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ROBOTIC SPINE FOR VERTICALLY ORIENTED MOBILE ROBOTS BALANCING BY CONTROLLING THE GYROSCOPIC MOMENTS

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Abstract

This paper introduces a novel self-balancing robotic spine, based on the principle of active control of the gyroscope momentum. Mobile and walking robots, especially vertically oriented machines, are able to achieve better mobility and rotation in small spaces and move faster if their vertical balance could be independently supported by a kind of automatically applied force, originated from the spine of the robot. Such effect can be reached by the real-time controlling of the momentums of the fast-spinning flywheels inside the gimbals, based on the data from the tilt sensor. Corrective force is applied opposite to the direction of the spine tilt. Depending on the angular speed of the flywheels their gyroscopic momentums could be strong, thus requiring the greater gear rate of the servomotors to overcome and control these momentums. This is what we call CMG (Control Moment Gyroscope).
Usually when an unexpected disturbance affects the robot, it maintains its balance with movements of the whole body and tilting of the body. Such balancing of the humanoid robot is reached by the software. Prevention of the falling is reached by applying a large rotation of the joints which repositions the CMG of the robot. Such software balancing often takes extra computing and power resources. If the disturbance exceeds the response capability of the robot, the robot may lose stability and safety of the robot may be put at risk by movements to maintain balance.
By using a pair or two pairs of counteract-rotating CMGs in our spine, the robot can maintain balance with just small movements of its body, creating at the same time a double balancing force. Smaller flywheels diameter, smaller mass and smaller gimbals can still produce a large compensating balancing force due to the higher flywheel angular rotation and high enough gear rate of the servo motors, overcoming the gyro precession torque, applied to the gimbals. Improved performance and stability were verified with experiments.

Keywords: Self-balancing; robotic spine; control moment gyroscope; brushless self-spinning flywheel; gyroscope precession; flywheel gimbal; tilt sensor; variable speed servo motor control.

1. Introduction

Robots are being deployed for industrial and civil applications due to their accuracy, strength, repeatability and intelligence. Common approach in the design of mobile robot ensures its stability by keeping the gravity vector through the centre of mass. Such stability fails when the robot moves at high speed as the inertial forces become significantly compared to the static gravitational force. However, the momentum of the moving structure can be exploited to enhance stability if it is dynamically controlled. This principle was used in building a gyroscopically stabilized single-wheeled robot “Gyrover” by the researchers at Carnegie Melon University [1],[2]. Another application of this principle had been implemented in a wearable balancing aid, consisting of a set of control moment gyroscopes (CMGs) contained into a backpack-like orthopedic corset, and was designed at the Department of Biomechanical Engineering, Delft University of Technology of Netherlands [5],[6]. Our design is assuming a similar principle for stability but uses a different construction and is aimed to become a universal part for different applications.

Motivation

Every time looking at the balancing of the different vertically-oriented robots, same question came to our mind again and again: why not design a universal self-balancing spine to free the robot from complicated attempts of balancing using the entire body? Indeed, why the self-balancing ball exists, self-balancing plate exists, but self-balancing spine for robot we have not met. We felt motivated to filling this gap.

Control Momentum Gyroscope - State of the Art

A gyroscopically stabilized single-wheeled mobile platform (GyroBot) was designed at the Department of Mechanical and Production Engineering of National University of Singapore according to the same principle used to design Gyrover, but included some modifications in the actuation mechanism to generate forward and backward motion [3].
A wearable balancing aid, consisting of a set of control moment gyroscopes (CMGs) contained into a backpack-like orthopedic corset, was designed at the Department of Biomechanical Engineering, Delft University of Technology of Netherlands [5,6].
A bipedal robotic ball-shaped chassis, namely “AnyWalker” with the unique kinematic scheme which has the possibility to locomote in complicated multi-level environment has been designed at the Kuban State University (Russia), AnyWalker is equipped with the system of compensation of external impacts with motor-wheels which can stabilize the robotic system in 3 dimensions[7].
An approach to control the orientation of the robot using CMG has been conducted at the Robotics Research Group from the University of Texas of Austin USA. They first designed a backpack mount for the gyroscope gimbal and conducted experiments using human subjects to estimate the performance of the system that could potentially be used to turn bipedal humanoid robots [8].
A study of the novel femto-satellite design that uses a micro-electromechanical system Control Moment Gyroscope is described in [9]. The focus was on the principal design, modelling, and discussion of the proposed Control Moment Gyroscope while detailing a controllable femto-satellite design that can make use of attitude control for simple sensing missions, as most femto-satellite designs have no attitude control capability due to the power and size constraints on attitude control actuators.

