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Design and Testing of Two-Wheeled Self-Balancing Robot

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Abstract:
The research on a two-wheeled inverted pendulum, which commonly known as the self-balancing robot, has attained momentum over the last decade in many robotic laboratories. The self-balancing mobile robot works on the principle of an inverted pendulum which is also, called Tilter. The robot is inherently unstable and without remote control it would roll around the wheels' rotation axis and eventually fall. Driving the motors in proper direction brings the robot to the upright position. Although the robot is inherently unstable, it has several limitation. The static stability of two-wheeled over multi-wheeled robot because it has only two wheels (two points touching the ground), it requires less space. Kinematic and dynamic models constructed. This project is successful in overcoming and achieving its aims to balance a two-wheeled autonomous robot based on the inverted pendulum model.

Keywords: *Inverted pendulum robot, self-balancing, tilting type, wheel*

1. Introduction

Robotics has always been an integral part of the human activities. The dream of creating robots that help in human thought and physical characteristics extends throughout the existence. The research on robot has gained momentum over the last decade in some robotics laboratories around the world. Evolution in technology over the past few years have well-established the foundations of making these dreams come true. Robotics is now achievable through the miniaturization of the microprocessors which performs the processing and computations [1]-[3]. The sensor is being used providing machines with the ability to identify the world around them in many different manners.

An efficient control system is designed to provide the robot with the capacity to manage itself and operate autonomously. Self-balancing robots are one variation of the robot which become a popular topic of research and exploration for engineers. They offer the freedom to develop control systems that are capable of maintaining the stability of an unstable system. This type of system called as an inverted pendulum [1]. This project aims to bring many of the previously mention aspects of a robot together to build self- balancing robot.

This field of research in robots offer an opportunity for improving the quality of life by introducing robot to the reduction of personal disclosure to dangerous environments and harmful chemicals and hazardous conditions, the provision of continual 24 Hr assistance and monitoring for people with medical conditions, etc. [1], [7]. Robots adopted in many applications within society including carrier, assistants and security

1.1. Inverted Pendulum Theory

An inverted pendulum has its centre of mass above its pivot point. Representation of the centre of mass of the robot can achieve through a mathematical model. Inverted pendulum theory also is known as Pole and Cart method. The self- balancing robot does not directly compare to the Pole and Cart. Within the system model, the cart method equates to the robot wheels and the pole relates to the robot chassis. The equations derived by utilising Newton's second law. These derived equations conclude that the gravitation acceleration is, in fact, a positive value and the frictional force between the wheel and horizontal surface.

Friction coefficient considered during the control systems design and implementation, which may need additional sensors and circuitry. The power consumption would be required toderive from the system while in operation. The time, effort and resources need to create this capability far exceed any benefits that could expect with their inclusion.

It is necessary to generalise the effects of the left and right wheels and incorporate them together under the combined term "wheels". Simplifies the calculations as both wheels will work to maintain stability. For determining specific torque requirements for each wheel, the wheels value can be divided into an approximate single wheel value [5]. This approach considered acceptable as the terrain and surface will vary between the wheels on certain grounds.

The aim of the inverted pendulum principle is to keep the wheels beneath the centre of the robot chassis's mass [5], [9]. If the robot begins to tilt forward, then to maintain stability, the wheel will need to move forward to return beneath the chassis mass. If this not maintained, the robot will just fall over. The following system dynamics associated with the mathematical problem.

2. Methodology

The robot consists of a wheel at its lower part. The wheel is used to make the robot move and balance in the longitudinal plane. The self-balanced robot navigation required an excellent performance of precision, reliability and autonomy. The error would accumulate ceaselessly with the time pass. To establish the mathematical models, the ADC used with Micro Controller Units to obtain the instruction of sensors, such as gyroscope and accelerometer. Gyro output continuous voltage signal, after 14 bit A / D conversion, provided by the gyro only larger power is because centrifugal not only the climate to reach a stable over time, gradually, standard output form, and ultimately tend to the dynamic stability. That shows the different characteristics of the gyro of time; Based observations indicate that the drift failure is mainly due to the influence of climate on the work process of the gyro, According to the ambient temperature deviation reduced to a positive or negative. The same method to analyze the accelerometer output value; we know that the error characteristics of accelerometers and gyro are similar, but different parameters to apply the correct voltage to the motors, it is required to know the accurate value of the robot tilt angle and position. The vibrations, readings from the accelerometer are noisy and have a delay while the problem with the gyroscope is its drift and offset.

