e-Yantra Robotics Competition

eYRC-BB#2403

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Design

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Instructions:

- There are no negative marks
- **Unnecessary explanation** will lead to less marks even if answer is correct
- Use the same **font and font size** for writing your answer
- If required, Draw the image in a paper with proper explanation and add the snapshot in your corresponding answer

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Q1:

Explain the significance of torque of motor in making the balance bot stable and responsive.

Answer:

Torque in motors is a necessity to maintain stability and response in the system. We are using the motors in differential drive configuration in which the torque is effectively applied to both motor shafts.

In a balance bot, the body experiences a torque at the point of the center of gravity due to gravitational force. Let **m** be the mass, **θ** be the tilt angle, **L** be the length from the motor shaft to the COG and **g** be the acceleration due to gravity. Torque acting on the body is given as $\tau = mgl\sin\theta$.

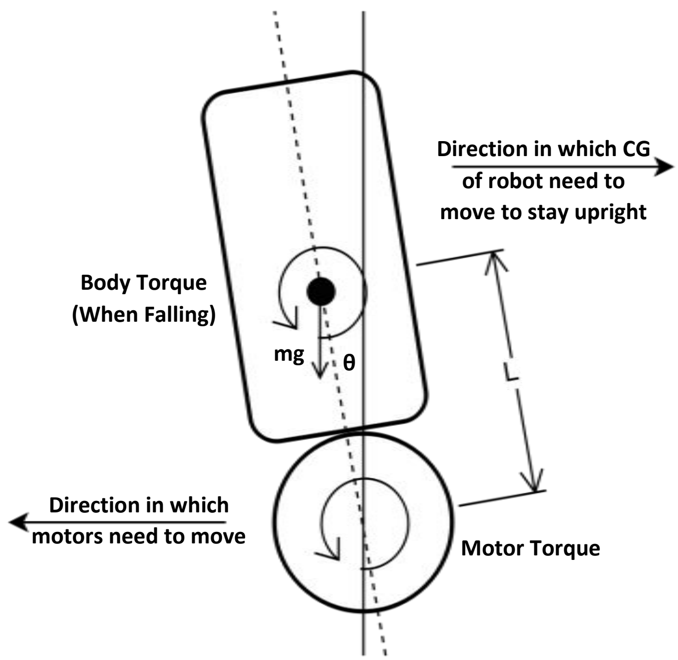


Figure 1.1: Free body diagram of the Balance Bot

Therefore, if the bot has to be stable, the motors should be capable of providing a torque greater than that acting on the body. If the torque of each of the motor is less than half the net torque of the body then the motors will not be able to overcome the body torque and bot will be unstable and topple over. The robot might start to rotate or tilt around the wheel shaft, if the static motor torque is too less.

The motors should move in the direction where the robot is falling to make the tilt angle 0. Hence, a greater motor torque will make the motors respond faster to offsets. High torque is also necessary if the robot has to climb a slope. However, if this torque (while moving) exceeds the frictional force acting on the wheels, slipping will take place, which is undesired.

In addition, the maximum torque provided by both motors sets the limit for the maximum angle the bot can tilt, beyond which the motors will not be able to balance it back.

$$\tau_{max} \geq mgl\sin\theta_{max}$$

Q2:

Compare the given types of motors for making the balance bot. DC motor, Stepper motor and DC motor with encoder.

Answer:

1. **DC Motors** are continuous rotation analog motors, which require only power signals to be driven. They have very high RPM and hence, they require gear reduction mechanism to provide sufficient torque, which is required for better stability for our Balance Bot. The gear mechanism introduces backlash error, which affects the motor response. DC motors are open loop actuators and do not provide any feedback. However, their operation is comparatively smooth, quiet and vibration-free.

2. **Stepper Motors** on the other hand require digital signals and they rotate in increments with the help of electromagnets. They provide higher accuracy because of this positional control no extra feedback programming is required. However, this working principle of rotational increments also reduces their reaction time and they will not be capable of balancing the robot quickly. Comparatively, they provide more torque at lower speeds. However, they have lower power efficiency. At higher speeds, the torque drops rapidly. They are bulky and are generally more expensive. Programming the rotation increments is slightly more complex compared to DC Motors.

