Two-wheeled self-balancing autonomous robot

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ABSTRACT

Two-wheeled balancing robots based on inverted pendulum configuration which relies upon dynamic balancing systems for balancing and maneuvering. The idea of a mobile inverted pendulum robot has focused in recent years and has attracted interest from control system researchers worldwide, research on a two-wheel inverted pendulum, which commonly known as the self-balancing robot. In this, the DC motor attached to the base frame of the robot helps it for maneuvering. Sensors like tilt and accelerometer used for balancing. Driving the motors in the right direction returns the robot to the upward position the model of the robot is constructed based on the Lagrangian function. These robots have zero turning radius, small foot step and high tolerance to violent force

KEY WORDS: inverted pendulum robot, lagrangian, Self-balancing Robot, maneuvering.

1. INTRODUCTION

The study on two-wheeled self-balancing robot has gained momentum over the last decade at research, industrial and hobby level around the world. This article understands with the design of the two-wheeled self-balancing robot. This article proposes a new approach by which the flaw of two self-balancing robots can decrease and avoids traditional Kalman filter which cannot fulfill real-time modulation. In this article, Correction algorithm can come out real-time robot aspect in the right way according to the characteristics of exploration modules fault from the iteration of nonlinear least-squares fault model based on the method dynamic Regulator. By computer simulation, the error through the tilt sensor and accelerometer can be revised. Kalman filter fused the data of tilt sensor and accelerometer re-work, and the failure of the sensors can occur change. The mathematical derivation of Dynamic Regulator shows this approach of reducing posture estimation fault is feasible and practical, and can achieve better accurate estimates in expensively. Recently many investigations have devoted to problems of controlling the two-wheeled self-balancing robot, which widely taken into a function in the field of autonomous robotics and advanced vehicles. Robots can move on the flat and complex terrain, such as on the ups and downs. Many workable systems have been achieved based on the self-balancing robot. Apart from the practical view, the self- balancing robot has attracted much concentration in the field of engineering and control theory because of its inherent unstable nature. Many control methods have studied. Two-wheeled self-balancing robot features a lack of drive, non-holonomic constraints, intrinsic instability, which is a nonlinear system. The robot has two wheel arrangement, powered by a separate motor, a body placed and the center of gravity of the axis and a posture controller which turns two wheels based on body state to maintain body position and walk upright. Much research on its balancing and modeling control has done. Grasser used Newton's method to establish control and three dynamic models its speed and posture using decoupling method.

TWR used Lagrange method to create its model on the flat ground and the feedback system used to design its controller. Huang built sliding mode controller and dynamic model on the slopes and designed without concentrating direction change. A closed-loop controller designed with attitude control using back stepping method while the position and movement control using Proportional Integral Derivative (PID). However, these control methods mainly concentrate the ground level. This article proposes the solution for the problem to balance a robotic two-wheeled bicycle. Problem statement in the actual robots navigation system, a variety of small factors, measures and interference random and noise variation, the accuracy of the standard Kalman filter will reduce. Therefore, the Dynamic Regulator focuses on the two self-balanced navigation. Self-balancing Robot system; we need to get the speed of the robot posture and acceleration information, it is on to build the sensor output model. Dynamic Filter can make the sensor information, the ability to use data integration to finish Dynamic Regulator (DR) and the suppression interference; it also allows the system has good dynamic performance. Some researchers added one or two manipulators on the self-balancing robot to construct a mobile manipulator, which is also an analysis trend of this kind of robot. Because of these shortcomings of the exploration sensors, they are always such as the clear signal and noise, such as always the interference of out factors, by random drift. According to the characteristics of the navigation sensors, we want to reduce the error, and need to create a random drift; a mathematical model is the best estimation method to deal with error compensation. The improved system will pass the self-balancing test of the two robots. The error of navigation sensors and low costs, the establishment of error models, the Dynamic Regulator to suppress noise and fuse the tilt and accelerometer data, this approach has not only excellent real-time achievement but also the algorithm simple; DR is a very practical method of the self-balancing robot navigation system.

