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Design and Development of a Two Wheeled Self Balancing Robot for an Application of Object Carrying

Aja Mariam Johnson
Electrical and Electronics Engineering
TKM College of Engineering
Kollam

Nasar A.
Electrical and Electronics Engineering
TKM College of Engineering
Kollam

***Abstract*— Two Wheeled Self Balancing Robot is a foremost research topic in the area of robotics and control engineering. The principle of operation behind a self balancing robot is an inverted pendulum concept. The major focus on this paper is the hardware development of a two wheeled self balancing robot for an application to carry objects from one place to another. The modeling of the self balancing robot is done in terms of the inverted pendulum .Since the two wheeled self balancing robot has some inherent characteristics like instability, non linearity different types of controllers like PID,LQR, LQR with precompensation are used and their performance are compared.Simulations are carried out in MATLAB/SIMULINK. A PID controller is incorporated in the hardware section to improve and ensure a good performance for the system**

Keywords*— *Self Balancing; Instability; Controlling; PID; LQR

I. INTRODUCTION

The research and new innovations related to self balancing robot has gained momentum in the field of robotics and control engineering. The basic working principle behind self balancing robot is an inverted pendulum concept. The examples of inverted pendulum in certain real applications includes rockets like MAXUS in its starting position,Segway the personnel transporter, a self balancing vehicle. Two wheeled self balancing robot is an important type among mobile robots. Unlike an ordinary robot, a two wheel self balancing robot requires just two point of contact with the floor surface. The unique stability control that is required to keep the robot upright differentiates it from ordinary robots. The basic idea of a self-balancing robot is simple drive the wheels in the direction in which the robot tilts. This is similar to the inverted pendulum model in control theory. It has great advantages like small size,flexibility,low cost because of these advantages ,it can be used in various application in the field of control engineering. The inherent complexity associated with control of this platform find its application in design and development of control system of automobiles,spacecrafts,transportation facilities including military transport. The developed hardware is used to develop an object carrying vehicle which can be used to reduce the human efforts in working places,offices,house hold applications. This is a cost effective solution using PID algorithm for this two wheeled vehicle

Problem Definition

The reason behind huge application of Self Balancing Robot in the various application in control engineering is its mechanical stabilty.Comparing with ordinary four wheel robot ,two wheeled robots have many advantages like cost reduction, size reduction, find its increased application like rockets, military transportation etc. But the instability associated with this make the design and modeling so much complex.

II. SYSTEM MODELLING

Two wheeled self balancing robot depend upon the principle of operation of inverted pendulum[1]. This concept is a common example found in all control engineering text books and a hot topic among the researchers focusing in control area. For the modeling of a self balancing robot for an object carrying purpose , an inverted pendulum with a cart system can be used. The system is completely unstable with out a controller. It can be make stable by moving the cart forward or backward if the pendulum tends to fall in forward or backward direction. This forward or backward force will give an acceleration to the wheels according to the angle between the vertical position of the pendulum and current position of pendulum. The inverted pendulum is an example of highly unstable, on linear dynamic system. Generally in self balancing robots controlling depend on the application for which it is used. In this paper the self balancing robot is meant for the application of object carrying so the two controlling sub systems are self balancing subsystem, for preventing the system from falling down when it moves forward or backward. And the second subsystem is yaw rotation subsystem for steering angle regulation when it moves left or right. The free body diagram of inverted pendulum with a cart is given in the figure.1. For this system, the control input is the force u that moves the cart horizontally and the outputs are the angular position of the pendulum θ and the horizontal position of the cart x.The terms used in the modeling are

- M is the mass of the Cart
- m is the mass of Pendulum
- b is the frictional co efficient for cart

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- l is the length to the pendulum center of mass
- I is the moment of inertia of pendulum
- Force applied to the cart
- θ is pendulum angle from vertical

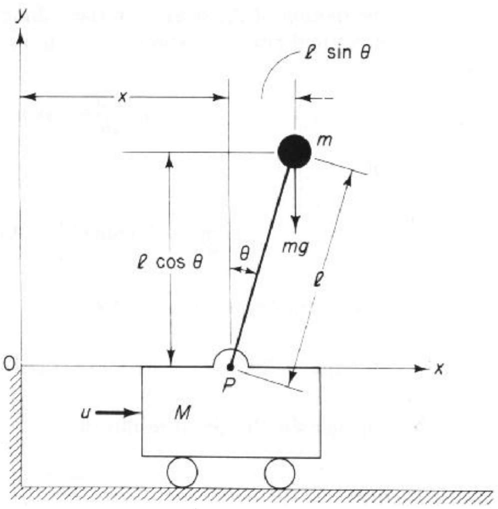

Fig 1.Free body diagram of inverted pendulum with cart system[1]