Several algorithms considered for stabilizing the robot. The first one considered was the Proportional Integral Derivative (PID) controller which controls the robot using only feedback variable. Testing and simulation showed that even though the robot is stable about the tilt, small disturbances eventually cause big changes in the position. Overcome these problems, the Linear Quadratic Regulator (LQR) controller, was designed. Unlike the PID, the LQR controller uses all state variables to calculate the control value allows the robot to hold the spot and the tilt angle at desired values.

3. Design Consideration

Design discussion is an important when compiling a design in self- balancing robot because they facilitate an informed decision on the operating conditions. This action may also highlight areas for further investigation that could improve, simplify or make a product more affordable. The other aspects that include the different material. It is used in the product to reduce the potential manufacturing costs. Design considerations for the two-wheeled robot should also concentrate on operating environments, motors, wheels, sensors, microcontroller, power source, safety features, and various forms of control. All these considerations were investigated to determine temperature parameters, dimensions, configuration, availability, efficiency, maintenance requirements, etc. Consideration of these factors combines to guarantee the necessary capability is achieved successfully within the timeframe and resources available. The size, shape and layout of the robot proved the most advantageous aspects of the robots design. The small chassis prove ideal for maneuvering on the spot. It is evident from assembly and performance maintenance activities on the robot as turning it on the spot allowed easy access from the one location to another. The small size made the robot easy to move, handle and to obtain each of the layers. The platform layout allowed grouping of systems and sensor without overcrowding.

3.1. Design of the Two-Wheeled Robot-Mechanical Structure

3D modelling software was used to develop the model of the self-balancing robot (fig.1). The robot body will be with a rigid structure as the robot with two wheels. Each model of the segment was created separately and assembled.

3.2. The Fabricated Structure

The body of the robot use to connect the wheel. The top face is used to carry board which is used to control the wheel. The critical parameter of the body given below

- Body is made up of plastic
- At the middle of the plastic material, there will be a hole to fix the motor where the wheel attached
- The construction of the robot as per its dimension made in the SOLIDWORKS software and the material type I selected to come up with the computer generated results of the weight of the body
- The body weight is estimated to be around 1.5kg including the wheel

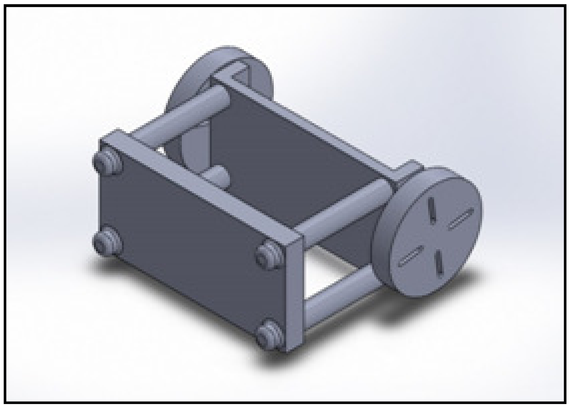

Figure 1: Robot design

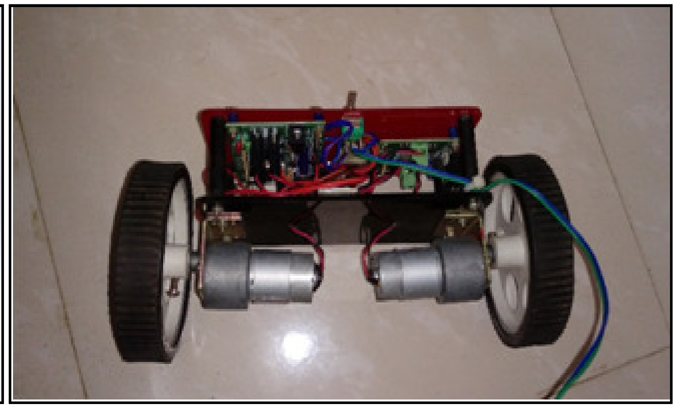

Figure 2: Fabricated robot

3.3. Drive System

Two DC motor where chosen to turn the wheel specification of the DC motor is given (Table.1). Motor with nominal power is 70mA (Max) directly mounted on the wheels. We use a small and light weight motor controller for this project. In total two of this motor were attached to the bottom of the frame. The specification of drive system used shown below (Table.2)

Parameter	Minimum rating	Maximum rating
Input voltage	9V	12V
Stall current	500mA	600mA
Shaft length	2.4cm	
Motor weight	110gm	
Sensor interface	Accelerometer, tilt sensor	

Table 1: Motor and motor controller specification

Variable name	value	Description
q_{max}	7000rpm	Speed of the motor
i_{max}	70mA	No-load current
$U_{A,max}$	12V	Maximum motor and motor control voltage

Table 2: Drive system

3.4. Sensor System

For field-oriented control of the motors and the controllers, the motor position was measured using accelerometer directly mounted on the shaft of each motor. A filter was used to approximate the motor velocities. To measure the current position and the angular velocity of the robotinertial measurement unit was mounted on the robot chassis. This measurement unit provides high-precision control of the robot.