Autonomous stability: Stability of the two-wheel self-balancing robot is its ability to maintain robot chassis in an upright, equilibrium position. Balancing a robot automatically without human interaction is known as autonomous stability, because it does this by self-governance. The inverted pendulum theory provides the equation required to ascertain motion, force and reaction that occur in the process. It is then necessary to apply an efficient control system that is responding to the sensory input within a minimal time frame so that stability can attain and then maintained

This project aims to solve this problem of keeping the stability of the two wheeled balancing robot by designing a reliable control system capable of functioning within a PIC microcontroller. A non-linear control system known as a fuzzy controller will developed be allowing a more robust and stable system compared to the linear equivalents currently available

The purpose of 2 wheeled robots is difficult to limit to a particular role as they can complete numerous tasks with necessary attachment installed.

a) It can adapt to the hazardous or confined environment which could be difficult to maneuver around for a track, for the multi- wheeled robot but this can be easily achieved by two-wheeled robot.

b) The robot could fulfill the role of a home health assistant as it does not require health assistant as it does not require rest. They could easily maneuver about the home and provide wireless connectivity to the internet.

c) It could utilize as a warehouse traction robot where item status can easily track as part of a schedule or manually when requested by client.

d) In a fire warden role, the robot could access smoke filled area and evaluated the risk before any human lives would place in danger. A camera could provide visual images to the fire commander while temperature sensor would measure hot spots. IR sensor will track videophone, fax when it receives a cell it utilize the sensor to locate the person by itself.

2. METHODOLOGY

In the self-balancing robot system, we use the MEMS-based accelerometer to measure the tilt angle. It measures all non-contact forces and hence its reading is also affected by pseudo forces due to acceleration. The analog output linked to the ADC input of the microcontroller. The system requirements are divided into two categories, depending on whether they are considered needed or desired. The robot needs to stabilize in an upright position reject disturbances, such as gentle pushes. The accelerometer has X, Y and Z values. If the bot leans forward, the DC motor spins in the same direction to match the balance. The ADC value to the microcontroller changes from X to Y of the accelerometer. In the normal position ADC value is from X. Then when the bot leans backward, the motor spins in the opposite direction to balance the bot. Now, again the ADC value to the microcontroller is from Y. The ADC converter in the microcontroller converts the varying voltages into its corresponding binary values. The microcontroller converts the binary values into its corresponding integer values. If the value overlaps a threshold value, then the microcontroller controls the motor accordingly. The Arduino board used in the self-balancing robot, is which it uses AT mega 328p microcontroller.

MEMS-based accelerometer with capacitors is typically a design that uses two capacitors formed by an adjustable plate held between two tightened plates. Under low net force, the two capacitors are same, but a change in force will cause the flexible plate to move closer to one of the tightened plates, increasing the capacitance, and further away from the other tightened reducing that capacitance. This difference in capacitance is identified and amplified to create a voltage proportional to the acceleration. The structure is of the order of microns.

An Analog to Digital Converter (ADC) is a very useful feature that converts an analog voltage on a pin to a digital. By converting from the analog to the digital, we can begin to handle electronics to interface to the analog around us. Not every pin can do analog to digital conversions on a microcontroller. On the Arduino board, the pins have an ‘A' in front (A0 through A5) to represent these pins can read analog voltages. ADC can vary significantly between microcontrollers. The ADC on the Arduino microcontroller is a 10-bit ADC meaning it can detect 1,024 (2^{10}) discrete analog levels. Some of the microcontrollers have 8-bit ADCs (2^8 = 256 discrete levels) and some have 16-bit ADCs (2^{16} = 65,535 discrete levels).

Relating ADC Value to voltage: The ADC reports a ratiometric (output is directly proportional to input) value means that the ADC allows 5V is 1023 and anything fewer than 5V will be a ratio of 5V and 1023. Resolution of the ADC / system voltage = ADC reading / analog voltage measured.

Design Consideration: 3D modeling software (Fig-1) was used to develop the model of the self-balancing robot. 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

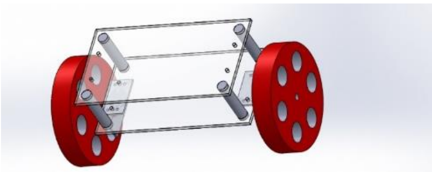

Fig.1. Robot Design

The body of the robot: 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
- Thickness is 0.3mm
- 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

Design and development: The literature conducted in the previous project gives a good amount of information on past robotics. The review provides the idea how to select the material, motor, sensor, etc. These include how it will move, how it will sense the environment around it, how it will power and what it will make off.