According to Newton's second law of motion cart equation is

$$F=M\ddot{x}+b\dot{x}+H \quad (1)$$

Horizontal motion of center of gravity of pendulum rod is

$$m\frac{d^2}{dt}(x+l\sin\theta)=H \quad (2)$$

$$m\ddot{x}+ml[\ddot{\theta}\cos\theta-\dot{\theta}^2\sin\theta]=H$$

$$m\ddot{x}+ml\ddot{\theta}\cos\theta-ml\dot{\theta}^2\sin\theta]=H \quad (3)$$

substituting (3) in (1)

$$F=M\ddot{x}+b\dot{x}+m\ddot{x}+ml\ddot{\theta}\cos\theta-ml\theta^2\sin\theta \,(4)$$

Rotation motion about center of gravity

$$I\ddot{\theta}=Vl\sin\theta-Hl\cos\theta \quad (5)$$

Vertical motion of center of gravity of pendulum rod is,

$$m\frac{d^2}{dt}(l\cos\theta)=V-mg \,(6)$$

$$ml\frac{d}{dt}(-\sin\theta)=V-mg \,(7)$$

$$V=mg-ml\dot{\theta}^2\cos\theta-ml\ddot{\theta}\sin\theta \,(8)$$

Substituting (3) (9) in (6),equations can be written as,

$$I\ddot{\theta}=mgl\sin\theta-ml^2\ddot{\theta}-ml\ddot{x}\cos\theta$$

$$I\ddot{\theta}-mgl\sin\theta+ml^2\ddot{\theta}-ml\ddot{x}\cos\theta$$

$$(I+ml^2)\ddot{\theta}=mgl\sin\theta-ml\ddot{x}\cos\theta \quad (9)$$

Equation (9) is non linear,

Linearising 4, 9 assume θ and $\dot{\theta}$ are small so

$$\sin\theta=\theta,\cos\theta=1,\dot{\theta}\theta^2=0$$

$$F=(M+m)\ddot{x}+bx+ml\ddot{\theta} \quad (10)$$

$$(I+ml^2)\ddot{\theta}=mgl\theta-ml\ddot{x} \quad (11)$$

Let us assume F=u,

Taking Laplce transform of equations (10),(11) and applying zero initial conditions

$$(I+ml^2)\theta(S)-mgl\theta(S)=mlX(S)S^2 \,(12)$$

$$(M+m)X(S)S^2+bX(S)-ml\theta(S).S^2=U(S)$$

From equation (12)

$$X(S)=\frac{(I+ml)\theta(S)S^2-mgl\theta(S)}{mlS^2}$$

$$X(S)=\theta(S)[\frac{I+ml}{ml}-\frac{g}{S^2}]$$

∴ Transfer function, with pendulum angle Θ(S) as output is given by

$$\frac{\frac{ml}{q}S^2}{S^4+\frac{b(I+ml^2)}{q}S^3-\frac{(M+m)mgl}{q}S^2-\frac{bmgl}{q}S} \text{rad/n}$$

Where $q=[(M+m)(I+ml^2)-(ml^2)]$

And the transfer function with a cart X(S) as output,

$$\frac{X(S)}{U(S)}=\frac{\frac{(I+ml^2)S^2-gml}{q}}{S^4+\frac{b(I+ml^2)}{q}S^3-\frac{(M+m)mgl}{q}S^2-\frac{bmgl}{q}S}$$

State Space Model of Inverted Pendulum System

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$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{-b(I+ml^2)}{S} & \frac{-m^2gl^2}{S} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{mlb}{S} & \frac{mgl(M+m)}{S} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{ml^2+I}{S} \\ 0 \\ \frac{ml}{S} \end{bmatrix}$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

Stability Analysis

From the derived transfer function of the inverted pendulum it is understood that system is highly unstable because of the pole location at the right side of the S-plane. The same result is also is obtained from the root locus plot clearly denotes the theoretical instability of the system.So in order to make the system stable a controller is necessary.