3. **DC Motors with Encoders** are the same as described previously but these form a closed loop system providing positional feedback with the help of incremental shaft encoders. Hence, we can measure accurate linear and rotational position of the robot, achieved through simple interrupt programming of encoder pulses. This is helpful in computing the robot's velocity for better motor control and hence overall stability of the robot. This is the best trade-off in terms of cost and performance.

Q3:

Compare the two designs shown in Figure 1 and Figure 2 in terms of stability, response, construction and programming.

Figure 1: Vertical Design

Image courtesy: www.intorobotics.com

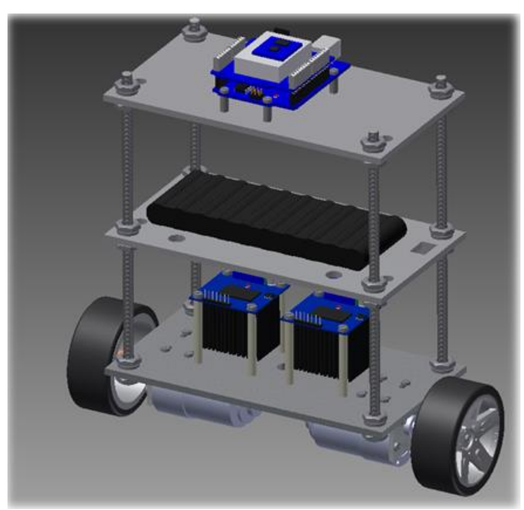


Figure 2: Stackable design

Image courtesy: http://letsmakerobots.com

Answer:

Fundamentally, for a given size of the robot, the design (vertical or stacked) does not affect the stability, response and programming much as they are both based on the principle of inverted pendulum. However, from a construction point of view, stacked design is much easier to implement and update.

Stability and Response – The mass moment of inertia of the robot must be high so that it tilts more slowly when external torque is applied. The mass in the vertical design is distributed evenly, whereas it is distributed as different tiers in the stacked design. Hence, the different tiers can be moved up and down in order to shift the center of gravity (Z_{cm}) as required. The taller the robot, more the stable it is.

Now, consider a performer on a tight rope with his hands spread wide or using long horizontal pole to balance him. It is much easier to balance by doing this, without which, he will sway more on the rope. In vertical design, all the components are in a vertical plane, reducing its depth (Y-axis width). The vertical design represents the performer without the pole. Therefore, by distributing the mass away from the pivot point, as in the case of the stacked design, we can improve the stability (Moment of Inertia increases and Angular Acceleration decreases, hence less tipping). Thus, response to offset tilts is also improved by slowing down the sway. Increasing this depth is very tedious in the case of a vertical design.

Construction – The stacked design is more feasible to construct compared to the vertical design. Various components can be easily mounted and removed, without having to worry much about the CG shift as the tiers can easily be shifted later as required. Another major advantage is that, the stacked design is scalable. For example, if we want the robot to carry some weight, this can be easily done in the stacked design by adding a new tier. The design can be constantly updated and new features can be incorporated with ease. On the other hand, creating vertical stacks (along the depth) is not very feasible.

However, if the design specifications and size constraints are already given and no much changes are required, the vertical design is much simpler to construct quickly and more compact in size.

Programming – From a programming point of view, one would generally opt for the stacked design while developing the model for the robot, as it is much easier to debug and calibrate the robot (in terms of PID control). Programming and Construction go hand in hand; hence for making changes in the hardware in order to meet the software specifications, stacked design is preferred.

Q4:

Where should be the ideal position for center of gravity while constructing a Balance Bot? Draw a rough sketch of your dream design using the components provided in the kit. Show the tentative position of center of gravity. Consider the size and weight of all the components, which you will use.