3.5. System Dynamics

The following system dynamics utilized within the mathematical problem of the two-wheeled balancing robots stability control (inverted pendulum approach)

x Displacement (Horizontal) (m)

$\dot{x}$Velocity (Horizontal) (ms^{-1})

θ displacement (Vertical) (rad s)

$\dot{\theta}$ Velocity (Vertical) (rad s^{-1})

$\ddot{\theta}$ Acceleration (Vertical) (rad s^{-2})

M_{wh} Mass of wheel and drive shaft (Kg)

M_{rc} Mass of the robot chassis (Kg)

M_{wh} Mass of the wheels and drive shafts (kg)

M_{rc} Mass of the robot chassis (kg)

F Horizontal force applied by wheel (N)

$F = F * u_x$

F_fFriction force between wheels and ground (N)

$F_j = -F_f * u_x$

F_f=-μ_{wh}[(M_{wh}+M_{re})g-M_{re}l($\ddot{\theta}$Sinθ +$\dot{\theta}^2$Cosθ)]Sgn(N_{wh}*$\dot{x}$)

N Reactive force on robot chasis from the wheel (N)

$N = N_x * u_x - N_y * u_y$

N_{wh} Reactive force on wheel (N)

$N_{wh} = -N_{wh} * u_y$

$N_{wh} = (M_{wh} + M_{re})g - M_{re}(\ddot{\theta}\text{Sin}\theta + \dot{\theta}^2\text{Cos}\theta)$

G Gravitational acceleration (9.8ms^{-2})

G_{wh} Gravity effect on wheels (Kg*m*s^{-2})

$G_{wh} = M_{wh} * g * u_y$

Gre Gravity effect on robot chasis (kg*m*s^{-2})

$Gre = M_{re} * g*u_y$

μ_{wh} Friction coefficient of wheels on surface

μ_{ve} Friction coefficient of drive shafts

N_x Reactive force in the X direction (N)

$N_x = M_{re} (\ddot{x} + 1* \theta\cos\theta - 1* \dot{\theta}^2\sin\theta)$

Ny Reactive force in the Y direction (N)

$N_y = M_{re} *g(l* \ddot{\theta}\sin\theta - l*\dot{\theta}^2\cos\theta)$

τ_{wh} Wheel torque (Nm)

$\tau_{wh} = F_{wh} * r_{wh} * \text{Cos}\,\theta$

r_{wh} Wheel radius (m)

F_{wh}Horizontal force on wheel (N)

$F_{wh} = \frac{F}{2}$

3.6. System Integration and Overview

In this, it says about how the flow occurs between the sensor and controller used in it which would allow real system integration with all components contained within the robot. The components utilized in this only connected to the microcontroller shown in fig.2. Upon the completion, the operation was undertaken

