An Evaluation of Methods to Achieve Better Performances of Wheeled Robots

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Executive Summary

Robots are becoming a significant force in manufacturing, medicine, agriculture, and other fields. In 2014, 1.4 million industrial robots were employed in the manufacturing industry, and in 2020 rising to 3 million employed. The U.S. government invests more than 2.2 million dollars in robot research annually. The benefits of utilizing robots are achieving higher accuracy and precision, improving quality of life, and reducing risks. The wheeled robot is a preferable solution than its legged counterpart because it is simpler, cheaper, faster, more durable, and more balanced. However, further improvements in designs are necessary for improving its performance. Thus, an evaluation of this topic is conducted in this report.

The analysis shows that the two-wheeled robot is the most competent structure. It has a better efficiency design and a more human-like appearance than other wheeled robots. However, the challenge of a two-wheeled robot is its balance. A two-wheeled robot requires four components, which are the controller board, the servo motor, the inertia measurement unit (IMU), and the battery. These components work together in performing the robot's motion. In a two-wheeled robot, the wheels and body form the inverted pendulum system, and the swinging back-and-forth motion is utilized to combat the inertia.

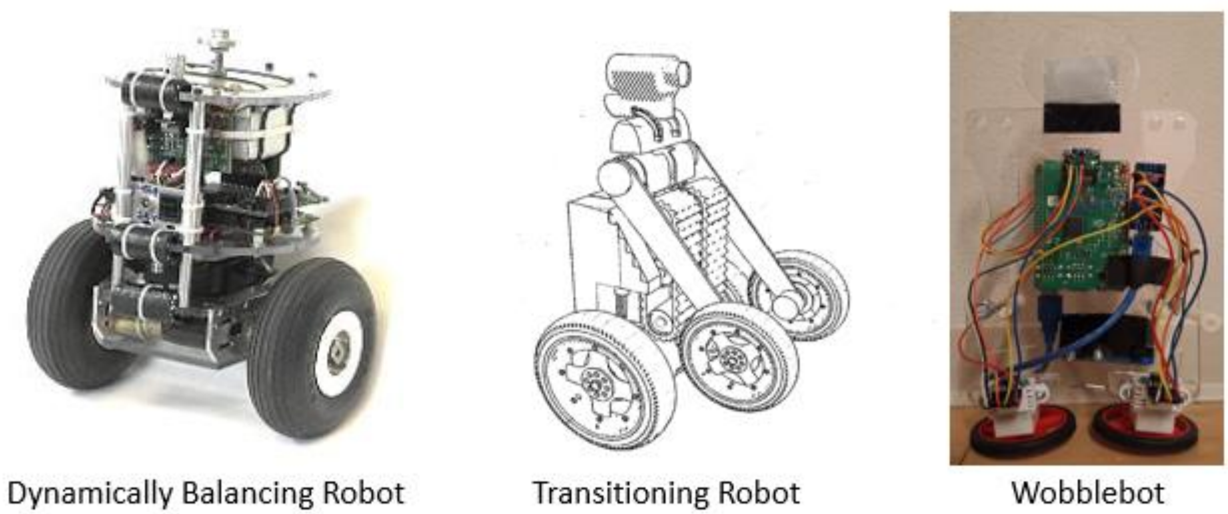

Figure 1: A picture containing three designs of the two-wheeled robot. The left shows a dynamically balancing robot, which has two vertical wheels placed at two sides of the robot. The middle shows a transitioning robot, which can transition between two-wheeled mode and four-wheeled mode. The right shows Wobblebot, which is a new design using the tilted-wheel feature and can achieve passive stability and dynamical balancing simultaneously.

Three different designs of the two-wheeled robot, as shown in Figure 1, are analyzed for their performances: dynamically balancing robot, transitioning robot, and Wobblebot. Dynamically balancing robot, with two vertical wheels at sides of the body, applies a feedback control loop system to balance itself constantly. It shows good performance in balance, but its stability and maneuverability are not ideal. Building upon this balancing technique, transitioning robot adds the transition between passively stable by a four-wheeled mode and dynamically balancing by a two-wheeled mode. This functionality provides robot prominent maneuverability, passive stability, and flexible control of its height, but its drawbacks are having to transition between modes and high complexity. To further address the issues in transitioning robot, Wobblebot was designed with its tilted-wheel feature to achieve passive stability and dynamical balance simultaneously. Previous experiments validated its outstanding balance, stability, and simplicity, but also showed its poor maneuverability. In the future, Wobblebot still needs a complete control loop architecture and more experiments to study its dynamics. As shown in Table 1, a comparison table was created from scoring 1 to 5, where 1 is the poor performing and 5 is the best performing.

Table 1.Comparison table between three different designs of two-wheeled robots. A scoring system from 1 to 5 was assigned to each criteria column. A score of 1 is the poor-performing, and 5 is the best-performing.

	Dynamically balancing robots	**Transitioning robots**	**Wobblebot**
Balance	4	4	5
Stability	3	4	5
Maneuverability	3	5	1
Simplicity	2	1	5
Total	12	14	16

Based on the results, Wobblebot outperforms the other two in the total score. However, since each robot has its advantages, they are distinctively useful in different demand. Dynamically balancing robots are recommended if high stability is not required. Transitioning robots are recommended if performing on extreme terrain. Lastly, Wobblebot is recommended if the ground is flat and tasks require distinctive balance and stability.

1 Introduction and background

Today, robots are becoming a major force in manufacturing, medicine, agriculture, and other fields. In 2020, three million industrial robots are expected to be deployed in the manufacturing industry alone, which is more than double the 1.4 million employed in 2014 [1]. To stimulate the development of robotics, the National Robotics Initiative (NRI) funds at least 22 million dollars annually on robotics research [2].