Answer:

Ideally, for a given mass of the robot, the **position of CG must be high** so that mass moment of inertia increases. When external torque is applied to the robot (such as the one applied by gravity, trying to make it fall), the robot tips more slowly (or the angular acceleration reduces) as the radius increases (distance of CG from wheel axles). Hence, a higher CG provides better stability and slower response to offsets, giving the motors more time to balance it back.

Ideally, in our case, the mass is almost equally distributed along the center of X and Y axes. However, along the Z axis, mass is unevenly distributed among the various tiers.

$$z_{cm} = \frac{1}{Total\ Mass} \sum_{k=0}^{n} M_k R_k$$

Where n is total number of components and M_k and R_k are the mass and distance of the component, with respect to the ground.

Motors ~ 180g each	Motor Driver Board ~ 50g	Acrylic Board ~ 30g each
Li-Po Battery ~ 180g	Wheels ~ 20-30g each	Frame Support ~ 150-200g
Development Board ~ 100g	GY-80 Module ~ 3-4g	Other Components ~ 20-30g

**Approximated weights of all components, Total Mass ~ 1kg*

Using the above values, we get Z_{cm} = 11cm above the ground, as shown in *Figure 4.1*. X_{cm} and Y_{cm} will be exactly at the center, parallel to the wheel axles.