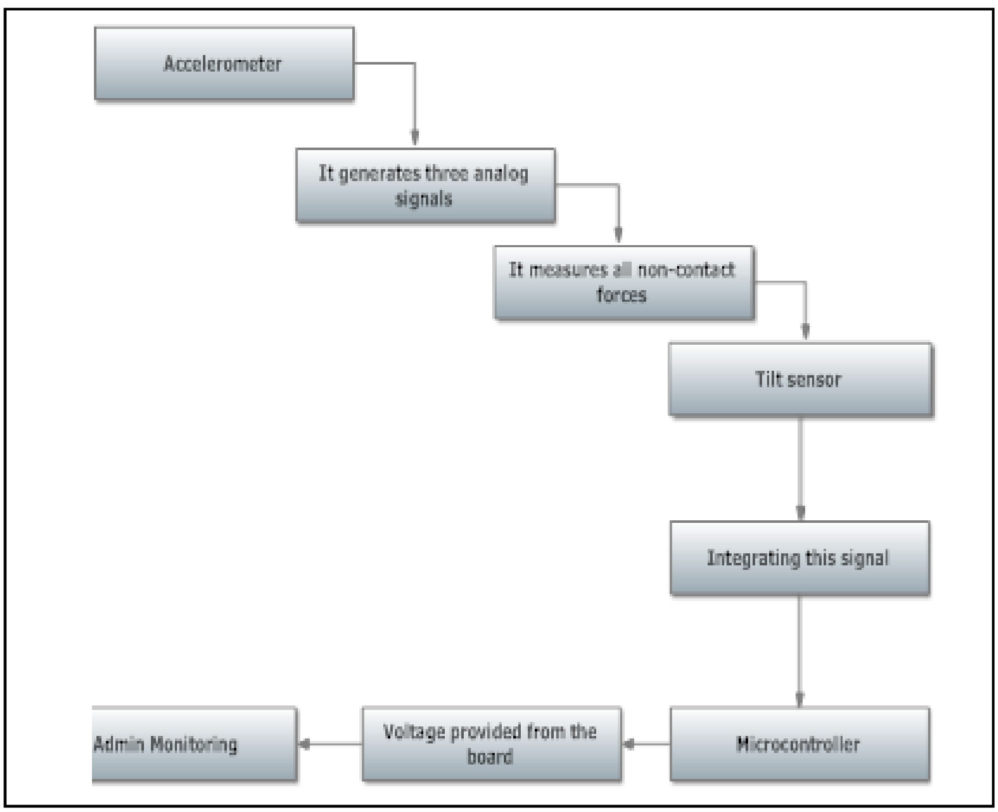

Figure 3: system architecture

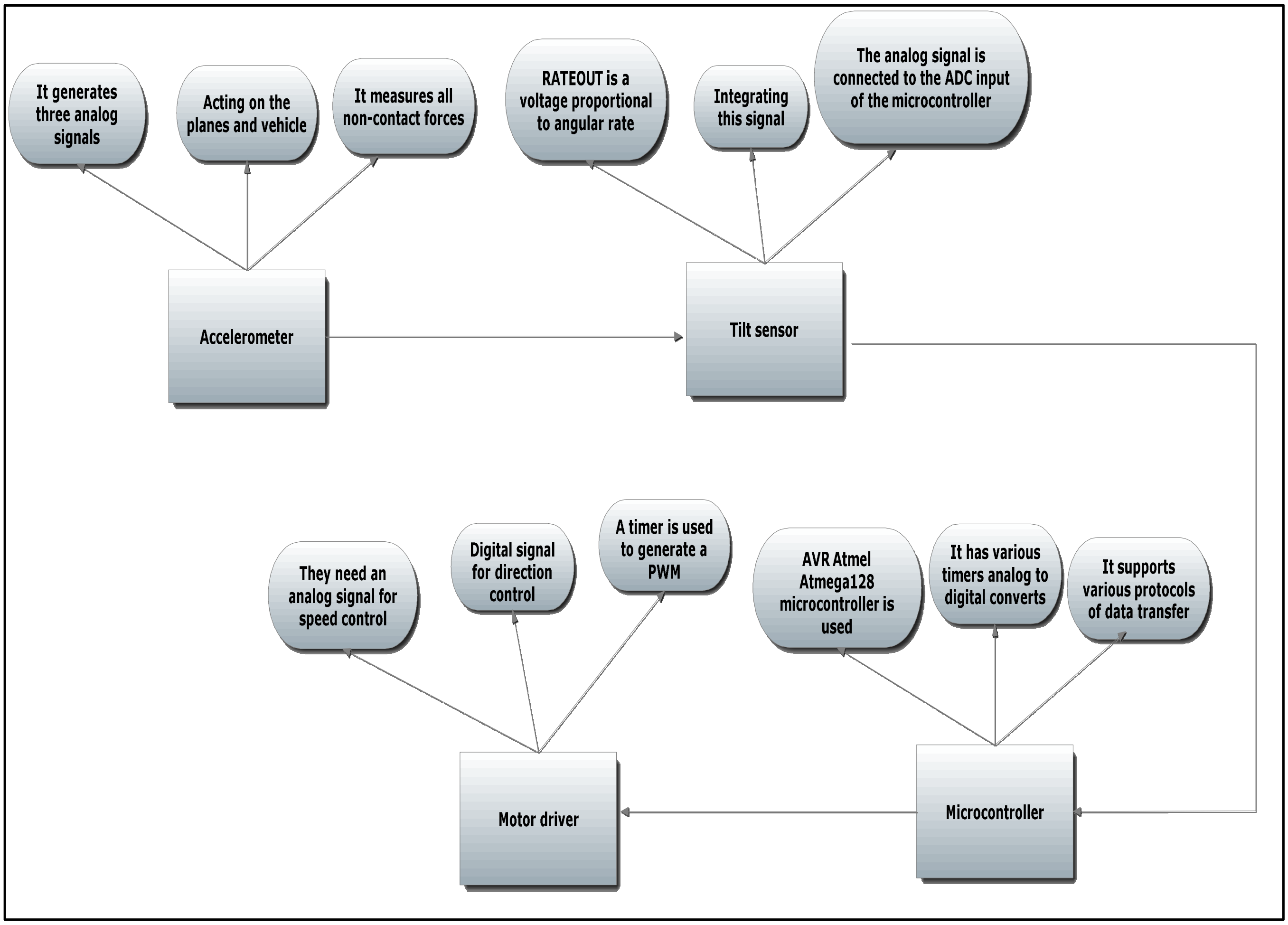

Figure 4: E-R Diagram

4. System Testing

4.1. Testing of System

This testing is the stage of implementation, which aimed at ensuring that system works accurately and efficiently before the efficient operation commence. Testing is the process of working a program to find an error. A good test case is one that has a high probability of finding an error. An accomplishment test is one that answers a yet unknown error. Testing is vital to the achievement of the system. System testing makes a logical belief that if all parts of the system are correct, the goal will successfully achieve. The candidate system is subject to the variety of tests-on-line response, Volume Street, recovery and security and usability test. A series of tests are e before the system is ready for the user acceptance testing. Any engineered product can test in one of the following ways. Knowing the specified function that a product has been designed to form, the test can be conducted to determine each function is entirely working. Tests can be carried out to ensure that "al gears mesh", that is the internal working of the product performs according to the blueprint and all domestic items have been adequately exercised.

4.2. Unit Test

The unit test is the testing of each sensor, and the elemental of the overall arrangement did. Unit testing becomes documentation efforts on the smallest unit of software design in the sensor called for ‘module testing'. The sensor of the system tested separately. This testing is carried out by the programming itself. In this testing step, each model is found to be working concerning the expected output from the module. There is validation analysis for the fields. For example, the validation analysis is done for check the data given by the end user where both format and effectiveness of the data entered included. It is very easy to find the error and debug the system.

4.3. Integrated Testing

Data can lose across the interface; one module can set back the other sub-function, when combined, may not produce the desired primary function. Integrated testing is systematic testing that can do with sample data. The need for the test is to find the overall performance of the system. There are two types of integration testing. They are:

i. Top-down integration testing.
ii. Bottom-up integration testing.

4.4. Black box testing:

- Black box testing is used to find inappropriate action
- Interface error
- Errors in external database access
- Performance errors
- termination and initialization error

