FEEDBACK CONTROL OF INVERTED PENDULUM USING RASPBERRY PI MICROCONTROLLER AND ARDUINO UNO

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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STATEMENT 1

This final year project report is the result of my own investigations, except where otherwise stated.

Other sources are acknowledged by giving explicit references.

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Proportional, Integrator, Derivative	PID
Final Year Project	FYP
Pulses Per Revolution	PPR
Full State Feedback	FSF
Fuzzy Logic Controller	FLC
Linear Quadratic Regulator	LQR
Proportional, Derivative	PD
Pulse Width Modulation	PWM

ABSTRAK

Bandul songsang merupakan suatu sistem yang komplex. Sistem bandul songsang dikaji secara meluas dalam banyak aspek kerana ia merupakan sistem yang rumit dan bukan linear. Sistem bandul songsang telah menyediakan eksperimen yang menarik kepada mahasiswa untuk melaksanakan kajian penyelidikan. Ia boleh dikaitkan dengan mudah ke aplikasi dunia seperti roket dan kenderaan elektrik imbang diri “Segway”. Tesis ini membincangkan sistem bandul songsang kos rendah bagi mahasiswa untuk melaksanakan kawalan ayunan dan kawalan stabil dalam keadaan songsang. Kawalan bandul songsang ini dilaksana menggunakan program Arduino bersama dengan Mikropengawal Raspberry Pi. Kawalan sistem dibahagi kepada dua bahagian, iaitu kawalan ayunan dan kawalan stabil. Kawalan ayunan berfungsi untuk mengayunkan bandul ke posisi tegak manakala kawalan stabil berfungsi untuk menstabilkan bandul dalam kedudukan tegak biarpun terdapat gangguan pada bandul. Teknik kawalan moden- pengawal Proportional, Integral dan Derivatif (PID) digunakan untuk mengurangkan kesilapan ke titik set yang dikehendaki untuk melaksanakan kawalan ayunan dan kawalan stabil. Algoritma untuk mengawal motor dan pengekod telah dibina untuk melaksanakan fungsi mereka masing-masing. Kemudian, semua algoritma digabungkan untuk membina gelung tertutup kerana pengekod dari bandul beroperasi sebagai maklum balas untuk mengubah kelajuan motor sepadan dengan kedudukan yang dikehendaki. Selepas itu, peranan parameter PID yang berbeza akan dianalisa dan dibandingkan dalam bentuk graf. Nilai PID yang ditala akhir bagi kawalan stabil ialah K_p=12.5, K_i=6 and K_d=50 manakala nilai PID bagi kawalan ayunan ialah K_p=0.15, K_i=0.005 and K_d=5. Penalaan nilai PID adalah berdasarkan kaedah percubaan dan kesilapan dengan menyesuaikan nilai-nilai yang berbeza untuk melihat kesan ke atas bandul. Sebagai kesimpulan, pelaksanaan Arduino UNO ke atas sistem bandul songsang adalah berjaya berdasarkan parameter PID yang ditala untuk kedua-dua kawalan ayunan dan kawalan stabil.

ABSTRACT

The inverted pendulum is a complex system, widely studied in many areas due to its complexity and non-linearities. Since the inverted pendulum is inherently unstable, it provides an interesting laboratory experiment for students to perform and can be easily linked to real-world applications such as rocket and Segway self-balancing electric vehicle. This thesis presents a low-cost inverted pendulum system for the students to swing up and control the inverted pendulum in upright position. The controlling in inverted pendulum is studied in the Arduino programming with the usage of Raspberry Pi microcontroller. The control system consists of two parts, which are swing up control and upright balance control. Swing up control swings the pendulum to upright position and upright balance control stabilizes the pendulum in upright position, resisting from a step of disturbances. Modern control techniques-Proportional, Integral and Derivative (PID) controller is used to reduce the errors to the desired set points in order to perform swing up control and upright balance control. The algorithms for controlling the motor and the encoder are built to perform their respective functions. Then, all algorithms are combined to perform closed-loop system as the angles from the pendulum's encoder act as feedback system to alter the duty cycle of motor corresponding to the set point. After that, the role of different PID parameters is discussed with the subsequent comparison between different parameters used for PID controllers. The final tuned PID value for stable upright control is K_p=12.5, K_i=6 and K_d=50 meanwhile PID value for swing up control is K_p=0.15, K_i=0.005 and K_d=5. The tuning of PID value is based on trial and error method by adjusting to different values to see the effects on the pendulum. The implementation of Arduino UNO to control the inverted pendulum system is successful as the pendulum can perform swing up and upright balance control respectively with correctly tuned PID parameters.