In certain contexts, reducing humans with robots can enhance accuracy and precision, improve quality of life improvement, and risk [3]. Due to the sophisticated computation skill and continually advancing technologies, robots are ten times more precise than humans in surgery; their movement can be accurate within one micron [4,5]. Such precision in surgeries can save lives. Deploying robots can free people from tough jobs and cruel working environments. Robots can work constantly for as long as they have sufficient power supply, thus improving efficiency and safety. Furthermore, robots can perform tasks in hazardous conditions, such as the toxic or oxygen-free environment. Space exploration or space assembly and servicing Robots improves cost-effectiveness [6,7].

A wheeled robot has a simpler design than its legged counterparts and is cheaper to build and easier to program [8]. Wheels are wear-resistant and less likely to break when moving. On a flat surface, wheeled robots have a good balance because the wheels are always in contact with the floor. Additionally, the wheels allow the robot to move quickly by reducing friction, and they can be easily controlled in steering [9]. However, wheeled robots also have disadvantages. The majority of wheeled robots lack the ability to move on certain terrain. They cannot stay balanced when moving on surfaces with rocks or potholes. These problems must be solved so that robots can successfully carry out tasks such as military patrol or Mars exploration.

This report will describe the structure of two-wheeled robots and examine how the inertia and inverted pendulum influence the robot's balancing ability. After explaining the two-wheeled robot, it will explore the different designs of two-wheeled robots, which are (1) the dynamically balancing robot and (2) the transitioning robot. Each of these two robots will be analyzed and their advantages and disadvantages will be discussed. After discussing these two robots, another robot, Wobblebot, with its special feature of installing the wheels with a tilted angle will be introduced. The robot will be analyzed in these topics:

a. The theory and experiments to validate the ability of the Wobblebot
b. Current work done to complete the robot
c. Future work and recommendation

After Wobblebot is thoroughly justified, it will be compared with the previous two robots in areas of balance, stability, maneuverability, and simplicity. After comparing three robots, I will make a conclusion and provide recommendations based on the information.

2 Description of Two-wheeled robots

Two-wheeled robots have two wheels installed parallel to each other on the left and right side of the robot. This type of wheeled robot has more efficient design than three- or four- wheeled robots and is more balanced than one-wheeled robots [9,10]. Besides, two-wheeled robots are more naturally friendly because of their human-like appearances [10]. The challenge in designing two-wheeled robots, though, is achieving its balance.

In general, a two-wheeled robot is composed of a controller board for controlling the robot, two servo motors for actuating the wheels, an inertial measurement unit (IMU) for measuring the angular rate and body acceleration, and a battery for powering the robot. These components have functions similar to certain parts of a human being as shown in Figure 2.1. The controller board is the brain, the servo motors the legs, IMU the vestibular system, and the battery the energy from food.

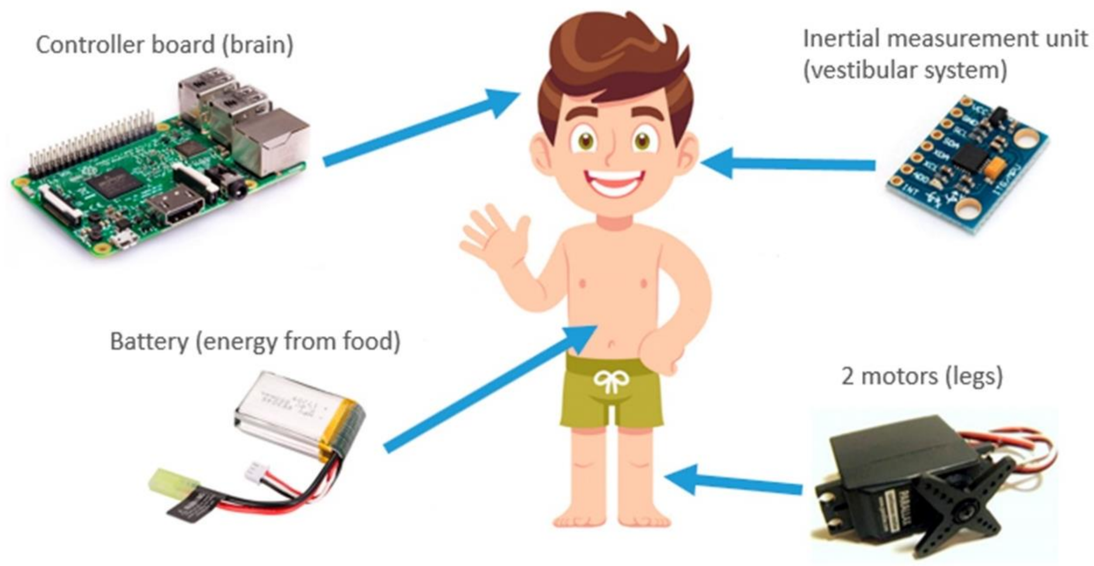

Figure 2.1: Each component has a distinct function like some parts of the human being. And they are shown on the human anatomy along with the related systems.

2.1 The basic robot components and structure

The controller board is an electronic-digital board that can connect to different peripheral devices and interface with the computer to send out commands and receive feedback [11]. It analyzes the data and adjusts the motor speed to prevent a sudden, destabilizing acceleration and to maintain balance. In some cases, the robot is paired with more than two different controller boards to handle different functions. Examples of controller boards are raspberry pi boards or Arduino boards.

The servo motors are electric rotary actuation devices of great precision. These motors draw energy from the battery to cause the component to rotate [12]. Each of the motors is also paired with an encoder, a tiny device that reads off digital pulses from the motors' rotational motion. This device mounted on the servo motors detects the speed and thereby calculates the position of the robot [13]. An example of a servo motor and its schematic are shown in Figure 2.2.