This testing is performed to verify a function which conforms to its blueprint of correctly performed all his duties. So this testing is also called as a 'black box testing'. It tests the outward behavior of the arrangement. Here the product can be certified by knowing the specified action that a product has been constructed to perform; tests can be conducted to demonstrate that each service is fully operational.

4.5. White Box Testing

White box testing is the test case design method that uses the control structure of the procedural design to drive cases. Using the white box testing methods, we derive test that assures that all independent path has exercised at least once

4.6. Validation Testing

After the black box testing, software is complete as a package; interfacing errors have corrected and end series of software validation tests begin. This testing can define as many, but a single definition is that validation testing becomes a success when the customer can wisely expect software functions.

4.7. User Acceptance Testing

User acceptance of the system is the critical factor in the success of the scheme. The system under consideration certified for user acceptance by always keeping in touch with the future system at the time of developing changes whenever required.

4.8. Output Testing

After performing the validation testing, the next step is output asking the user to the format required testing of the proposed system, since no system could be useful if it does not produce the necessary amount in the particular form. The output displayed are generated by the system. Here the output format is studied in two ways. One is screen the other one is printed form. The output format on screen is found to be correct as the form designed in the system phase according to the user needs. For the paper also, output comes out as the specified requirements by the user. Hence, the output testing does not result in any connection with the system.

4.9. System Performance and Results

It anticipated that the manufactured robot would have been entirely capable of achieving stability, locomotion.

5. Conclusion

Conclusions are necessary to provide comment on each aspect undertaken as part of the project. This project was successful in achieving its aims to balance a two-wheeled autonomous robot based on the inverted pendulum model. Control strategies have been implemented to address the problem of balance control for the system. The project has been carried out from design production of particular parts and integration of electronics, and mechanical components and the software. It can expand into several recommendations for improvements, the addition of extra capabilities and future areas of investigation which provides the opportunity to share an awareness of the problems encountered that would complement the future work recommendations.

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