Idea of the Gyroscopic Spine Construction and Steering

A drawing of the idea of one section of the self-balancing robotic spine, based on the principle of active control of the gyroscope momentum is shown in Figure.1.

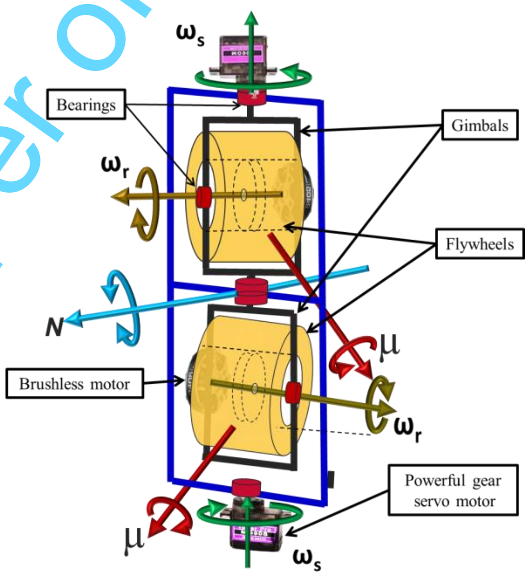


Figure1. A section of the robotic spine

Idea is as follows. Two actuators are capable of modifying their angular momentum to impact a torque on a body of the Spine. They consist of 2 self-rotating flywheels mounted inside the gimbals, which, in turn, are swivelled by the two

servomotors. Usually by changing the angular velocity ω_r of the flywheels, an angular moment μ is generated and affects the gimbal. But here, the rotation of an outer gimbal (by swivelling angular velocity ω_s reorients the flywheel and produces a significantly larger gyroscopic moment denoted by **μ**.
Because this momentum is orthogonal to the gimbal and flywheel spin axes, it is applied directly to the gimbal bearings. This allow to apply a relatively smaller gimbal motor torque and power, and considerably larger output momentum *N* is possible.

Figure 2 shows a scheme for parrying disturbances acting on a precessing flywheel. A sector (quadrant) of the rotating flywheel is highlighted, which is installed inside the gimbal, which, in turn, is attached to the housing using bearings. For calculations, we visualize the spinning of the flywheel quadrant by quadrant.
Symbols:

- Flywheel rotation – spinning;
- Body tilt around the Y axis – roll;
- Body tilt around the X–axis - pitch;
- Rotation of the gimbal around the vertical Z axis – yaw, turn.

All parts of the highlighted flywheel quadrant move towards the rotation around the vertical Z axis. The flywheel rotates at a constant speed. Each time the mass of the quadrant approaches the Z axis of rotation, it tends to "outpace" the movement in a circle. The red arrows in the drawing reflect this trend. Conversely, when the mass moves away from the Z axis of rotation, it begins to lag behind. Collectively, in all four quadrants, the flywheel will have a strong tendency to roll. If the flywheel mounted inside the gimbal has a random roll, then the roll axis will tend to become co-axial with the axis of rotation around the vertical Z axis. The pitch DOF is mechanically fixed. Our goal is to prevent roll by limiting the roll freedom, and use this torque to prevent the entire spine body from falling. This is reached via the forced swivel control of the gimbal by the gear servomotor.