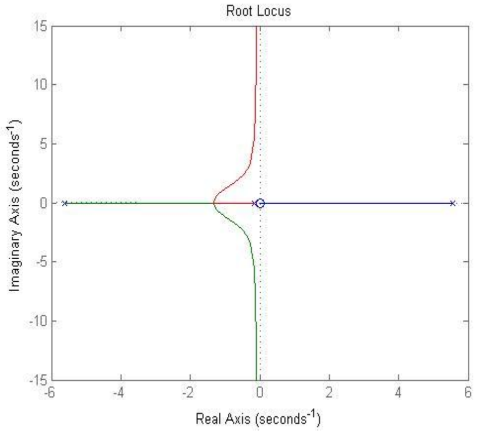

Fig 2:Root locus diagram of inverted pendulum model

III SIMULATION AND TEST RESULTS

The inverted pendulum with a cart system is not stable with out any controller. From the impulse response of this system clearly shows the runaway nature that implies the complete instability of the system. This instability is because of the presence of open loop pole in the right half of the S-plane. So in order to make the system stable a controller is necessary. Different controller is used and a performance evaluation is also done in this session.

PID Controller

The PID controller has mainly three constant parameters. The Proportional (P), The derivative (D),The Integral (I).This is closed loop control system and also called as negative feedback system. Input to the controller is error form the system .Error is deviation between the desired state and the measured state and this is error ,which is fed as the input of the controller is used for three purpose. The error term will be used on the controller is to execute the proportional, integral and derivative term. The P component is used as for the purpose of error elimination. It simply calculates the angular measurement of the robot and makes the motors move in the same direction to stop the falling of the robot. The Integral term will find the average of past errors and this term has an important role in reducing the steady state errors. The Derivative component will handle the overshoots and reduces the robot vibrations of the robot. The gains of the PID controller is chosed based on trial and error method. The output of the controller is given by,

$$V(t) = K_p e(t) + K_i \int e(t) + K_d e(t)$$

Response with PID

Before going with a controller certain assumption took in the design are, the controller will maintain the pendulum vertically upward when the cart is subjected to an applied force of 1-Nsec impulse. Under these conditions, the design criteria are:

- Settling time of less than 5 seconds
- Pendulum should not move more than 0.05 radians away from the vertical

In fig3 a simulink model of inverted pendulum system with PID controller is given and the in fig 4.4 impulse response of pendulum without a controller is also given.In that the overshoot is more and settling time is more than that of design criteria. So to get a stable response PID controller is added in the subsystem. The simulink model and responses are given above. The settling time of the response after inserting a controller is 1.64 seconds, which is less than the 5 seconds which satisfy the requirement .The steady state error approaches zero in a fast manner. The peak response is larger than the requirement of 0.05 radians. However the overshoot is somewhat higher in the response we had obtained so in order to reduce the overshoot it is necessary to increase the amount of derivative control. For K_d=20,the overshoot is reduced and more satisfactory response is obtained.

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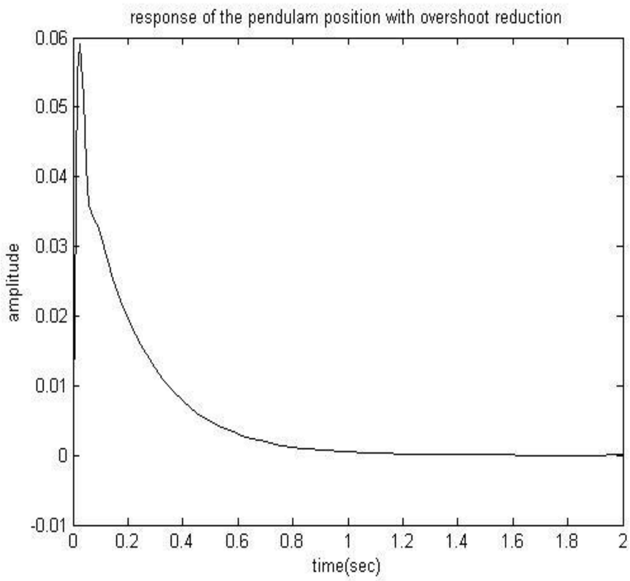

