DESIGN AND IMPLEMENTATION OF A LOW COST INVERTED PENDULUM STRUCTURE FOR EXPERIMENTATION PURPOSES

Adeel Ahmad[#1], Usman Zahid[#1], Osama bin Naeem[#2], Kamal Shahid[#3], Dr. Yasir Saleem[#2]

[#1] Department of Technology, University of Lahore.

[#2] Department of Computer Science and Engineering, University of Engineering and Technology

[#3] Department of Electrical Engineering, (CEET), University of the Punjab, Lahore.

Lahore, Pakistan

[1]adeel.ahmad@tech.uol.edu.pk, [2]*usmanzahid50@gmail.com* [3]osamabinnaeem@gmail.com

[4]kamal.ee@pu.edu.pk [5]*ysaleem@gmail.com*

ABSTRACT— *Main aim is the stabilization of an inverted pendulum using an economical procedure. This is done by designing an inverted pendulum structure, control mechanism and motor driving circuitry. The other main focus is to enable horizontal motion of pendulum while being oscillating about its axis. Conveyor mechanism is used to fulfill that requirement. The last objective is to create a Personal Computer (PC) based Graphical User Interface (GUI) and inter-communicating hardware using a microcontroller. The GUI design must provide a convenient interface with the hardware which will allow the user to set the position of pendulum and also to plot its response. The microcontroller provides two kinds of services: to control the horizontal position of pendulum and to build an interface between the hardware and PC. The controller collects the incoming real time information and send it serially to the PC which plots it in GUI using MATLAB.*

Keywords— Inverted Pendulum, Graphical User Interface, Stability, Conveyor, Microcontroller, Matlab

I. INTRODUCTION

Since the introduction of modern technology, the control of systems are increased and are made complex [1]. The most common of the example is the control of car. With the passage of time, the modern technology is introduced as efficient breaking system, efficient turning effect and cruise control etc. In the real world many systems have to be made stable, because they are unstable in nature. Inverted pendulum is also an example of unstable and nonlinear system [2]. Inverted pendulum is the best example to study control of the system. Inverted pendulum is the very appealing topic for the researchers as well. It helps them to study deeply the stability of the system and to understand the difference in linear and nonlinear system.

Following are some applications where study of inverted pendulum stability is applicable:

- Two wheeled mechanical structure with electrical control is required to be stable and to be in equilibrium.
- Flight of plane experiences some kind of turbulence. The plane's safety and stability is essential and lifesaving.
- Robotic structures comprised of one/two legs are needed to maintain stability and equilibrium for smooth movement.

All the above tasks are challenging and they are impossible to be performed without the adequate knowledge of how to make unstable system stable. Inverted pendulum system helps to understand this concept [3].

The basic operation of inverted pendulum is that it has a pendulum mounted on the cart. The movement of cart is controlled in order to make the pendulum balanced [4]. The task is to control the equilibrium of inverted pendulum and cart in short time, as shown in Figure 1. Meanwhile oscillation, speed and angular velocity are kept under controlled limits [5].

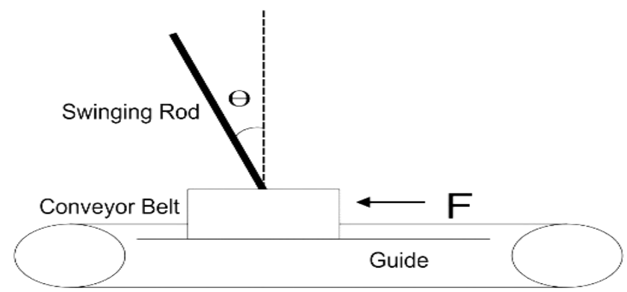

Figure 1: Inverted Pendulum working principle

In past few years, projects related to robotics got a great importance which adds to the importance of control system. The inverted pendulum system has the benchmarks for all such systems.

This paper explores the control of horizontal motion of inverted pendulum and the stabilization of pendulum in inverted position using comparator. It also has some theoretical analysis of the system dynamics of inverted pendulum, as well as a summary of the components used in hardware and implementation.

The horizontal motion of the pendulum while keeping it balance is a challenging task. This phenomenon is used in biped robots as shown in Figure 2.

motion using Graphical User Interface (GUI). GUI helps the user in easy visualization and user interactive control of a whole system. Matlab can be used to have more intuitive and organized solution.

To summarize, this paper has three main objectives and their implementation in an economical way: the stability in the inverted position, horizontal motion of the system and the design of GUI in an economical manner.