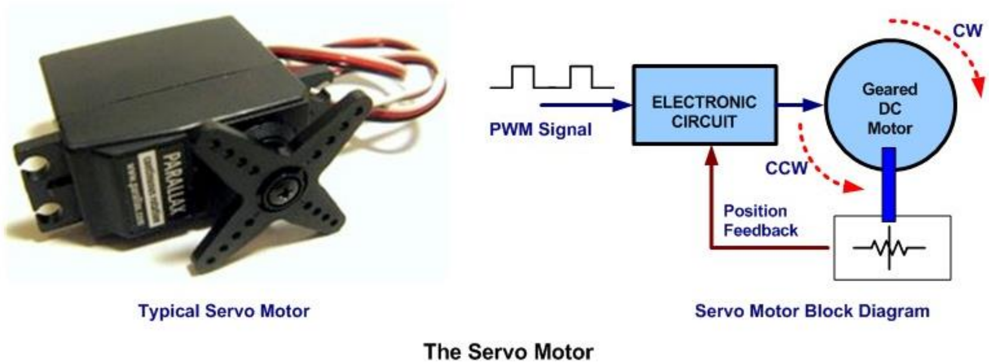

Figure 2.2.: The left side shows a typical servo motor. The motor rotates its spindle as the electricity is converted through motor device. The right side shows the servo motor schematic. The motor is rotated by electromagnetic power, and its rotation is captured by the encoder for analyzing the current position [14].

Once the motors enable movement, the robot must acquire information about its speed and body angle for balance. The inertial measurement unit, or IMU, shown in Figure 2.3, is an electronic device that measures the rotational and translational movements and it constantly sends essential feedback to the control board [9]. The IMU comprises two or three different sensors, accelerometers and gyroscopes and occasionally magnetometers [15]. The accelerometers measure the linear acceleration, gyroscopes measure the rotation occurred on the device, and magnetometers measure the magnetic field strength. The data from these sensors is collected and sent to the computer or controller for further action. Implementing IMU improves flexibility and control in navigational tasks [2,3,4]

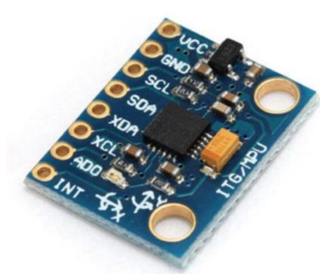

Figure 2.3: An example of an inertia measurement unit (IMU) and this unit is called MPU-6050. It can be used to sense angular rotation and acceleration [18]

The battery also plays an important part in the robot because it fuels every other component of the robot and must have appropriate capacity and power density. Since actuating the robot requires a very high motor torque, the battery needs to have enough voltage for driving the motors. For Nawawi's robot, IPM 100, a 36V battery, was used to apply power to drive the robot's motor [19].

When all components above are chosen, the robot is ready to be assembled. To achieve balance, the mechanical design requires a low center of mass that reduces the momentum in motion. For the structure, the lower body is occupied by the motors and encoders, whereas the upper body is occupied by IMU, controller board, and battery. The motor is not a significant weight factor in since it is not heavy and low stations. The upper body, however, contributed the majority of the weight and is very significant in balancing a robot. Especially, the battery is heavy and can normally represent 30% of the total robot mass [12]. Thus, it is ideal for the battery to be placed lowest among the upper body while all components are encouraged to be placed as low as possible. This can provide better overall stability for the robot. An example structure diagram of robot weight distribution of components is shown in Figure 2.4.

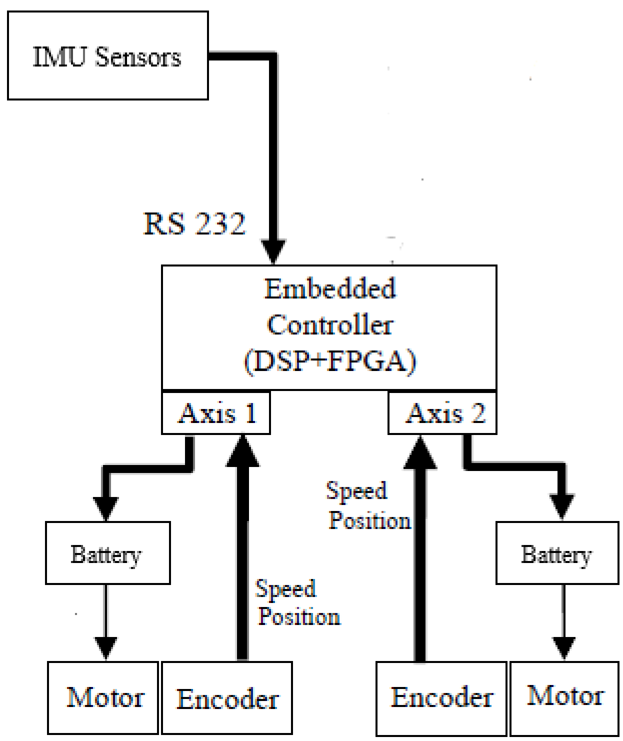

Figure 2.2: A structural diagram of robot. The components of IMU, controller, battery and motors are drawn from top to bottom, and this sequence also complies with weight distribution of the robot body [19]

2.2 Elements related to achieving balance

Inertia is important in balancing a two-wheeled robot. As shown in Figure 2.5, the robot will be affected by inertia on its body when accelerating and slowing. When a two-wheeled robot falls, usually it has accelerated or stopped too quickly and its inertia causes it to fall. To combat the inertia, the two-wheeled robot will implement a closed-loop control system using an inverted pendulum model.

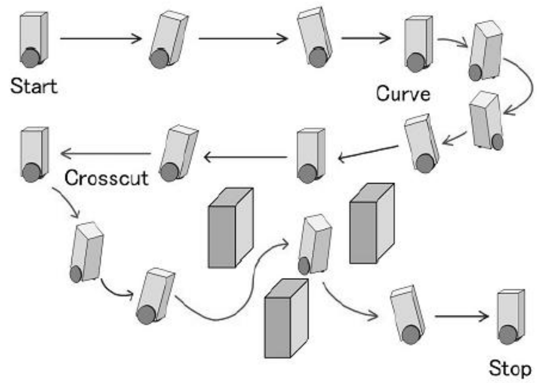

Figure 2.3: The graph shows the Intermittent instants of a two-wheeled robot in its trajectory, where the body is affected by the inertia. When the robot accelerates, the body is tilting backward because the body is lagging. In contrast, when the robot slows down, the body is leaning forward because the body is not responsive as the wheels.