The two-wheeled balancing robot will break into two distinctive components of operation. The first is the balancing part "Microcontroller system" which will fulfill the fundamental goals of the project. This encompasses the sensors, chassis, locomotion and microcontroller with its associated control system.

Design consideration: Design consideration is the important factor that should be considered while developing a robot it also includes the information decision on the limitation, operating condition and capabilities of the final product further investigation could improve, simplify or make the product cost effective

Design consideration of the two-wheeled robot focuses on the operating environment, motors, wheels, sensors, microcontroller, power source and various form of controller. All these considerations were then investigated to determine configuration, temperature parameters, dimensions, availability, etc. Consideration of these factors combines to guarantee the necessary capability is achieved successfully within the timeframe and resources available.

Material size and weight: The materials used in design limit the durability, strength, energy efficiency and operating capability of the product. They also impact on contribute, and size to the total load of the end design. A dense material such a metal is typically stronger than the materials such as plastics, but it requires higher energy to move. The size of the design clashes on its ability to move

Materials that could have used in the construction of robot include metals, alloys, wood, plastics and other synthetics. Heavier metals were rejected early due to the increased weight that would affect the stability control of the robot. Although wood was an option, it is a potential ignition source in higher temperatures and is also tough to mold. Rubber strips used as a shock resistant that may experience from falls, bumps or rough terrain but this was only incorporated to support the battery, motors, and microcontroller within their mounts as the robot will employ in people environment. The robot chassis has a multi-layer where each layer contains different components of the robot systems. An average height of 2 cm will separate each layer except the power level.

Several options available for connecting the chassis parts together such as bolts, rivert, and welding but screw were the preferred method in this case. Screws employed in joining the plastic pieces together. Additional plastic brackets were manufactured to attach sensors and PCB's which also affixed into place with screws. The completed chassis weights initially 1.5 Kg but 1 Kg exceeded this by the final manufactured product.

Wheels: The wheels provide locomotion and traction for the robot as well as support for the robot chassis. The diameter of the wheel should be adopted to reflect best the torque requirements of the machine. The tire used will impact on traction and the smoothness of the locomotion experienced by the inertial sensors and components onboard. The number of wheels to employ in a design should depend on requirements of the capabilities. The number of wheels used in a design should depend on requirements of the capabilities

Higher levels of torque required which is ultimately supplied by the motor, to overcome the traction. Ideally, the tire should have maximum contact with the ground and minimal resistance through the drive system. A width of 25-30 mm of a rubber tread deemed acceptable as it would provide reasonable grip for most terrains. It would also prove ideal for turning on the spot (360-degree rotation) which is a major feature of a two wheeled balancing robot.

Each of the two wheels will independently control in either direction by an individual motor. The diameter required for the wheels was approximately between 5 - 6 cm. so that proportionality could maintain with the absolute robot height. Two plastic wheels with solid rubber tiers have chosen due to their reduced cost.

Motors: Motors are an essential component for providing locomotion. Several types of motor are available including Alternating Current (AC) or Direct Current (DC) types. Variances of these motors include the brushless, brush, servo and permanent magnet motors. Another consideration for the motor is its Revolutions per Minute (RPM). As most motors rated at 200-700 RPM, some form of gearing is required to reduce the rate experienced at the wheel.

The idea of using a separate motor on the two-wheel is to obtain differential drive and also it reduces the potential manufacturing cost of using one motor. Using two motors will also allow the torque to be more efficiently applied to the wheel shafts thus reducing the need for complex calculations for frictional and rotational losses. As the right motor moves forward and the left motor runs backward, the robot chassis will be turned to the left. If equal torque applied to each of the motors, the robot would activate the spot. Other considerations for the turning of the robot should include the angle of the robot chassis. With this in mind, the primary goal would be to tilt the frame in the direction the robot is about to travel.