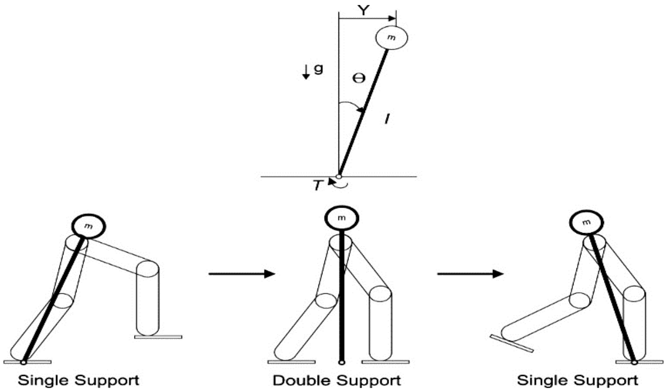

Figure 2: Inverted Pendulum implementation

The other focus of this paper is to use of Matlab (Matrix Laboratory) software for control implementation of horizontal

LITERATURE SURVEY

May research works are done on inverted pendulum due to its importance in control technology. Inverted pendulum, stability, conveyor system and GUI are the important characteristics related to an inverted pendulum upon which literature survey is done.

Some of the researches related to these topics are discussed in following topic.

A. Inverted Pendulum and Its Balancing

For any mechanical system which tend to move towards instability, inverted pendulum act as a yard stick in making them stable. Stability of such systems can be improved by the study of inverted pendulum. Reaction wheel pendulum shown in Figure 3 is the practical example [6].

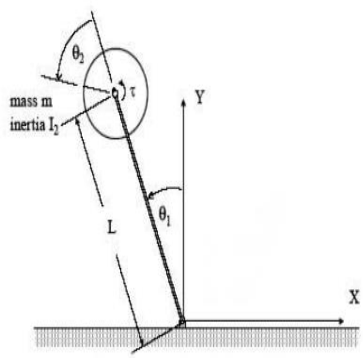

Figure 3: Reaction Wheel Pendulum

Many varieties of inverted pendulum exists. One of them is rotational arm as shown in Figure 4, the other one is cart mounted inverted pendulum as shown in Figure 5 [7].

The stability of cart mounted inverted pendulum depends upon two things: one is angle of pendulum, second is cart speed. If angle is greater, cart have to move with greater acceleration. With larger angle of pendulum, the stability control is difficult [8].

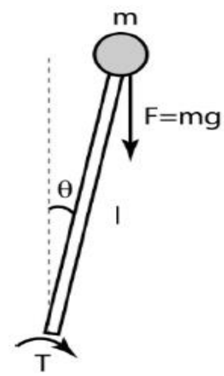

Figure 4: Single arm pendulum

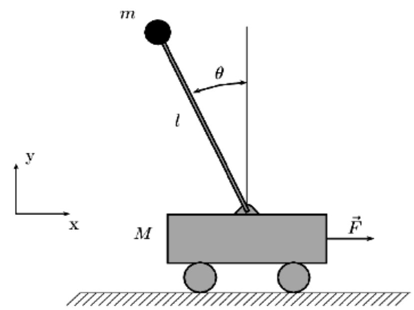

Figure 5: Cart Inverted pendulum

1) Inverted Pendulum in Control Technology Education:

Inverted pendulum is an educational and interesting topic in academics. While studying, all the frictional and opposing forces are ignored. But in real world these forces are present and makes lots of difference [9].

B. Stability

If the system maintains equilibrium, it is said to be in stable state. Stability is very important and essential property of any dynamic system. For every system there are some conditions of operation in which system remain stable. If those conditions are not fulfilled, the system may become unstable [10].

Speed is the core characteristics of the dynamic system. There should be a proper blend of speed and stability. Modern vehicles conquer high speed and remain stable at the same time. This is become possible with the thoughtful research of control systems to keep system stable [11].

For the stability of inverted pendulum, the angle should be kept in acceptable range. If some disturbance force is applied which makes angle larger, the system will be more difficult to be stabilized [12].

Conveyor Systems

Conveyors are used in the transportation of material form one point to another. They are of great importance in industries. Heavy products are transferred with their help. The conveyor's speed and other specifications may be adjusted and selected properly in order to transport material without damaging [13].

There are two performance parameters of the conveyor system: reliability and availability. Reliability refers to the safety and quantity being delivered. While availability is the quality and life duration of the conveyor [14].

There are many types of conveyor system. Types may include: chain, roller, belt, screw conveyors. Belt conveyor system is shown in Figure 6. The materials may be transported with constant or adjustable speeds, as required. Research is done in making such designs and selection of materials to increase the speed and reduce the operational noise. [15].