An inverted pendulum is a self-regulating system with a swing back-and-forth motion, similar to the motion of keeping an umbrella or stick vertically from tilting [20]. This system is required on the two-wheeled robot for balancing, and Figure 2.6 shows the inverted pendulum system for the simple two-wheeled robot. The robot body is illustrated as the long stick that will tilt due to gravity or inertia, whereas the wheels on the lower part are the center of the swing motion. Because the two wheels are located on the left and right side of the body, the robot is likely to fall forward or backward. By installing the feedback control, when the falling is detected or predicted, the motor generates torque and accelerate accordingly to balance the body and prevent it from falling. With the function of an inverted pendulum system, the two-wheeled robot tends to be more stable than a three-wheeled robot when transporting loads [21].

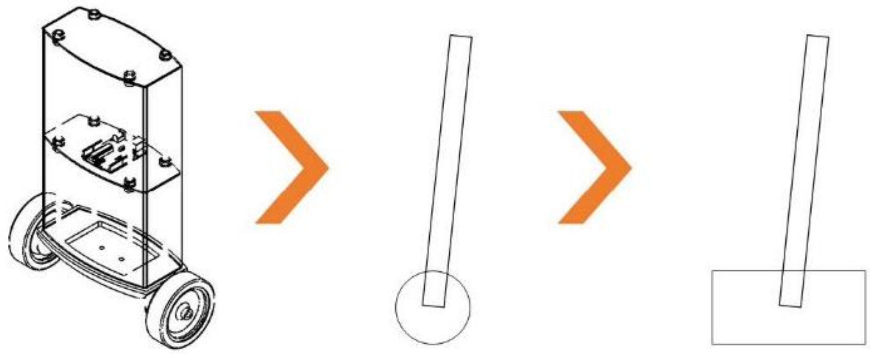

Figure 2.4: The example of a simple two-wheeled robot figure and its inverted pendulum. In the middle figure, the robot wheels are illustrated as a circle and the robot body is illustrated as a long stick. The whole body and wheels together become the inverted pendulum. The wheel will make a corrective torque when the body angle is tilting and keep the body vertical [10]

3 Different designs of two-wheeled robot

Having the essential components assembled alone does not complete the two-wheeled robot. The robot will require further system design so that the robot can keep the body vertical while move to the target. The dynamically balancing robots are the typical design of two-wheeled robots. To improve upon that, there's a transitioning robot, a design in which the robot can transit between four-wheeled and two-wheeled body structures.

3.1 Dynamically balancing robots

The design of the dynamically balancing robots is used in 95% of the projects related to a two-wheeled robot [22]. And this robot installs the wheels vertically on the two sides of the robot, as shown in Figure 3.1.

Figure 3.1: The example of a two-wheeled robot for its dynamically balancing feature

This design has appeared in commercial products such as Segway robots as shown in Figure 3.2. Not only their products can achieve balanced motion, but also they have the capacity to carry the weight of a person on top while being smoothly balanced. Segway robots are employed in various settings including factory and outdoor trails. The size of the wheels enables the robot to maneuver on the moderately tough terrain with potholes. Recognized for their small size and load-carrying capacity, people purchase their products to replace large vehicles for commuting purposes.

Segway i2 SE Personal Transporter Loomo Personal Robot

Figure 3.2: The figure shows two types of Segway robots as two-wheeled robots achieve the self-balancing and can carry a person on top. The left figure shows a factory worker riding a segway two-wheeled robot navigating among the cargos, and the right figure shows a personal robot Loomo, which can follows a person automatically and carry a load or carry a person

For dynamically balancing robot, the center of mass must be designed in the middle. Slightly off-center of mass in robot leads to an unbalanced mass structure, and the robot's balance will be weakened. The fundamental idea of achieving the balance and reducing the effects of off-center mass is implementing a feedback control loop system in the controller board. The loop consists of four steps: 1) acquiring the tilted angle from IMU, 2) computing the control variable using the controller board, 3) sending the control variable command to the motors for adjusting its torque, and 4) adjusting the robot tilted angle. The feedback control loop is required to be at a high update rate so that it provides good stability on the robot. In Shimizu's control loop design, the update rate is 1000 Hz [20].

The PID Controller, or Proportional Integral Derivative Controller, is the closed-loop feedback controller that calculates the control variable in the robot system. The controller contains three constant gains, Kp, Ki, and Kd, that required to be tuned manually on the robot. This controller takes in the error $e(t)$, which is the number calculated by subtracting the current measured value from the target value. The output control variable $u(t)$ is calculated by summing three different adjusting computation terms. The first term is the proportional term, where the error is multiplied by the proportional gain Kp; the second term is the integral term, where the error is integrated over the period and multiplied by the integral gain Ki; the third term is the derivative term, where the rate of change of error with respect to time is multiplied by the derivative gain Kd [23]. And the calculation for this computation is resulting in Equation 1.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\, dt + K_d \frac{de(t)}{dt} \tag{1}$$

The feedback system block diagram of the PID controller is illustrated in Figure 3.3.

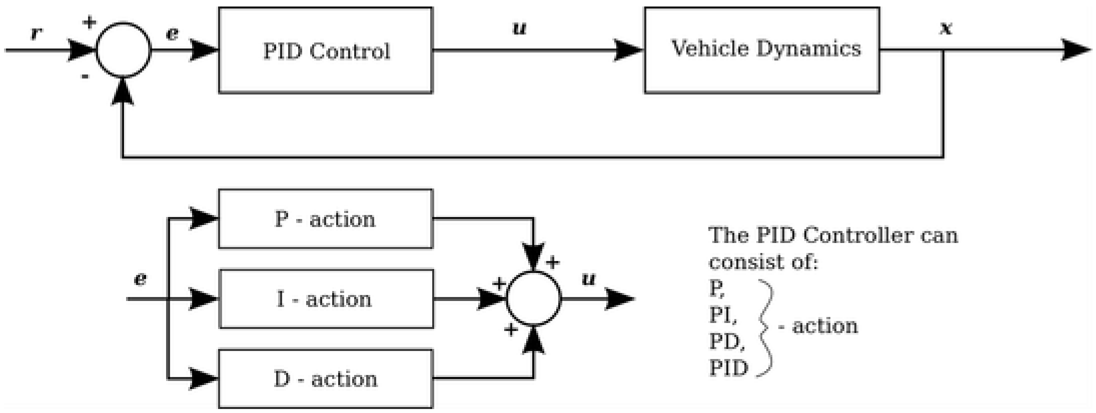

Figure 3.3: The figure illustrates the feedback system block diagram of the PID controller. The targeted value r enters from the left, and it is subtracted by measured value x to result in the error e. The PID controller takes in the error and outputs the control variable u. The motor generates the torque according to the control variable and thus the robot adjusts its tilted angle and reaches the balance.