Fig 3: impulse response of pendulum with overshoot reduction

Linear Quadratic Regulator

The LQR algorithm is basically used to find the state feedback controller. It is a special type of optimal control problem which deals with linear system and minimization of cost or objective functions i.e. LQR the L terms denotes a linear plant Q term denotes the quadratic cost function and R terms is a regulator .In LQR function the cost function is also considered than other conventional controllers like PID.While designing the LQR controller both the cart position and pendulum angle are considered. The basic principle behind the controller design for an inverted pendulum is if the pendulum is displaced, the controller will determine the cart position to make the angle displaced from the vertical position to zero(ϴ=0).

The first step in designing the LQR controller is to check whether the system is controllable or not. The system is completely state controllable if and only if the controllability matrix must have rank n where the rank of a matrix is the number of non zero rows .To check the controllability first form the controllability matrix C.

Where C= [B AB A^2B ….$A^{n-1}B$] and obtained as

$$c = \begin{matrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{matrix}$$

Controllability =4

Therefore, system is completely state controllable and so the linear quadratic regulation method can be used as the state feedback control gain matrix $\mathbf{K}$. The MATLAB command is ‘lqr ‘allows to choose two parameters, $\mathbf{R}$ and $\mathbf{Q}$, which will balance the relative importance of the control effort (u) and error (deviation from 0), respectively, in the cost function that is needed to optimize. Here the value of R ia assumed as 1 and Q=C’C .The cost function corresponding to this R and Q places equal importance on both the control and the state variables which are outputs the pendulum's angle and the cart's position. lqr method has an advantage of control of both outputs. More desirable response can be obtained by changing the non zero elements in the Q matrix

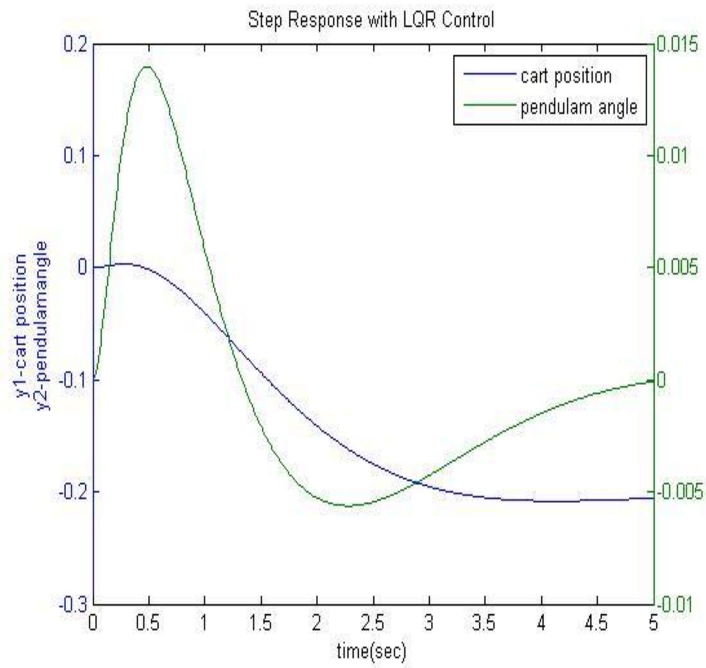

Fig 4: Step response with LQR controller

Here Q(1,1)=1 and R=1 ..The value k matrix is obtained as [-1.0000 -1.6567 18.6854 3.4594] .From the graph it is obtained as there is a considerable reduction in the overshoot But the there must be reduction in the settling time so inorder to make a better response assume Q(1,1) =6370 more values of Q(1,1) yield better response.This is because while Increasing the magnitude of Q there is a reduction in error but requires a greater control force ‘u’. This will leads to more control effort generally corresponds to greater cost thati.e. if we have to supply a large energy the Cost of components like actuators will be higher