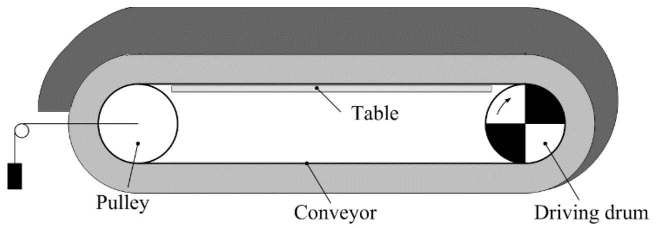

Figure 6: Conveyor belt system

Coal, cement and other major industries rely very much on conveyor systems. Their process heavily depend upon control of conveyors system. Synchronization can be done in two ways: in the first one the conveyor speed is matched with the process speed. While in second method conveyor speed is kept constant and process speed is adjusted accordingly. Synchronization adds complexity in the system but reduces the mechanical stress on the conveyor [16].

C. GUI

Before GUI, Command Line Interface (CLI) was used. CLI works on one command per line. User had to remember all the commands in order to use it. GUI provide convenience to user. GUI is much easier and convenient in use. It gives visual access and interactive control of system for user.Matlab provides GUI designing tool. Many projects are done to on it. One thesis is done on designing a GUI for motor control [17].

II. State Space Modeling of Vertical Stability

Let the mass of the cart be "M" and the force exerted on the cart is "u", "l" be the length of bob, "H" be horizontal force and "V" be vertical force exerted by the cart as shown in Figure 7.

Newton's law of linear movements is applied to get the following equations

$$M\frac{d^2x}{dt^2} = u - H \quad (1)$$

$$H = m\frac{d^2}{dt^2}(y + l\sin\theta) = m\ddot{y} + ml\ddot{\theta}\cos\theta - ml(\dot{\theta})^2\sin\theta \quad (2)$$

$$mg - V = m\frac{d^2}{dt^2}(l\cos\theta) = ml\,(-\ddot{\theta}\sin\theta - (\dot{\theta})^2\cos\theta) \quad (3)$$

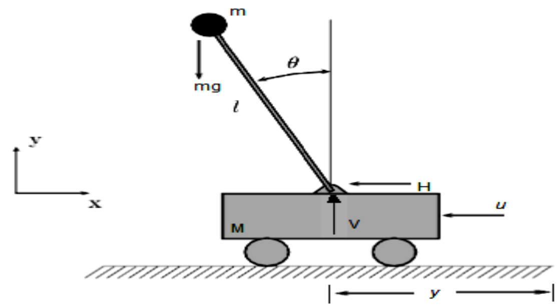

Figure 7: System Parameters

By applying Newton's law of the rotational movement of the pendulum around the hinge, the equation can be written as

$$mgl\sin\theta = ml\ddot{\theta}\,.\,l + m\ddot{y}l\cos\theta \quad (4)$$

As θ and $\dot{\theta}$ be very small, it can be assumed that:

$$\sin\theta = \theta$$
$$\cos\theta = 1$$

By retaining only linear terms θ and $\dot{\theta}$ and dropping terms with $\theta^2, (\dot{\theta})^2, \theta\dot{\theta}, \theta\ddot{\theta}$

The above equations 2, 3 and 4 becomes

$$V = mg \quad (5)$$
$$M\ddot{y} = u - m\ddot{y} - ml\ddot{\theta} \quad (6)$$
$$g\theta = l\ddot{\theta} + \ddot{y} \quad (7)$$

From equation 6

$$M\ddot{y} = u - m(\ddot{y} - l\ddot{\theta}) \quad (8)$$

From equation 7

$$M\ddot{y} = u - mg\theta \quad (9)$$

And

$$Ml\ddot{\theta} = (M+m)g\theta - u \quad (10)$$

Taking Laplace transform of equations 9 and 10, with zero initial conditions

$$Ms^2\hat{y}(s) = \hat{u}(s) - mg\hat{\theta}(s) \quad (11)$$
$$Mls^2\hat{\theta}(s) = (M+m)g\hat{\theta}(s) - \hat{u}(s) \quad (12)$$