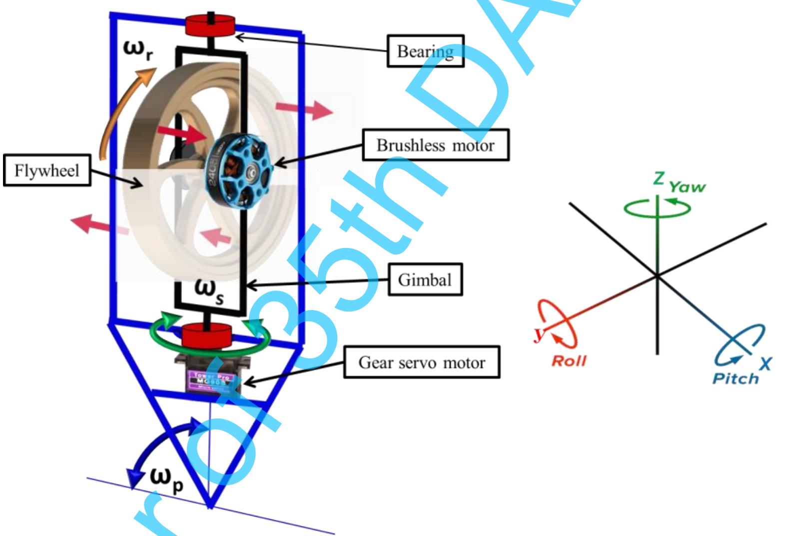


Figure 2. Scheme of parrying disturbances

CMG Torque estimation

It was necessary to evaluate the following:

- Given a certain rate of rotation and roll, estimate what torque is required to prevent the entire spine structure from rolling (falling)?

We performed an estimated calculation for a simple case: a brass flywheel with a radius of ***R*** and a mass of ***M***. At the same time, we noted several basic concepts:

- The moment of inertia when controlling the gyroscopic moment (CMG) can be calculated by multiplying the mass of the flywheel by the square of its radius of rotation.
- The radius of rotation is an indicator of how much mass is distributed relative to the axis of rotation. The units of measurement of the moment of inertia are usually **kg.m²**. It is a unit of inertia of rotation, which is a measure of the resistance of an object to changes in rotation.
- The efficiency of the CMG is directly related to its torque. A higher efficiency means that more torque can be generated at a given angular velocity. This allows to more accurately control the position of the spine.

- The moment of inertia of the CMG can usually be adjusted by changing the mass or radius of rotation of the flywheel. This can be done by adding or removing mass, as well as changing the shape or material of the flywheel.
- In our case, gyroscopic moments are controlled by synchronous rotation of gimbals with flywheels using servomotors with powerful gearboxes based on data from spinal tilt sensors, which reorients the flywheels.

Then angular moment or torque enough to compensate the falling is:

$$\mu = \omega_s \omega_r M R^2 \qquad (1)$$

where:

ω_r - angular velocity of the Rolling flywheel,
ω_s - angular velocity of the Swivelling servo motor,
M – mass of the flywheel,
R – diameter of the flywheel.
In our case:
R = 3cm = 0,03m
ω_r = 7000 rpm = 733 rad/sec
ω_s = 6.53 rpm = 0.68 rad/sec
M = 330g = 0,33kg
μ = = 0.68 rad/sec x 733rad/sec x 0.33kg x 0.0009m^2 = **0.15 kg-m = 1,47 N-m**

This means, that the maximal possible torque obtained from the single control momentum gyroscope (CMG) module consisting of a single flywheel diameter of 6cm, mass 330g, spinning at constant speed of 7000rpm, and swivelled by the single gear servo motor at maximal angular speed of 0.68 rad/sec, can produce a maximal pitch-compensating torque **μ = 1.47 N-m** (Figure.4a).
By using a pair of counteract-rotating and counteract-swivelling CMGs in our spine, this torque doubles. Counteraction prevents from the slow rotation around the yaw axis of the entire construction (Figure.4b). Adding another pair of CMGs along with the pitch-balancing pair, adds a roll-balancing option. Then the spine, consisting of four interlaced CMGs for pitch & roll balancing should be able to maintain balance with just small movements of the swivelling servos, creating at the same time a double balancing torque N=**2.94** ***N-m*** around pitch and roll axes (Figure 4c). Final torque N is counter-directed to the pitch and roll directions of the spine, which is measured by the dual-axes tilt sensor +/-90º.