There are different methods of implementing feedback control loop systems. The Cascade Control Strategy, for example, proves to be efficient in balancing the two-wheeled robots. As shown in Figure 3.4, this control loop system employs two PID controllers in series: an inner loop to control the pitch angle, and an outer loop to control the linear velocity. The sequence of angle loop and velocity loop prevents the disturbances of the pitch angle to be measured until they affect the robot's velocity. Therefore, the performance of controlling the robot is improved, as disturbance in angle is corrected before it affects the velocity. The experiments of Velazquez1 shows that when no disturbance is introduced, the robot installed with this system is well stabilized and keeping the robot pitch angle under 1° from its equilibrium position.

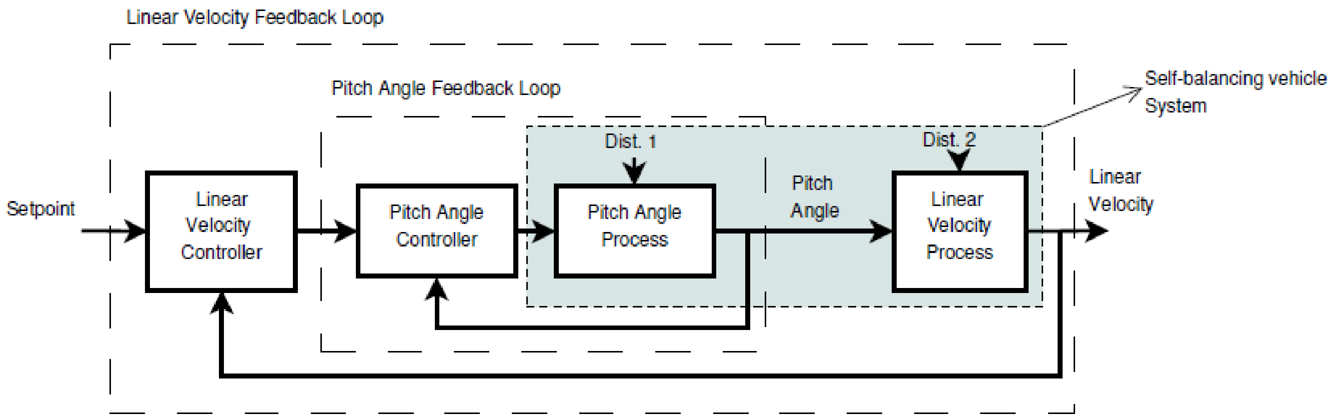

Figure 3.4: The figure is the system diagram of the Cascade Control Strategy, where the inner loop controlling the pitch angle is filled with blue color, and the outer loop controlling the linear velocity is shown outside of the blue color area.

The dynamically balancing robot has reasons to be recommended. The robot can achieve a good balance to perform the motion. By changing the size of the wheels, the robot can achieve well maneuverability in different terrains.

However, the robot still has the room to be improved. The stability of the robot is still causing headaches to the engineers. It is hard to achieve a perfectly centered mass, and due to this reason, the robot requires a frequent adjusting loop to perform stabilization. When the robot is required to be static at one location, unless it is well designed with the perfect center of mass, the robot tends to fall due to the unbalanced weight caused by gravity. One result of this disadvantage is that the robot will swing back and forth so that the inertia is offset by the motion, which leads to a very unstable performance. Besides, the two-wheeled dynamically balancing robots alone have many potential issues if they were required to be deployed in rigorous tasks within an environment such as forest or Mars, which has various sizes and shapes of obstacles. In addition, once the two-wheeled robot falls, without any special design or manual help to lift it up, the robot will have no use in completing tasks. Because the two-wheeled dynamically balancing robot lacks passive stability, these disadvantages are concerning.

3.2 Transitioning robots

The transitioning robots, designed and patented by Hutcheson and Pratt, address the concerns that a two-wheeled robot doesn't have the passive stability by enabling it with a four-wheeled mode [24]. This robot can transit between two-wheeled mode and four-wheeled mode for different purposes, as illustrated in Figure 3.5.

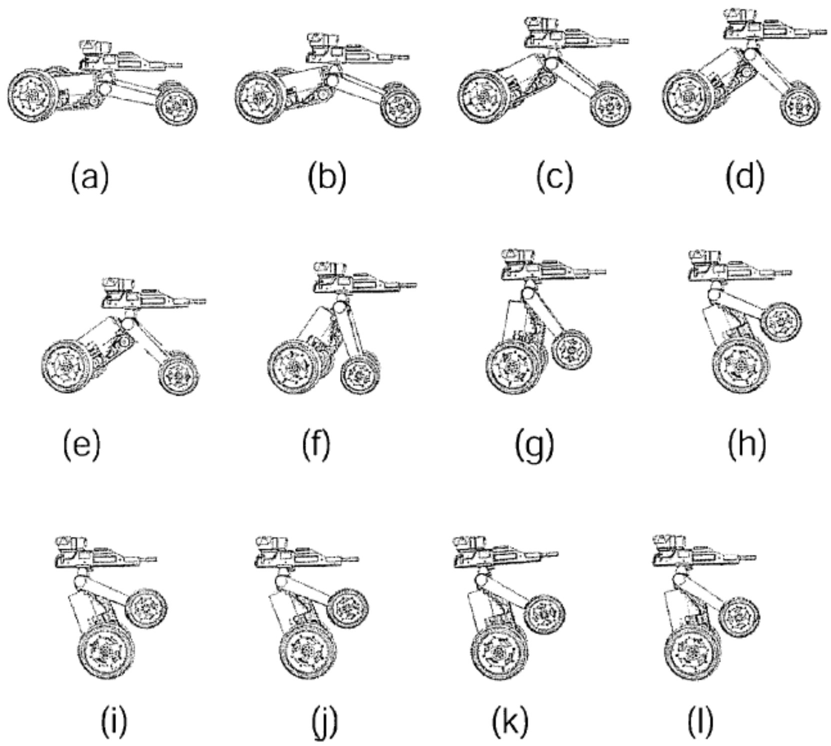

Figure 3.5: The figure shows the transitioning diagram of how the robot transits from four-wheeled mode into two-wheeled mode.