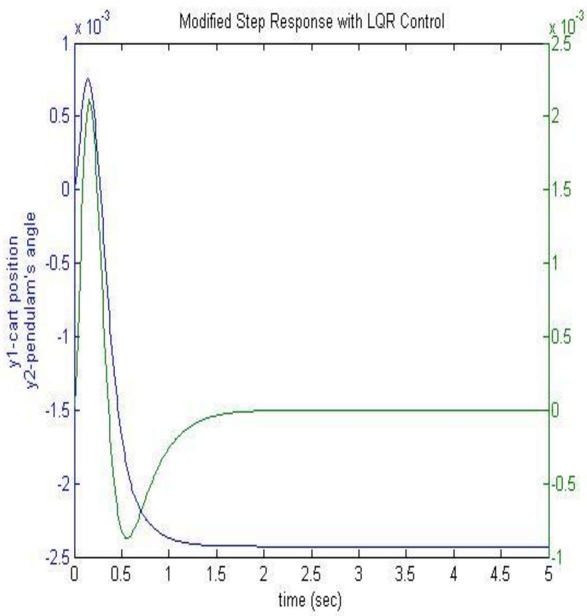

Fig:5. step response with Q(1,1)=6378

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Even though the controller designed using LQR technique meets the design consideration. there is still problems associated due to the influence of the steady state error. In comparison with other design methods, output is feedbacked and compare it to the reference input to compute an error, with a full state feedback controller all states are feedbacked.

Linear Quadratic Regulator with Pre Compensation

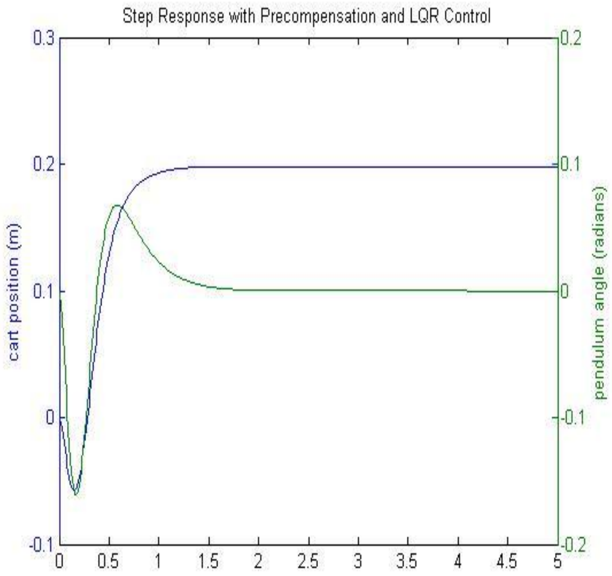

Fig 6:step response with LQR Pre Compensation

the steady state error is reduced and also settling time. and the pendulum's overshoot is within specified range.The precompensator N̄ employed here is calculated based on the model of the plant and the precompensator is located outside of the feedback loop.. The precompensator is able to eliminate the steady-state offset using knowledge of the plant model

IV HARDWARE IMPLEMENTAION

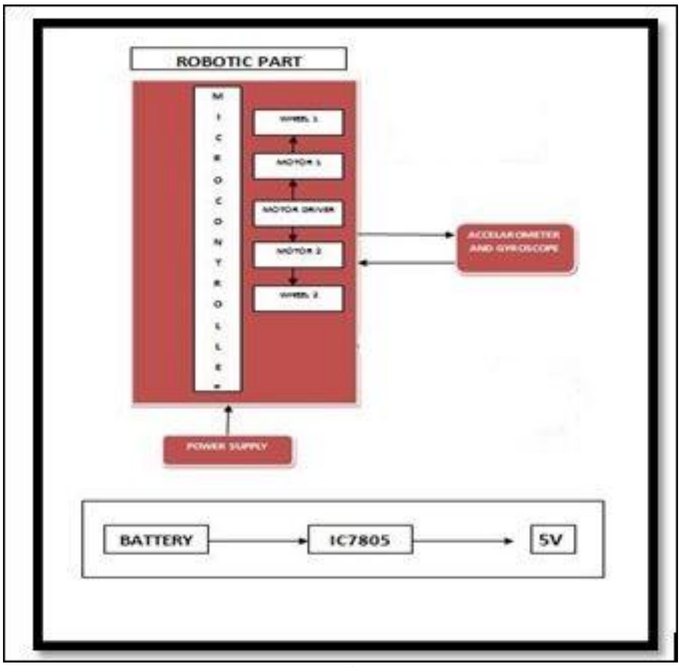

Fig:7.Block diagram of the robotic system

The robot consists of three platforms .Top most platform is used for carrying the objects from one place to another. Second platforms will accommodate the microcontroller arduino UNO, an Inertial Measurement Unit and a motor driver mounted on it. On the lower part of the base platform, the two motors with a torque (126 rpm) are clamped. The whole structure of the robotic body gets balanced on two wheels .The wheels have a required grip providing sufficient friction. The figure of the robotic body is given below.