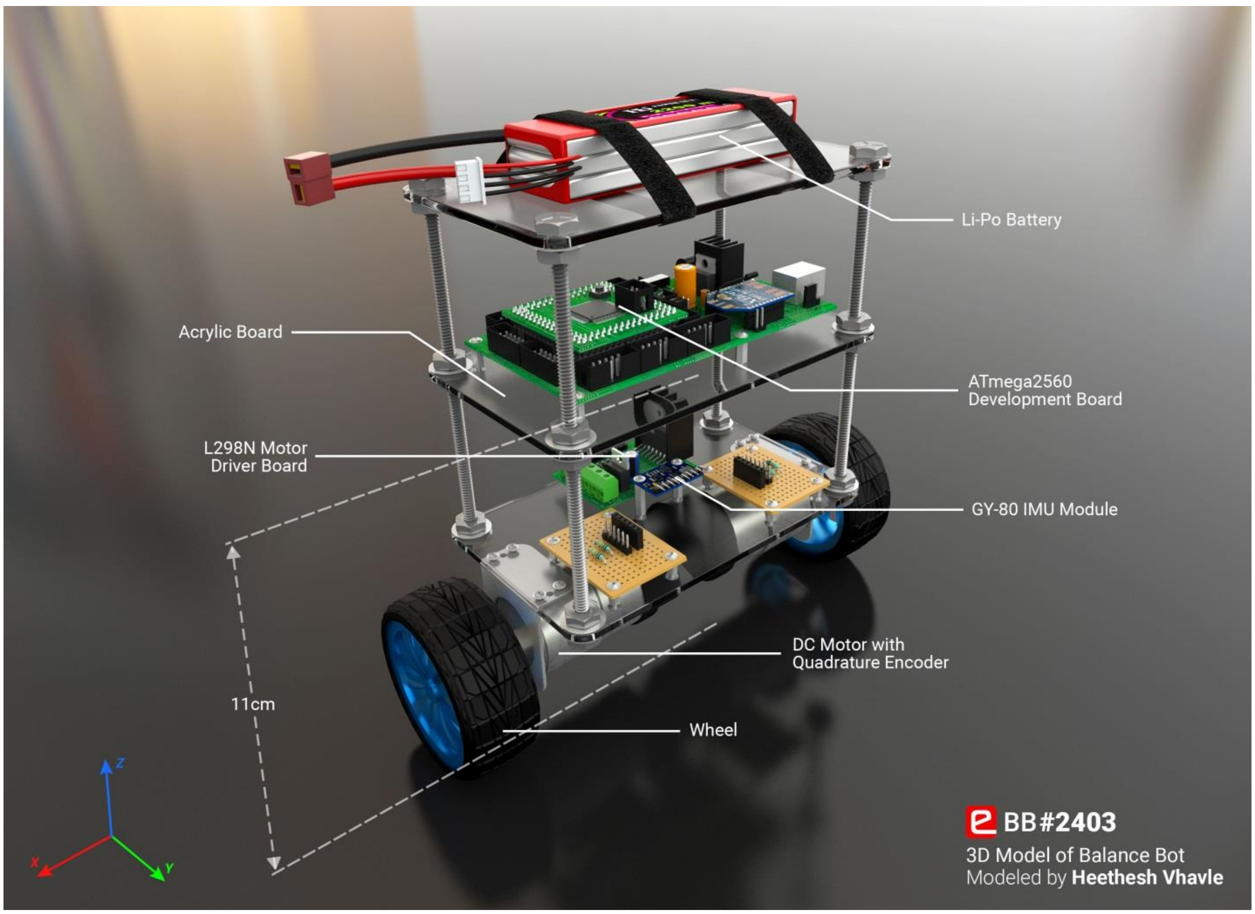


Figure 4.1: 3D Model of the Balance Bot showing the position of center of gravity along the z-axis.

NOTE: The 3D model shown above is for representational purposes only, showing the tentative position of the center of gravity. In actual, the position of CG can be adjusted by shifting the Microcontroller Board Tier a little higher, or by adding extra weights at the top tier.

Q5:

What will be placement of the tilt sensor (GY-80) in your dream design?

Answer:

The GY-80 sensor module will be placed on the **bottom** most tier. The sensor will be placed exactly along the line joining the center of gravity and parallel to the wheel axles, as shown in *Figure 5.1.*