CHAPTER 1 INTRODUCTION

1.1 Project Overview

Control system is an interconnection of components forming a system configuration that will provide a desired system response. The basis for analysis of a system is the foundation provided by linear system theory, which assumes cause-effect relationship for the components of a system. [1] Control system can be divided into open loop system and closed loop system. In this project, the inverted pendulum used closed loop control system to perform the function in both swing up control and balance upright control.

Inverted pendulum control is one of the fundamental and interesting problems in the field of control theory. [2] Recently, inverted pendulum has been done by many scientists for research using various methods. It is because inverted pendulum system is a popular demonstration of using feedback control (closed loop system) to stabilize an open-loop unstable system. [2]

Inverted pendulum is an inherently unstable system. Force must be properly applied to the pendulum to keep the system intact. To achieve this, a proper control theory is needed. If the desired output is the angle of the pendulum relative to the vertical axis (in upright position), the system is unstable. It is because the pendulum will fall down if it is released with a small angle. To keep the pendulum in upright position, a feedback control system must be used. [3]

Feedback control system is very important in controlling the pendulum to stay in upright position. A feedback system is one in which the output signal is sampled and then fed back to the input to form an error signal that drives the system. [4] A feedback control system often uses a function of a prescribed relationship between the output and reference input to control the process. The difference between the output of the process under control and the reference input is amplified and used to control the process so that the difference is continually reduced. The difference between the desired output and the actual output is equal to the error, which is then adjusted by the controller. [1] Figure 1.1 shows a closed-loop control system in which the process of reading sensors to provide constant feedback to the set point. [5]

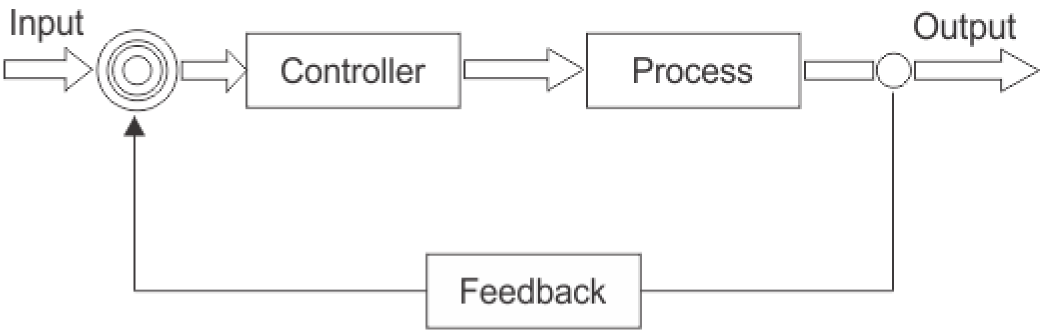


Figure 1.1: Block diagram of a typical closed loop system [5]

In this project, PID controller is used to adjust the duty cycle of the motor according to the encoder's angle relative to the set point. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows the users to operate them in a simple, straightforward manner. [5] PID controller is a 'control loop feedback' mechanism which continuously calculates an error and applies a corrective action to resolve the error. The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating proportional, integral, and derivative responses and summing those three components to compute the output. [6]

1.2 Project Background

The inverted pendulum is a classic problem in dynamics and control theory and is used as a benchmark for testing control strategies. Many researchers have been done to carry out the inverted pendulum experiment using Matlab programming and PID controller.