From above equations 11 and 12, the transfer function becomes:

$$\hat{g}_{yu}(s) = \frac{s^2-g}{s^2[Ms^2-(M+m)g]} \quad (13)$$

$$\hat{g}_{\theta u}(s) = \frac{-1}{Ms^2-(M+m)g} \quad (4.14)$$

In order to develop state space equations, select state variables as:

x1 = y
x2 = $\dot{y}$
x3 = θ
x4 = $\dot{\theta}$

From equation 9 and 10

$$\begin{bmatrix}\dot{x}1\\ \dot{x}2\\ \dot{x}3\\ \dot{x}4\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & -mg/M & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & (M+m)g/Ml & 0\end{bmatrix}\begin{bmatrix}x1\\ x2\\ x3\\ x4\end{bmatrix} + \begin{bmatrix}0\\ 1/M\\ 0\\ -1/Ml\end{bmatrix}u$$

And output y as

$$y = [1 \quad 0 \quad 0 \quad 0]\,x$$

III. SIMULATION IN MATLAB SIMULINK

After designing a system it is preferred to check the system's response using suitable software before implementing the system on hardware. Response of the system may be diverting from the desired output. Thus by changing the values of some parameters the system response can be obtained as required. For this purpose, Simulink is selected as a simulation software to check the system's output response.

Table 1 represents the some of the parameters used:

Table 1: System parameters

Name of variable	Abbreviation	Value
M	Mass of the Cart	600gm
m	Mass of the Pendulum	500gm
b	Friction of the Cart	0.000 N/m/sec
L	Length of pendulum to Centre of Gravity	1.5 m
I	Moment of Inertia (Pendulum)	2 gm-m^2
g	gravitational Constant	9.8 ms-^{2}
F	Force applied to the cart	Variable
x	Cart Position Coordinate	Variable
q	Pendulum Angle with the vertical axis	Variable

The simulation block made in Simulink of equations 1 to 4 is shown in Figure 8

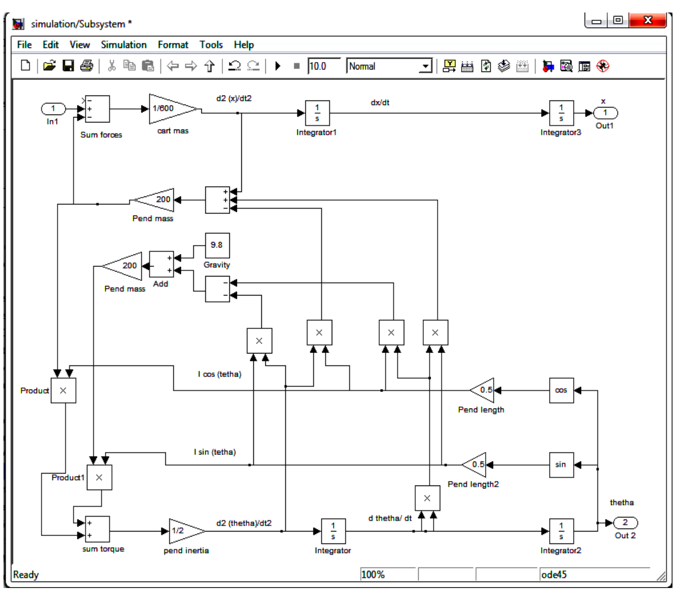

Figure 8: Simulation in Simulink

A. RESULTS IN MATLAB SIMULINK

All the simulation blocks can be represented into one single block (sub-system) having input and output ports as shown in Figure 9. The input is applied with the help of function generator, while the output is plotted on the oscilloscope.

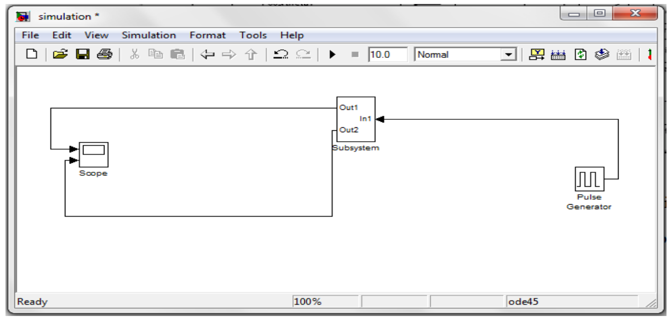

Figure 9: Sub-System

By applying the input from pulse generator, the output can be seen on oscilloscope, as shown in Figure 10.