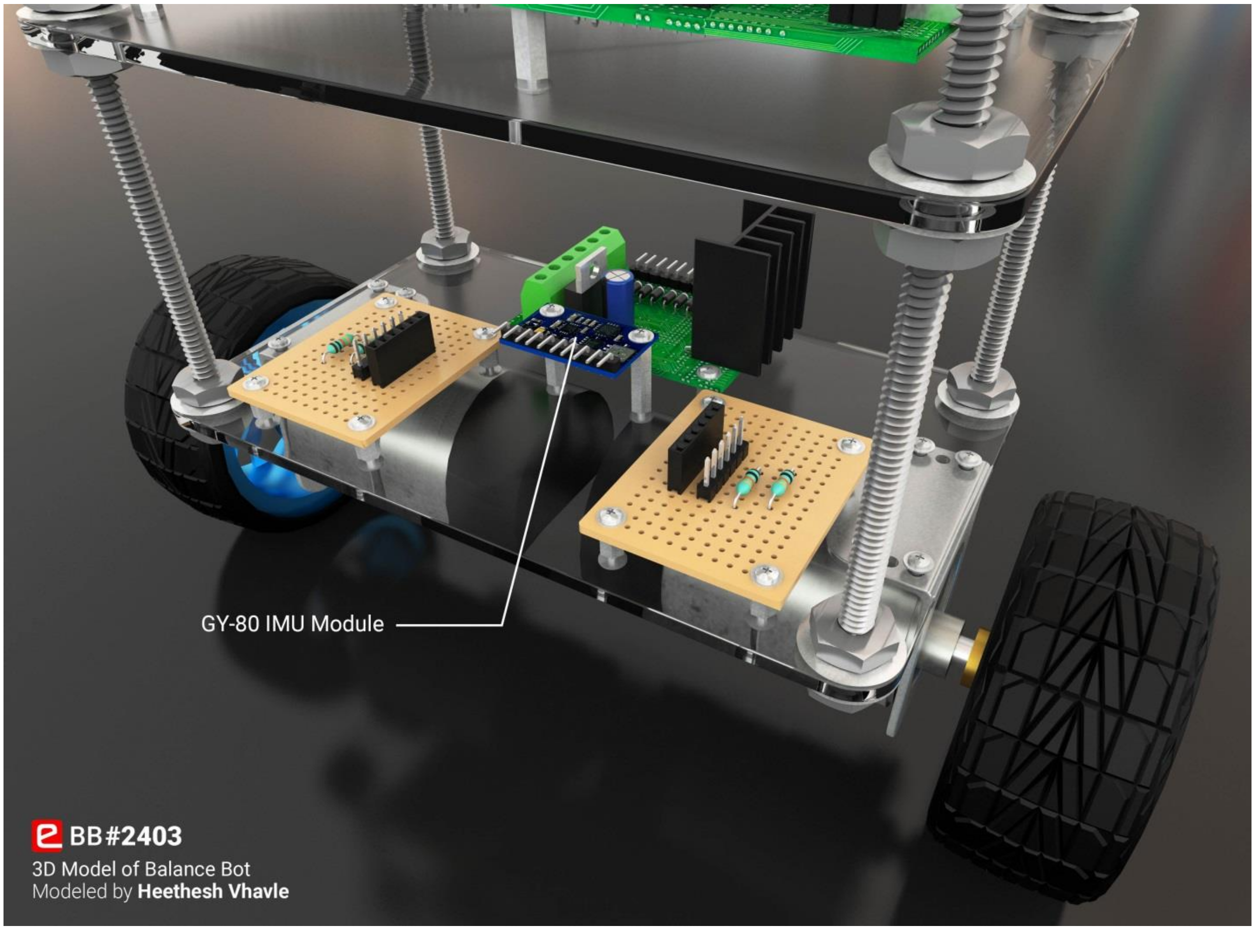


Figure 5.1: 3D Model of the Balance Bot showing the position of GY-80 IMU Module.

The angular rate measured by the gyroscope is not affected by the placement of the sensor, as it will vary by the same amount at all points on the robot. However, as the distance from the ground increases, linear acceleration and vibrations, measured at higher points, increases. This could lead to false readings on the accelerometer. Therefore, the sensor is placed at the bottom.

Q6:

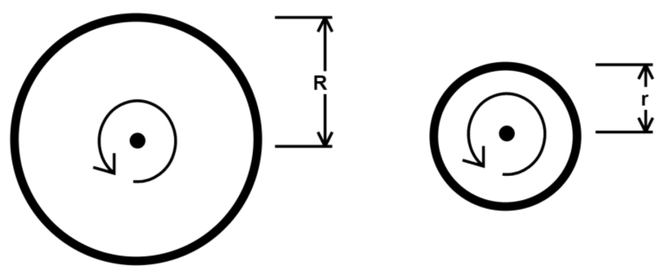
What will be the effect of diameter of the wheel while making a balance bot in terms of stability and response?

Answer:

The wheels of a robot play an important part not only in locomotion but also in supporting the weight of the entire robot. The diameter of the wheels should be chosen in order to meet the torque and response requirements of the system. The net torque, which the motors exert on the wheels, is expressed as,

$$\tau = I\alpha$$

Consider two wheels with a radius **r** and **R**.



We know that Moment of Inertia,

$I \propto Mr^2$ or $I = Mr^2$

$$\therefore \tau = Mr^2\alpha$$

$$\therefore \alpha = \frac{4\tau}{Md^2} \quad ----(1)$$

$\boldsymbol{\alpha}$ is the Angular Acceleration here. Let $\boldsymbol{a}$ be the linear acceleration.

$$\therefore \tau = Mr^2\frac{a}{r} = Mra$$

$$\therefore a = \frac{\tau}{Mr} = \frac{2\tau}{Md} \quad ----(2)$$

Equation (1) shows that for a given torque, an increase in the wheel diameter decreases the angular acceleration, slowing down the tilting of the robot, hence making it more stable against offsets and giving the motors more recovery time to balance it.

On the other hand, *equation (2)* shows that an increase in diameter also slows down the linear acceleration, effectively decreasing the response time of motors to move quickly in the direction of the robot falling, in order to balance it.

Thus, the selection of diameter of the wheel is a trade-off between the stability and quick response of the robot.