The transitioning process is achieved by generating the torque on the rear motors and controlling the legs by the actuated joints. The four-wheeled mode has a low center of mass and can achieve passively stable. This vehicle like configuration enables the robot to move quickly and stably on different terrains. On the other hand, the two-wheeled mode has a high center of mass and use a feedback loop to achieve dynamically balancing. The mode allows the robot to reach a higher altitude, so the camera can capture more information such as obstacles and targets. In addition, the two-wheeled mode adds the feature of zero-turn-radius, which allows the robot to rotate without moving forward. Combining these modes allows the robot to have a narrow width so that it can pass through narrow passages.

However, transitioning robot still has drawbacks in its functionalities. When the robot is in one mode, it cannot instantly transit to another mode because of the time required by the transiting process. Moreover, even though the robot has additional mode achieving passive stability, the robot has an unbalanced weight at two-wheeled mode. This unbalanced weight will lead to a large inertia effect on the robot and require a more robust balancing system. Furthermore, this robot needs sophisticated programming and additional components. To achieve the transition process, different state programs of four-wheeled state, transitioning state, and two-wheeled states must be installed on the robot. The robot body also requires strong materials to handle the transitioning and more components need to be installed such as actuated joints.

4 Two-tilted-wheeled robot Wobblebot

To achieve dynamically balancing and passively stable simultaneously, the Wobblebot, a robot installed with two tilted wheels, is introduced by Professor Adamczyk, the director of UW BADGER Lab. This robot is shown in Figure 3.6, and it is named Wobblebot because the tilted wheels passively balance the robot in a wobble motion.

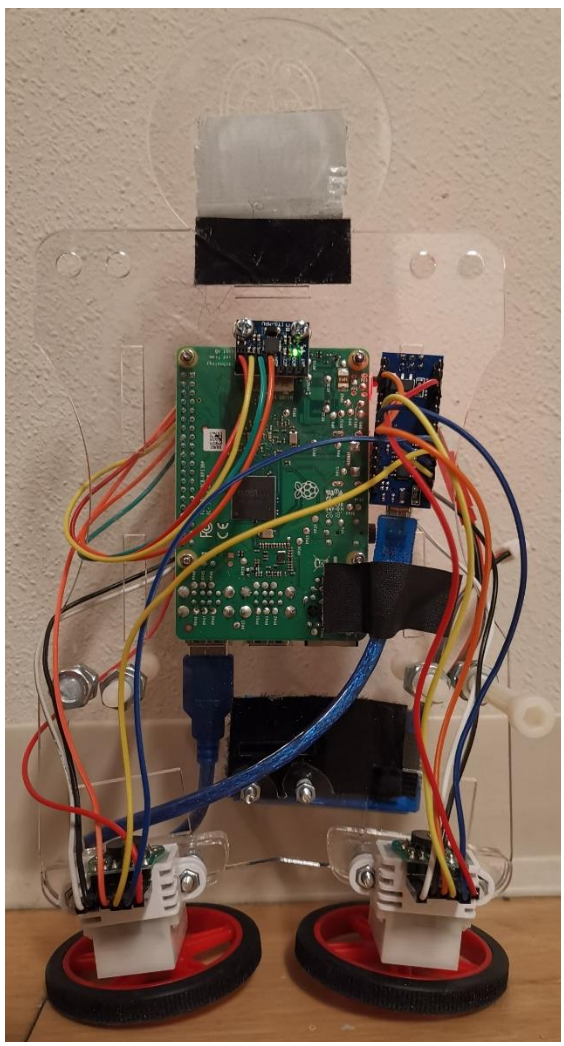

Figure 3.6: The picture of the actual Wobblebot after components are assembled.

4.1 Tilted angles and passively self-balancing moment

The feature of tilted angles on two wheels achieves the passive stability on Wobblebot, because of the self-balancing moment produced by the center of mass.

The tilted angle was determined through calculation. The drawings in Figure 4.1 are illustrated to understand the relationship between the four variables. In the picture on the left, there is the zoomed-in drawing of the wheel. The r represents the radius of the wheel, and the β represents the tilted angle between the wheel and the ground. In the picture on the right, there is an abstract drawing of the robot, where the dashed line in the middle is the robot's vertical center of mass axis and the lower circle is the virtual circle involving the two wheels. In this drawing, the R represents the distance from the tip of the robot to the contract point of the wheels, and the θ represents the change degree of the contact point on the wheels.

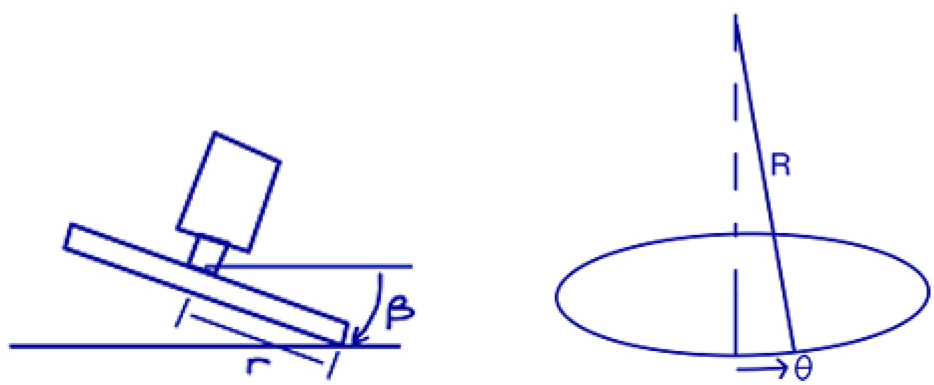

Figure 4.1: The left picture is the drawings of one robot's wheel. The right picture is the abstract drawing of the robot center of mass axis and wheel contact angle of the robot. When the robot experiences inertia, the robot is tilted and the ground contact point of its wheels is departed from the center point, and the angle of this departure is the θ.