The motors would be better mounted on the robot chassis to allow a higher clearance from the ground. Otherwise, the lower chassis layer may drag into the field at a very lower angle of tilt. Stepper motors are too slow to react due to the stepping action and will not be capable of balancing the robot efficiently. A motor with a high volume of torque was a necessity with the final choice.

Actuator: The actuator to balance the robot is via two DC motors. Each motor has a gear reduction of 54.2:1 and a torque constant of 6.9203 x 10-4 kg-m/A. These motors controlled by a motor drive which explained in this paper.

Motor drive: L293D type motor drive used. This driver allows DC motor to drive in either direction. It can control two DC motor simultaneously in any direction. It works on the concept of H-bridge circuit which enables the voltage to flow in either direction. Voltage needs to change its way of being able to rotate the motor in clockwise or anticlockwise direction. There is two H-bridge circuit in the IC which can turn two DC motor independently.

Table.1. Motor and motor controller specification

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.2. Drive system

Variable name	value	Description
q_{max}	30rpm	Speed of the motor
i_{max}	70mA	No-load current
$U_{A,max}$	12V	Maximum motor and motor control voltage

Sensor system: Sensors like accelerometer and tilt sensor used in it. The position of the motor was measured using accelerometer which directly mounted on the shaft of each motor. It is also used to measure the motor velocity. The tilt sensor attached to robot chassis which is connected to the controller when the robot tilts the tilt sensor will produce a voltage fluctuation which is read by the controller and signal is given motor to bring the chassis in an upright position which provides high precision control to the robot.

Power supply: The power supply consists of the battery. The 3.3V and 5V PCB fitted on the bottom layer to reduce the susceptibility. The switches have glued to the underside of the power layer for easy removal. Alternatively, these bumper switches could be moved directly to the power layer at a later stage if they are fastened with bolts thus entirely freeing up the additional coating.

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_f Friction force between wheels and ground (N)

$F_j = -F_f * u_x$

$F_f=-\mu_{wh}[(M_{wh}+M_{re})g-M_{re}l(\ddot{\theta}\text{Sin}\theta+\dot{\theta}^2\text{Cos}\theta)]\text{Sgn}(N_{wh}*\dot{x})$

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

$N = N_x *u_x – N_y * u_y$

ISSN: 0974-2115
www.jchps.com Journal of Chemical and Pharmaceutical Sciences

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)

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

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)

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

Center of gravity calculation: All the components used in the final fabrication are taken in into consideration (Fig-2) to calculate the center of gravity including motor and motor clamp

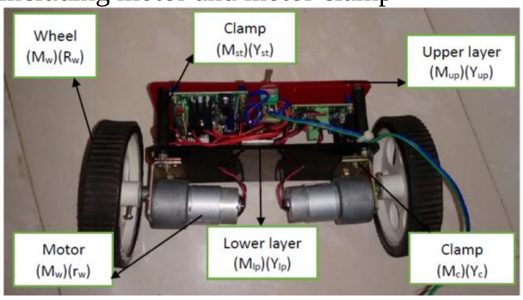

Fig.2. Notations of CG

$CG = 2M_w(r_w) + 2M_m(r_m) + M_{lp}(Y_{lp}) + M_{up}(Y_{up}) + 4M_{st}(Y_{st}) + 2M_c(Y_c) / 2M_w + 2M_m + M_{lp} + M_{up} + 4M_{st} + 2M_c$

M_w = 50g, R_w = 5.5cm, M_m =250g, R_m =4.5cm, M_{lp} =20g, Y_{lp} =8cm, M_{up} =20g, Y_{up} =12.7cm, M_{st} =150g, Y_{st} =9.5cm, M_c = 150g, Y_c = 6 cm, ans= CG=5.50cm.

System integration and overview: Integration of the sensors and motors with the microcontroller shown in was successful which will allow real system integration with all components contained within the robot (Fig-3). The components and devices chosen allowed simple connectivity with the microcontroller through its digital, analog and PWM input/outputs.

Upon completion of the construction, an operation was undertaken as expected with no rubbing, noise and vibration experienced.

