exact idea. Other possibilities that will be investigated for efficiently turning a humanoid robot include addition of several miniature gyroscopes distributed throughout the robot that will be responsible for turning.

CONCLUSION

The use of gyroscopic precession torque has been successfully demonstrated for turning a bipedal robot prototype using a gyroscope mounted on a gimbal. Two different actuation systems, a servomotor and a pneumatic cylinder, prove the potential of a control moment gyroscope in producing large angle turns that are not possible in alternate methods using reaction wheels. A backpack-style mount was also demonstrated for potential extension to biped humanoid robots. There are several benefits to our approach. The use of gyroscope simplifies turning motion and avoids complex motion planning requirements. As the device does not rely on shifting the center of pressure, complicated feet actuators are not required. This approach can potentially be used in rehabilitative and gait assistance devices and for producing human-like turning motion in under-actuated humanoid robots to successfully navigate harsh environments.

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