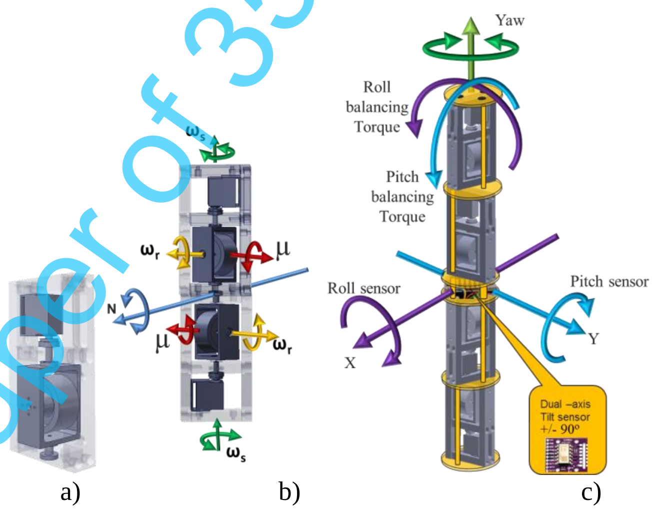


Figure.4. 3D model of the CMG self-balancing robotic spine

Self-balancing Spine – The Construction Requirements

From the equation (1) we could see, that CMG moment is proportional to its mass, angular velocity of the flywheel, angular velocity of the swivelling servomotor and to the square of the flywheel radius. In other words:

- Doubling the mass, doubles the momentum,
- Doubling any of the angular velocities, doubles the momentum,
- Doubling the radius, quadruples the momentum.

Usually the easiest solution would be selection of a flywheel of bigger radius and mass. But we are creating a spine and it should be as thin as possible and also not too heavy. We have prototyped multiple different construction combinations of flywheels shape, mass diameter, spinning motors and gimbals. Few of them are shown in figure 5.

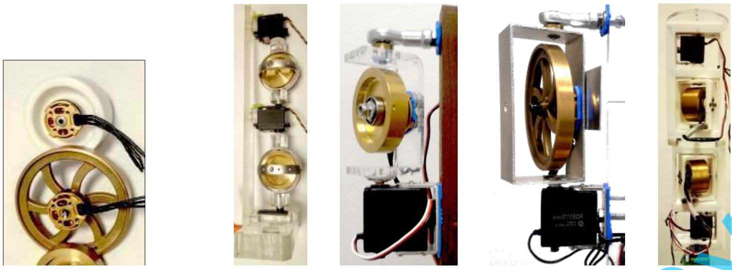


Figure.5, Evolution of the attempts of CMG prototyping

After conducting experimental tests with the flywheels of different mass, diameter and material, we have come to implement a brass flywheel of 3cm radius, 3cm depth and 300g mass. This flywheel should be self-rotating. In our meaning it should be a kind of brushless "Hub motor", shaft of which with coil inductors around is stator, and outer heavy wheel with permanent magnets spinning around those coils, is rotor. This would be a self-spinning flywheel.
Our requirements for the flywheels were a high speed of angular rotation at minimal level of vibration. Our search for a small size of such hub motor brought us to a few available products, maximal angular velocity of which did not exceed 3000rpm.
Hence we began prototyping a flywheel, driven by the separate motor, which would provide angular velocity of at least 7000rpm, have enough torque to start rotation of heavy flywheel, and to be mounted inside this flywheel. Such motor was found. We used brushless motor M2205S 2600KV for Quadcopters (45g).

Description & Features of the brushless motor:

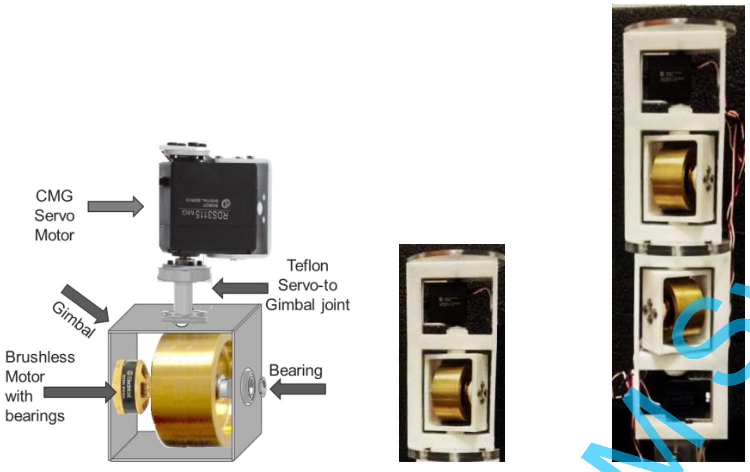
- Model: M2205S;
- Shaft: M5;
- Weight: 45g;
- Max Angular velocity - 24500rpm at 12V 30A control.
- High Strength N52 Neodymium Magnets;
- Active Cooling Fins Greatly Reduce Motor Temperatures;
- Race Spec Performances;
- Active Cooling Fins Greatly Reduce Motor Temperatures;
- Light Weight Design;
- Japanese Bearing For Performances.