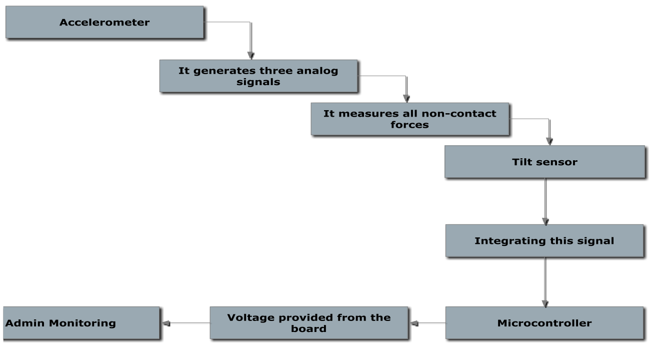

Fig.3. System architecture

Analysis: Analysis has done in every material that used in the robot. The materials that employed in the robot are shown below in fig. 4.

The analysis is done to know the total deformation, stress, and strain of each material used in robot this is done to know how much load the robot will withstand, and the weight of the robot should be less because it is a self-balancing robot. The materials used are steel, aluminum, ceramic (Table. 3). The total deformation of the whole robot is shown in fig. 5, and maximum principle stress and strain in shown in fig. 6 and fig. 7.

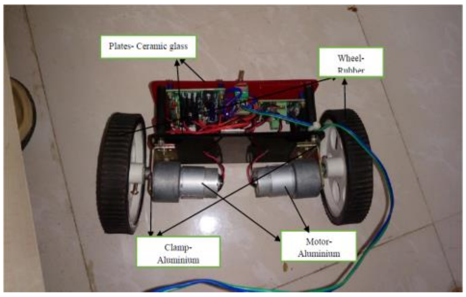

Fig.4. Material used

Table.3. Result for steel, aluminium, ceramic

	steel	aluminium	ceramic
Total deformation	1.6868 mm	2.444 mm	0.035 mm
Max-stress	5.3164 N/mm^2	7.536 N/mm^2	2.563 N/mm^2
Max-strain	8.8675	9.333	5.663

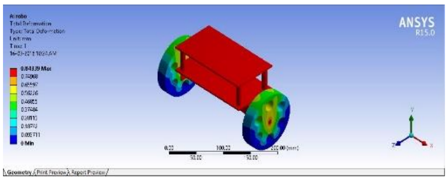

Fig.5. Total deformation

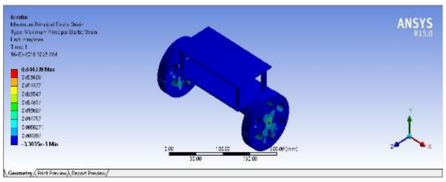

Fig.6. maxi principle strain

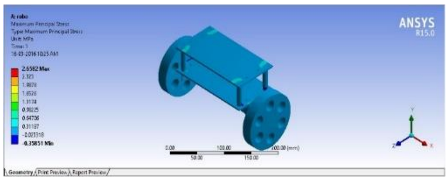

Fig.7. maxi principle stress

System Testing:

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.

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.

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.

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 is 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.

3. EXPERIMENTAL PROCEDURE

To validate the modules, design, and microcontroller, analysis conducted; they include:

Balance experiment: The robot placed on the ground and the power button was switched on then robot stood in upright position and maintains its balance. The balancing test was carried out with or without friction compensator. Friction state proposed can improve steady state error sufficiently. When friction state not compensated, there is crawling phenomenon.

Straight line movement: Straight movement can achieve by implementing offset angle to the reference angle of the self-balancing robot. Larger offset makes the robot moves faster. The operator changed the offset angle.

4. CONCLUSION

The various design taken into consideration, their limitation and challenges were studied, and the suitable design is selected. The literature review has conducted in the every component that used in the robot. The robot which we made, attain the task of self-balancing and further we can make this robot autonomous by adding additional components such as a camera for vision etc. This type of robot can be adopted in various hazards environment where humans cannot go.

5. ACKNOWLEDGMENT

I feel greatly indebted to my project guide Mr. V.P Haridasan**,** and I thank him for the sincere interest shown in this project and for motivating me to do my best.

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