With a simpler illustration of the two important parts on the robot, we can make assumption on these variables. Since the r and R are known, β can be calculated using Equation 2

$$R = \frac{r}{\sin\beta} \tag{2}$$

Through calculation, β is determined to be 8.6°. Then further assumptions are made for θ, and the resulting equation is shown as Equation 3

$$\theta_{lim} = \tan^{-1}(\sqrt{\frac{r^2}{R^2}\sin\text{^}4\,\beta - \cos\text{^}2\,\beta}) \tag{3}$$

The pitch angle θ has the limit of 90°, which is the farthest contact point the robot can reach when tiling forward. In this case, as θ is reaching 90°, β is determined to reach 14°. The same will apply if the direction of the angle is the opposite direction.

Drawing conclusions upon these results, the tilting angles of the wheels must be within 8.6° and 14°. Thus, the robot was designed and assembled according to the conclusion, and the actual tilted angle was measured to be 9.6° as shown in Figure 4.2.

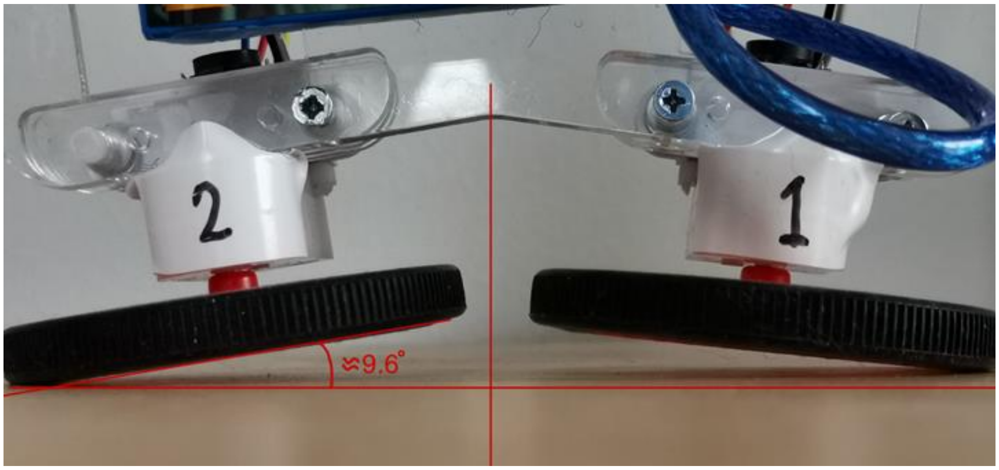

Figure 4.2: The picture of the lower part of Wobblebot, and its tilting angle of the wheels is able drawn to better visualize it.

The axis for the vertical center of mass is also drawn in Figure 4.3, and the components on the robot body are assembled around this axis to achieve well-balanced mass distribution.

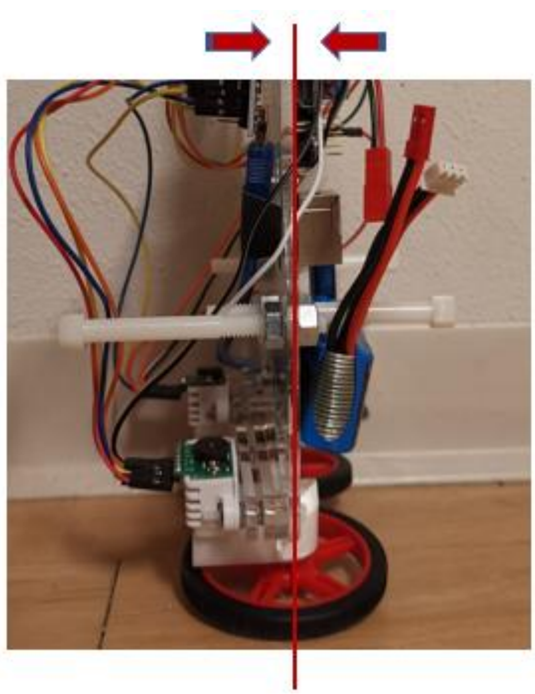

Figure 4.3: The picture is the view from the robot's left side, and the ideal vertical center of mass axis is drawn upon the robot body

4.2 Current work and experiment

After assembly, the robot had shown its passive stability without any programs to control the robot. The robot was tested by applying a force on the robot body so that the robot leaned forward. As contact point moved farther forward than its center of mass, a self-righting moment was produced on the robot by its center of mass. Resulting from the tilted wheels, the robot had the potential energy that balanced the robot back to its equilibrium position. Through trials, the robot proved to be stable and balanced back to its equilibrium position when the robot body pitch angle was within 12°, as shown in Figure 4.4.