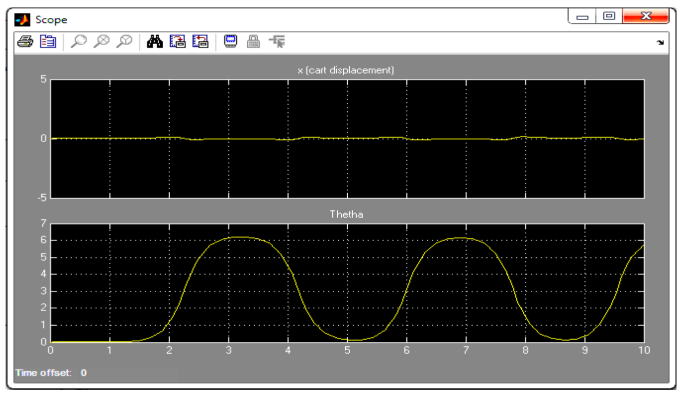

Figure 10: Simulation results

Simulation result shown in Figure 10 has two parts. The above graph shows the cart movement "x" and the lower graph displays the pendulum angle "thetha". The cart movement is very small as it practically vibrates at its position to keep pendulum in upright position. The pendulum angle is a periodic, stable and finite signal. These simulation results show that the design can be implemented on the hardware.

IV. HARDWARE IMPLEMENTATION

The physical anything providing desired results is the hardware. After validating mathematical design of system and simulating the design in software, it is now more safe and economical to implement in hardware.

The hardware implementation of this paper contains three categories:

1. Implementation of Inverted pendulum
2. Implementation of conveyor belt
3. Microcontroller circuit

Following lines discusses these categories in detail.

A. Implementation of Inverted Pendulum

The leading objective of this paper is to complete all objectives by designing an economical hardware structure. All the commercial available equipment is very expensive.

Some commercially available inverted pendulum hardware available in online market in terms of thousands of U.S. Dollars. Some inverted pendulum prices in online market is shown in Table 2.

Table 2: List of Inverted Pendulum Prices

Sr. #	Inverted Pendulum model	Price	Currency	Source website
1	Quanser Engineering Trainers for NI ELVIS (QNET Rotary Inverted Pendulum)	5,875	U.S. Dollars	http://sine.ni.com/nips/cds/view/p/lang/en/nid/210176
2	GLIP2011 - Linear flexible 1-stage inverted pendulum	4,720	British Pound	http://www.imexshop.co.uk/contents/en-uk/d227_Inverted_Pendulum.html
3	GLIP2101 - Network control linear 1-stage inverted pendulum (Ethernet)	5,034	British Pound	http://www.imexshop.co.uk/contents/en-uk/d227_Inverted_Pendulum.html

To achieve this objective, a customized structure is designed. Hardware structure is broadly categorized into three parts:

- Physical structure of inverted pendulum
- Control mechanism
- Motor controlling circuit

1) Physical Structure of Inverted Pendulum:

To make an economical structure, new structure is designed using structure of old dot matrix printer. The hardware is changed according to needs. Reliability and structure strength is given great importance.

Figure 11 shows amended physical structure. Some physical parameters are shown in Table 3.

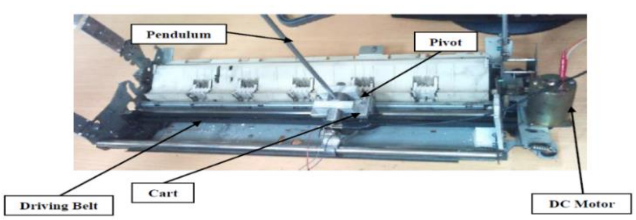

Figure 11: Inverted pendulum structure

Table 3: Physical Parameters

Parameter	Specifications
Structure	Dot matrix printer body
Motor	DC gear high torque motor (3000 rpm)
Pendulum Material	Brass
Pendulum Length	0.5 m

The important part of inverted pendulum is the cart. It plays an important role in the stability of pendulum. That is the reason why its designing is done very carefully. The limitation of design is to fit it on the available printer's header base in addition to the balancing of pendulum. The structure strength is also an important aspect to be kept in mind while designing the hardware because of its high influence in balancing the pendulum.

The cart specifications are shown in Figure 12 and in Table 4

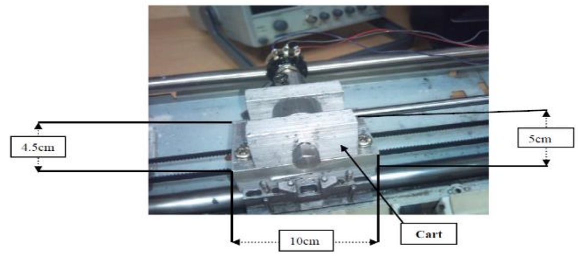

Figure 12: Cart specifications

Table 4: Cart Parameters

Parameter	Value
Cart length	10 cm
Cart width	4.5 cm
Cart weight	0.6 kg

2) Control Mechanism

The whole designing is done in order to achieve the stability of pendulum. For stability, designing of control mechanism is done. For controlling, feedback is provided by potentiometer. It gives angular displacement in terms of voltages shown in Figure 13.