Tilt sensor

To measure the tilt angle and angular velocity of the robot, an inertia measurement unit (IMU) was used. CJMCU-100 is a dual-axis tilt sensor chip measuring 90 °, based on 3D-MEMS technology. The sensing axes of the internal sensing elements are parallel to the mounting plane and are orthogonal to each other. Low temperature drift, high resolution, low noise and robust design made the SCA100T an ideal choice for horizontal instruments. Murata's tilt sensor is better able to withstand vibrations and can withstand up to 20,000 shocks. The IMU consists of an inclinometer) and a gyro sensor. Even though the inclinometer can accurately measure the tilt angle of the body, it cannot measure the correct angle during fast rotation because of centrifugal force. On the other hand, the gyro sensor used to measure the angular velocity of the body can estimate the angle of the body by integrating angular velocity.

CMG Module

The module consists of two CMGs. Each CMG has two actuators. One actuator rotates the flywheel and the other rotates the gimbal in which the flywheel is spinning. If both flywheels are controlled to rotate with the same magnitude and in opposite directions, then both gimbals are also to be controlled in opposite direction. Then the final torque doubles. The CMG generates torque in a direction perpendicular to the rotational axes of the flywheel and gimbal. The magnitude of the torque is the product of the angular velocity of the gimbal and the momentum of the flywheel. In order to generate enough torque, it is necessary to have a bigger moment of inertia and a faster flywheel speed. To ensure that the torque of the CMG is accurate, the two flywheels need to rotate at the same constant speed. Thus the PWM controller is sending the same PWM pulses to both flywheel motor controllers. To reach doubling the torque the second CMG was mounted so, that it was mirrored vertically and horizontally (Figure.6 (c).

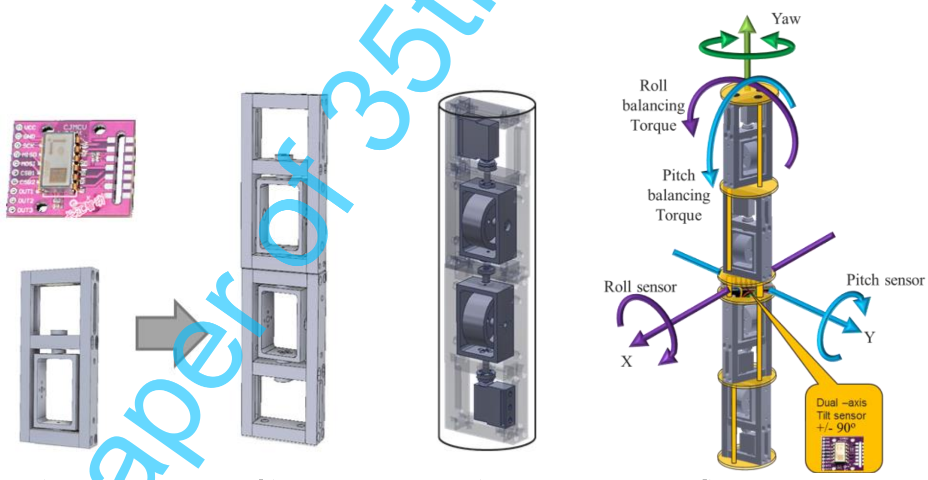


a) b) c)

Figure 6. Brushless motor and CMG module

The gimbal motors used in the CMG do not need high speed, but just sufficient torque. The Robot Digital Servo RDS3115MG was selected. Torque varies between **1.3 - 1.6 N-m**, which is commensurate with the required torque estimation.

The outer frame and the gimbal were made of the white Teflon material, which is a synthetic fluoropolymer that can take temperature of +/-200 degrees Celsius and has good resistance against chemical and corrosion. Another reason, why Teflon has been selected, is its exceptional low frictional coefficient, making it one of the prime choice for sliding plate applications. This feature of Teflon allowed us to avoid using bearings. As a result, the frame construction obtained a capability to dampen the vibration from the extremely high speed (up to 20,000rpm) flywheel motors (Figure.7).



a) b) c) d)

Figure.7. Dual-Axis tilt sensor + evolution of Gimbals & Frame + future construction

Figure 7b shows a design for balancing both tilt and pitch, which we plan to assemble and test as the next step.