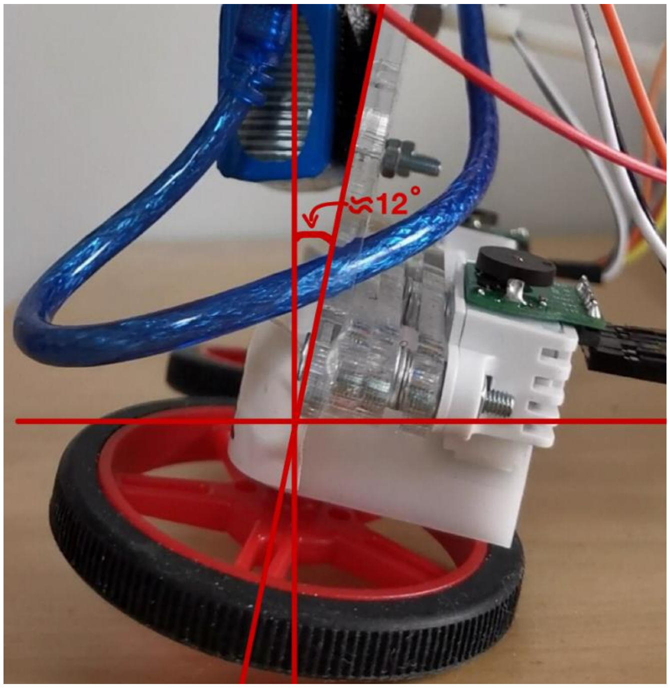

Figure 4.4: This is a picture of the robot tilting forward. As drawn in the graph, the robot at this moment is tilting forward 12°. Under this situation, the robot can still wobble back to its equilibrium position

With the robot proved to have passive stability, the dynamically balancing system was required to further improve its performance. A PID controller was implemented on the robot to reach the desired velocity. On a flat wooden ground, the robot was tested for about 100 times, and PID was tuned to reach the optimal gains. The optimal setting for PID was Kp of 20, Ki of 8, and Kp of 0.2, and one of the velocity-to-time graphs for this setting was plotted through Matlab as shown in Figure 4.5.

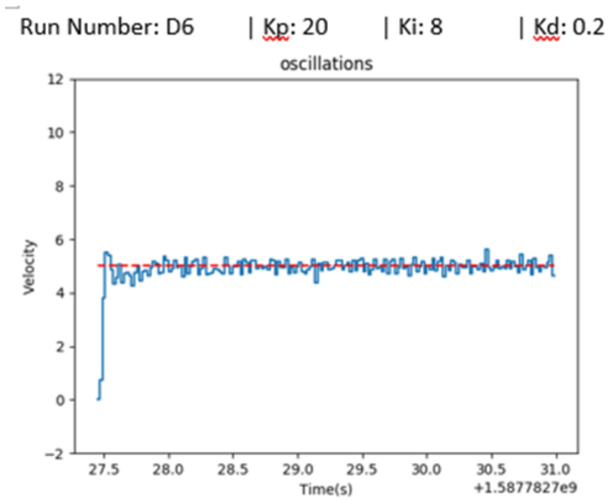

Figure 4.5: This plot is a velocity-to-time graph drawn using Matlab. This plot records the measured velocity of the robot for 5 seconds as it reaches the desired velocity of 5. And the update rate of the plot is 50 Hz.

In this setting, the Wobblebot shows the best performance in its balance, stability, and rise time. The plot also confirms its performance as the oscillation appears to be stable and consistent throughout.

4.3 Wobblebot's future works and conclusion

Though some conclusions were drawn based on the Wobblebot's performance, further works are still required to be complete for better understanding of its dynamics. Currently, only one PID controller is installed on the robot to reach the desired velocity. In the future, another PID controller must be installed to control the angle, and this controller will combine with the installed controller to form a cascade control system.

With these two controllers, Wobblebot then completes its balance control architecture and it can proceed to the next phase, which is experimenting on different ground settings. This will allow further understanding of its dynamics and capabilities. In addition, the Wobblebot can be redesigned to carry a load. The addition of the load can cause more disturbance on Wobblebot, and thereby it can be tested for its load capacity.

In conclusion, Wobblebot is still being developed and tested. At this point, the robot has shown outstanding balance. Due to the tilted angle feature, the robot is harder to tilt forward or backward which improves the overall stability. Also, Wobblebot has high simplicity since it does not require any power or energy to balance the body vertically. However, to further understand Wobblebot, future works must be done for a complete balance architecture and a final experiment needs to be conducted. At the same time, due to the low tilting wheels, it is expected that Wobble has poor maneuverability in navigating through a rough surface of some obstacles such as rocks.

5 Comparison between three robots

To better distinguish each design of a two-wheeled robot from another, in Table 1, a comparison table is created to evaluate three types of two-wheeled robot designs in areas of balance, stability, maneuverability, and simplicity. These four criteria were chosen because they directly related to the performance of the robot in navigation. Durability, however, was not chosen to be compared because it affects only Wobblebot, and it is less significant given increasing the durability of the wheels' materials can offset its low durability due to tilted angles in its wheels. Each score is determined within 1 to 5, in which 1 represents poor performance and 5 represents the best performance.

Table 2. Comparison table between three different designs of two-wheeled robots. A scoring system from 1 to 5 was assigned to each criteria column. A score of 1 is the poor-performing, and 5 is the best-performing.

	Dynamically balancing robots	**Transitioning robots**	**Wobblebot**
Balance	4	4	5
Stability	3	4	5
Maneuverability	3	5	1
Simplicity	2	1	5
Total	12	14	16

As Table 5 shows, Wobblebot outperforms other robots in criteria of balance, stability, and simplicity, where the transitioning robot has the highest score in maneuverability. Summing up the scores, Wobble wins the total scores among the three robots under this comparison table.

6 Conclusions and recommendations

In conclusion, three different designs of the two-wheeled robots are discussed. Since three robots have their own advantages and disadvantages, they could each be used in distinctive settings.

Dynamically balancing robots are recommended if there is no high demand on balance and stability. This robot can achieve fair balance and maneuver on different terrains, but its lack of passive stability weakens its stability and simplicity.

Transitioning robots are recommended if the robot is deployed on extreme tough terrain. The transitioning function allows better flexibility, stability, and maneuverability, but it increases the complexity significantly.

Lastly, Wobblebot is recommended if the ground surface is moderately flat and good balance and stability are desired. By simultaneously achieving passively stable and dynamically balancing, Wobblebot has very stable and balanced performance. The body without external help or internal adjusting can balance back to its equilibrium position. However, the lowered wheels lead to poor performance in its maneuverability. Wobblebot also requires future works in completing a balance control architecture and conducting experiments to understand its dynamics.