Robot Chasis Specifications

The Self balancing robotic chassis is electrically powered by two 12V, 126rpm, DC metal gearmotors. It has a 28mm width between the wheels with wear resistant rubber grip gives greattraction, which is necessary to make it self balancing. It has 3mm thick aluminiumbodyforms a rigid platform which holds the motors and wheels.

Tyre Specifications

- Outer dia of wheel: 65mm
- Width of wheel: 28mm
- Brass fitting suits 4mm shaft

Motor Specifications

- Rated Voltage(DC): 12V/6V
- No load speed: 126rpm/75rpm
- No Load Current: 46mA/30mA
- load Speed: 100rpm/60rpm
- load Current: 250mA/280mA
- Power output: 1.25W/1.25W
- load torque: 1.2kg.cm/0.8kg.cm
- Stall torque: 4.2kg.cm/2.5kg.cm
- Stall Current: 1A/900mA
- Gear ratio: 1 : 34

The Arduino Microcontroller

The microcontroller used is Arduino Uno which basically uses ATmega328 . There are 14 digital input and output pins.Six of them can be used as PWM outputs and also six analog inputs. A16 MHz ceramic resonator is used to provide the clock. The Arduino can be simply poweredvia using a USB connection or with external supply. Externally it can be powered with a AC-to-DC adapter or battery. The leading advantages of the this microcontroller are in expensive, operates on cross platform, simple and a clear programming environment, availabilityof open source and extensible software.

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Inertial Measurement Unit and I^2CProtocol

In robotic applications it is necessary to use sensors such as accelarometer, gyroscope for measuring some essential quantities like rate of angular tilt, vibrations etc. The major area where the applications of IMU are most common includes aircrafts, spacecraft, satellites, unmanned areial vehicles etc. The feature of this IMU are tiny, prescence of mounting holes , accelerometer and gyro ,3.3V input ,I2C interfacing.

The function of the accelerometer is to give the components of acceleration along its axis and these data are more sensitive and noisy while gyroscope gives the components of angular velocity along its axis and these data are less sensitive and I2C is the mode used for communication .SDA (Data) and SLC (clock) are the two important lines of the I2C bus which can be run in parallel to communicate with several devices at once. I2C facilitate upto 112 slaves like sensor to be controlled by a single master like Arduino microcontroller. The slave device which are connected to the bus must have it's own unique address so the master can communicate directly with that particular device.

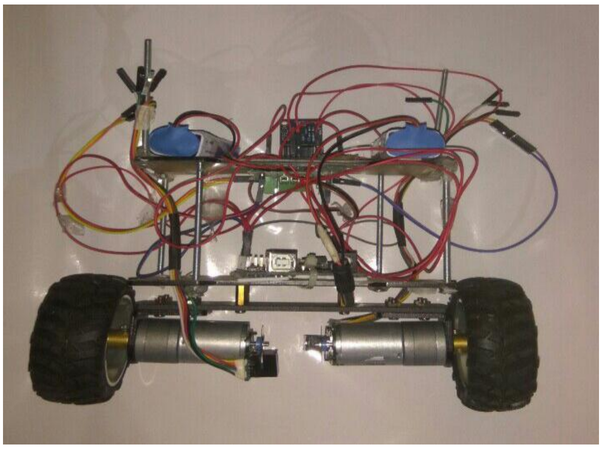

Fig:8. Developed Hardware

VI.CONCLUSION

Design and Development of a two wheeled self balancing robot with object carrying is done .The peculiar application implemented is the robot is able carry an object without falling. The modelling of the self balancing robot is done with the help of inverted pendulum concept. Since the modelled system is highly unstable it is necessary to use appropriate controllers and a comparative study of different controllers like PID, LQR, LQR with precompensation, were done. The analysis of the impulse response of the system for the different controllers are simulated with MATLAB/Simulink.LQR with precompensation offers a much better performance and satisfies the design consideration of settling time less than 1 sec and vertical angle of pendulum less than 5 radian

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