As the pendulum changes its position, the potentiometer changes its value. This change in value of resistance causes the output voltage to change. While standing up right, at centre point of pendulum it gives 2.46V at output. Table 5 summarizes the feedback properties.

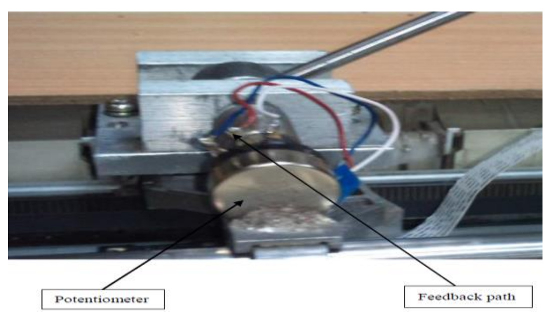

Figure 13: Feedback element

Table 5: Feedback Properties

Parameter	Value
Resistance	1k Ω
Supplied voltages	10 V
Output voltages at center	2.46 V

The signal from potentiometer is given to LM741 operational amplifier. This amplifier is used as a comparator. It receives the feedback and compares it with set point.

The comparator circuit is shown in Figure 14.

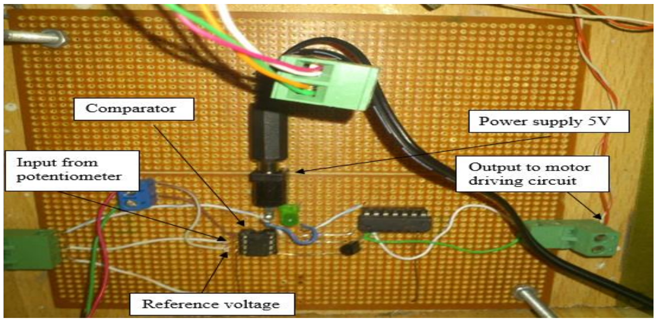

Figure 14: Comparator circuit

The set point is set at the value which potentiometer gives at 90^o of pendulum. The comparator gives either 0V or 5 V after comparing the feedback signal. If the feedback value is less than that of set point, it will give 0V, and 5V for the other scenario. Table 6 shows the comparator input values.

Table 6: Comparator Inputs

Parameters	Values
Reference	2.46 V
Input from potentiometer	2.45 V – 2.49 V

3) Motor Controlling Circuit

Next stage after comparator is motor driving circuit. It receives signal form comparator and provides gating pulse train to H-bridge circuit. Driving circuit and H-bridge circuit is in charge for the direction control of DC motor.

The cart movement is controlled by these circuits. The efficient and appropriate control of cart movement enables the pendulum to achieve stability. Table 7 shows some main components used in the circuit and their working. Figure 15, Figure 16 shows the motor driving circuit and H-bridge respectively.

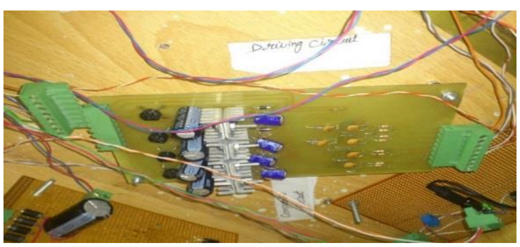

Figure 15: Motor driving circuit

Table 7: Components of motor driving circuit

Components	Purpose
Opto coupler A3120	Use to isolate supply
Bridge	Use to convert AC into DC (35V ac to 35 V DC)
Regulator 7824	Use to sustain DC voltage level (35V DC to 24V)

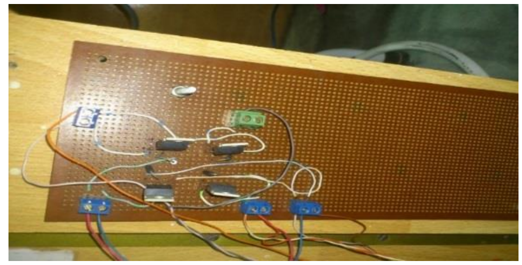

Figure 16: H-bridge circuit

B. Implementation on Conveyor

The second objective is to create horizontal movement while keeping pendulum in stable condition. This goal is accomplished by adding one additional motor, which is responsible for movement of conveyor system. The pendulum structure is mounted on it, which creates horizontal movement. The overall mechanism of pendulum mounted on conveyor is shown in the Figure 17 and some specifications are given in Table 8.