Alternative analog tilt sensor approach for CMG control

Initially, the control of the brushless flywheels motors and gimbal servomotors, as well as the reading of tilt sensors and the generation of control signals for the gimbal servomotors was carried out by an Arduino microprocessor.

It seemed to us that in some cases the control was somewhat delayed, as a result of which the spine twitched excessively when returning to balance.

Alternative approach was to use the analog outputs of the tilt sensor to control the CMG due to their higher speed of operation.

The CJMCU-100 tilt sensor has three analog voltage outputs for each axis. We have implemented such analog control for the RDS3115MG servo motor, intended for gimbal swivelling.

The idea is that we generated a triangular voltage at the PWM frequency of the servo control and used a comparator to compare the triangular pulses with signals from the tilt sensor to generate pulses in the range of 1-2 milliseconds.

The functional and electrical circuits are shown in figures 8 and 9, respectively.

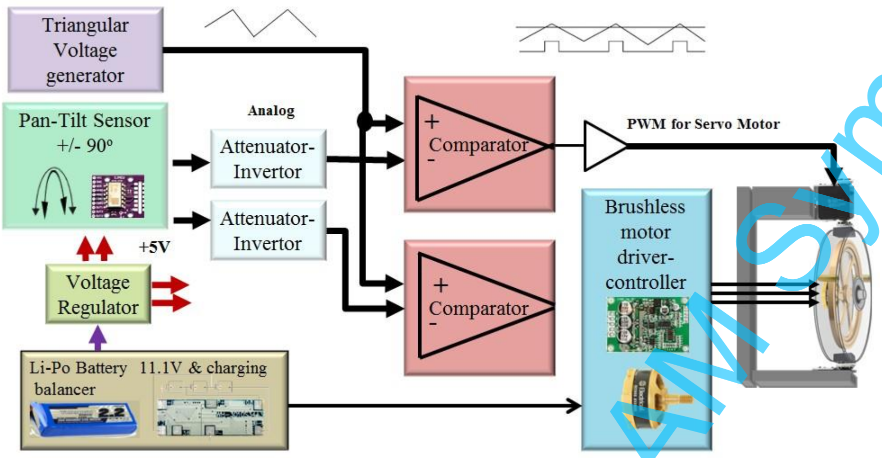


Figure 8. Functional Diagram of the CMG Analog control

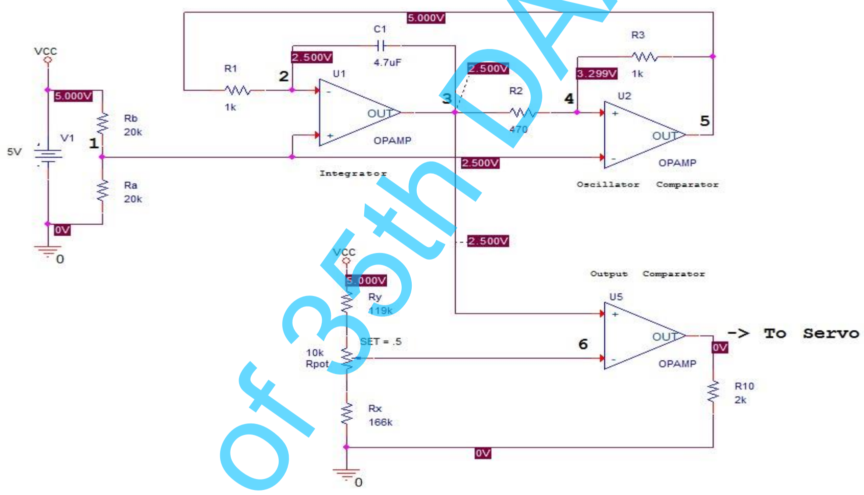


Figure 9. Electrical diagram of the CMG Analog control

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Conclusion

By prototyping, experimenting, research and development, a working prototype of a self-balancing robotic spine has been created. It meets our expectations to implement it in vertically oriented robots. We consider this device as a kind of an instrumentation tool for implementation in different mobile vertical oriented robots.

Future work

As a first step we are hoping to implement this spine in a “Telescopic retractable unobtrusive vertical self-balancing mobile robot for reconnaissance on the ground from a telescoping height”.

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