Table 8: Conveyor details

Terms	Details
Conveyor Martial	Metallic chain
Motor driving conveyor	DC motor
Motor voltages	12 V DC

Figure 17: Inverted Pendulum on Conveyor system

The direction of this conveyor is controlled by two relays. The connections are made in such a way that one relay is used for forward direction and other one if switched on changes the polarity. These relays are controlled through GUI via microcontroller.

C. Microcontroller and Serial Communication

The microcontroller is used for horizontal position control and responsible for establishing serial communication between hardware and PC. RS232 protocol is used for establishing communication.

The microcontroller circuit is shown in Figure 18.

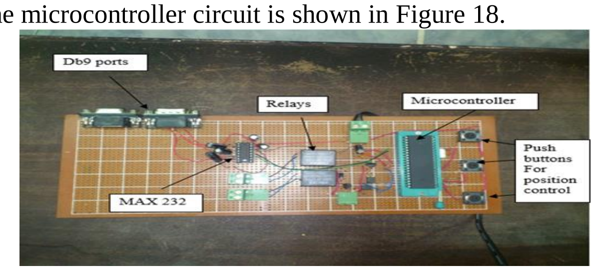

Figure 18: Microcontroller circuit

Table 9 shows some main components and their details.

Table 9: Microcontroller Circuit specifications

Component	Detail
Microcontroller	PIC18F452
Serial Communication	MAX232
Port	Db9
Oscillator	20MHz

D. Finalized Hardware Structure

The final hardware implementation is shown in Figure 19 which comprises of the inverted pendulum mounted on a conveyor. As discussed above, conveyor is responsible for horizontal movement of the inverted pendulum. This horizontal movement is controlled by GUI. The communication between PC and hardware is established by microcontroller circuit using serial communication. The power supply is used to provide power to circuits and motors.

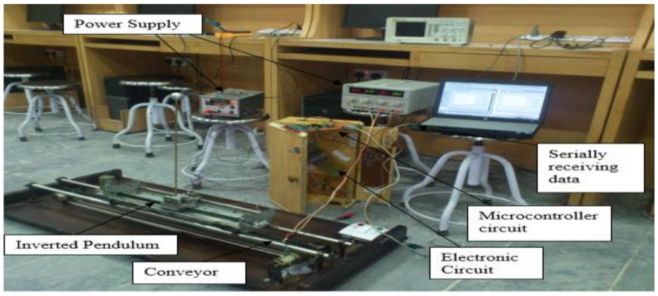

Figure 19: Overall Hardware

V. GUI DESIGN FOR AUTOMATION OF INVERTED PENDULUM

The properties of good GUI are: easy to understand, easy to operate and should be properly labelled.

GUIDE (Graphical User Interface Development Environment) in Matlab helps the user to create a GUI in an easy way. The steps to create GUI using GUIDE are discussed in the following lines.

There are two steps in making a GUI with the help of GUIDE:

1. To make an appropriate layout of the design.
2. To program m-file created by GUIDE according to desired operation to be performed. This m-file contains the call backs (which are executed when any of interactive buttons are used).

After adding all the components an m-file is created by GUIDE as shown in Figure 20 and a resulting GUI is shown in Figure 21.

A. Finalized GUI Appearance

The GUI displays graph of the values that are received at serial port. These are the output voltages that potentiometer is providing to the comparator. The final GUI also contains three push buttons. While pressing any of these buttons, the GUI writes single character (C= centre, R= right, L= left) as assigned on that push button to the serial port. By reading that character, microcontroller acts and moves the conveyor position to the appropriate position. These push buttons help in automating the horizontal motion of inverted pendulum. The graph helps the user to keep an eye on the current status of the system. The outlook of final GUI is shown in Figure 22. The plot's x-axis contains the voltage levels and y-axis contains the sampling time of the controller. From this sampling time system's time period and frequency can be calculated as follows:

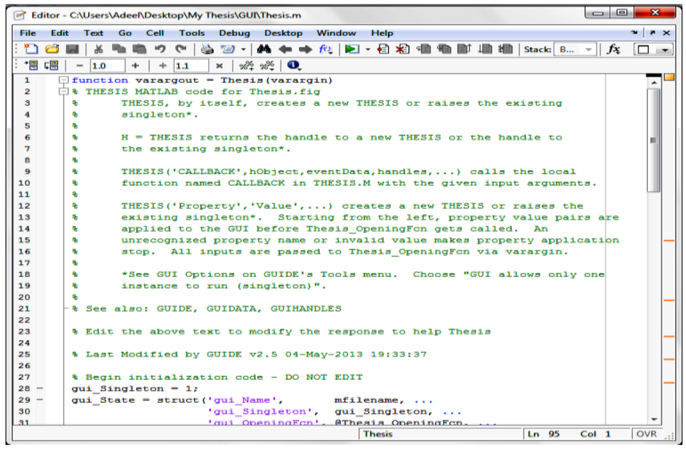

Figure 200: GUI m-file

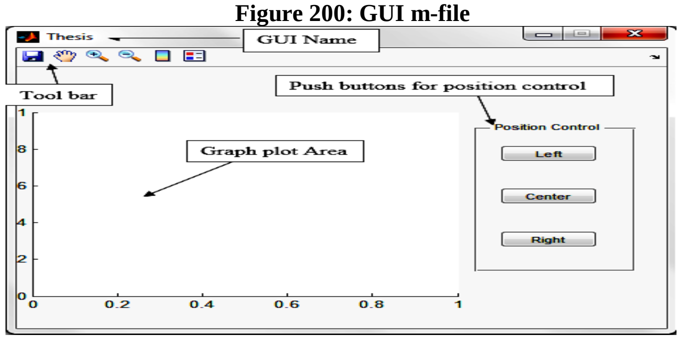

Figure 211: GUI layout

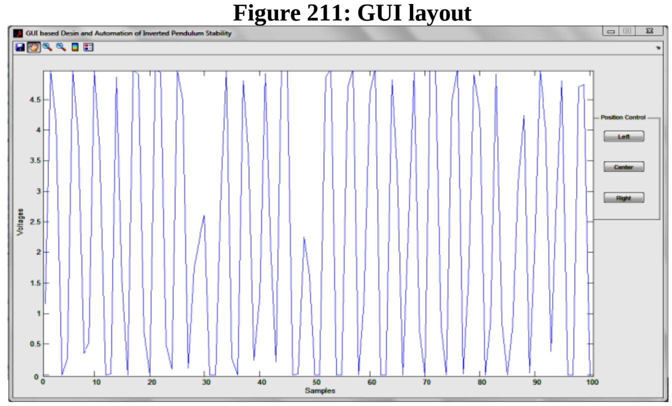

Figure 22: Output waveform of pendulum angle

Microcontroller frequency = 20 MHz

Sampling time = $\frac{1}{20\ M}$ = $0.05\text{x}10^{-6}$

Time period of plot in terms of samples = 5

Time period of system = 5 x $0.05\text{x}10^{-6}$ = $0.25\text{x}10^{-6}$

Frequency of system = $\frac{1}{0.25\ M}$ = 4 MHz

VI. CONCLUSION AND FUTURE RECOMMENDATIONS

A. CONCLUSION

The inverted pendulum is implemented successfully achieving all the required goals. The stability is achieved with the help of potentiometer feedback, set point, comparator and signal trains of driving circuit to H-bridge. All these circuits work altogether in order to move cart in an appropriate direction. This creates the stability of pendulum.

Horizontal movement keeping pendulum stable is achieved by designing the conveyor system. The pendulum mounted on this conveyor enables the horizontal movement.
GUI is designed using Matlab. It contains graph and user interactive buttons for the position control of horizontal movement.
Table 10 shows the objectives of the paper and their results

Table 10: Conclusion

Objective	Status
Inverted pendulum stability	
Horizontal Movement	
Serial Communication	
GUI design	

Commercially available structures of the inverted pendulum are quite expensive. Thus efforts were made to make an economical hardware structure. Table 11 shows the bill of materials of this thesis.

Table 11: Bill of materials

Sr. #	Component / Circuit	Quantity	Price (Pakistani Rupee)
1	Printer Structure	1	2000
2	Motor for cart	1	200
3	Conveyor Mechanism	1	2000
4	Conveyor Motor	1	1000
5	Overall wooden structure	1	5000
6	Motor driving circuit (including components)	1	1500
7	Controller circuit (including components)	1	500
8	H-bridge circuit (including components)	1	500
9	Power supply	1	3000
10	Potentiometer	1	100
11	Pendulum + Bob	1	2500
12	Cart Structure	1	3000
13	Overall Lath work	1	5000
14	Microcontroller circuit (including components)	1	700
Total (Pakistani Rupees)			27000

B. Future Recommendations

Following are some of the future recommendations which can be suggested:

- Increased speed of data transfer
- More economical system
- GUI with detailed functionality

To speed up the data transfer rate instead of serial communication, parallel communication can be used.
The ways and procedures can be found for more economical design of the hardware as compared to the stats mentioned in Table 10.
A GUI may be designed which may show more operating conditions or may have more functional buttons. Moreover some other softwares can be used for designing a GUI.

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