Inverted pendulum is among the most difficult systems to control in the field of control engineering. Due to its importance in the field of control engineering, it has been chosen for Final Year Project (FYP) to analyse its model and provide another alternative for the users to control the inverted pendulum in upright position. The concept of inverted pendulum has become more important in our daily life which adapts the stability concept. For example, helicopter used the stability concept to reject windup disturbances and the missile that moving fast without any problems. [3]

Previously, in EMC 322 Automatic Control experiment, the inverted pendulum is controlled by Scicoslab and desktop computer. However, the cost of experiment increases as it is needed to connect with desktop computer and control unit box to perform the experiment. Therefore, the usage of Raspberry Pi microcontroller is largely affordable than desktop computer. Raspberry Pi is small and low powered mini-computer which is portable and can serve as a platform to perform the same function as traditional desktop computer. Students can just buy a Raspberry Pi microcontroller with the affordable price and make the experiment at anytime, anywhere together with Arduino UNO. Arduino UNO is a microcontroller board that has 14 digital input/output and 6 analog inputs. Besides that, it is an open source software which convenient the users to find any information from the Internet

In this project, it involves developing some hardware and mainly on software. Raspberry Pi microcontroller serves as a mini computer and Arduino is connected to the microcontroller to perform the experiment easily with the Arduino software downloaded inside the Raspberry Pi microcontroller. The wiring connections between the hardware and Arduino UNO need to be carried out carefully in order to prevent short-circuited problems of hardware. However, the interface problem between the software and hardware are the most difficult part as to make sure that they are connected to each other. Next, the algorithms of encoders must be correctly developed because it acts as important sensor to feedback to the entire closed-loop system. The rotating angles of encoder is needed to perform precisely so that the swing up control and balance upright control can be carried out accurately with the help of PID system. At last, the graph performance of inverted pendulum is plotted to show the results with the use of different PID parameters.

1.3 Problem Statement

The control of inverted pendulum has been largely studied by many authors and it is a common example in Control Theory. [7][11][13-19] However, there are very limited literatures focussing on the usage of Raspberry Pi microcontroller and Arduino UNO to control the inverted pendulum. The usage of desktop computers and control unit box to control the inverted pendulum had burden the expenditure especially in universities. Hence, Raspberry Pi microcontroller is used as a platform together with Arduino UNO to perform similar functions as in the Automatic Control experiment. The main problem is on how to interface DC motor and encoder to Arduino using PID system. Besides that, another problem is on how to read the encoder data accurately and give command to motor to perform stable upright control and unstable swing up control respectively.

1.4 Objectives

There are several objectives that need to be achieved in this project, which include:

- To propose another alternative that is cost savings to the users to control the inverted pendulum by using Raspberry Pi microcontroller and Arduino UNO.
- To perform the pendulum in balance upright control, resisting from a step disturbance using Arduino UNO with correct tuning on the PID controller.
- To perform the pendulum in swing up control using Arduino UNO with correct tuning on the PID controller.

1.5 Scope of Work

This project focuses on creating the algorithms using Arduino programming in Raspberry Pi microcontroller, followed by experiment and performance analysis. First, the features and models of all components will be studied to know the specifications of current model. Then, the components will be interfaced with Arduino UNO in Raspberry Pi microcontroller with suitable algorithms by controlling the motor position and encoder's counter, so they are compatible to perform the function. PID algorithms are then created to perform feedback function to the desired value. Next, tuning will be done on the PID system to make sure the inverted pendulum can successfully perform balance upright function and swing up control. Continuous experimental will be done on the inverted pendulum to make sure the pendulum can swing up and stay upright respectively when it is connected to the Raspberry Pi microcontroller. Finally, the performance of the pendulum will be analysed based on different PID parameters.

CHAPTER 2 LITERATURE REVIEW

2.1 Research Background

Inverted pendulum is an under actuated and extremely non-linear system due to gravitational forces and the coupling arising from the centripetal forces. The non-linearity makes the control more challenging. [7] The inverted pendulum system is the favourite example of control system to be performed by the lecturers or scientists which is widely used for testing various concepts of control techniques. The control system involves swinging the pendulum from its hanging position to its unstable equilibrium point and stabilizing the pendulum in vertical position.

The inverted pendulum is a pendulum that is in unstable state in which its centre of gravity over its axis of rotation. The normal pendulum has its centre of gravity under its axis of rotation, so it is in stable state when it directs downwards. A raised problem is how it is necessary to control the inverted pendulum so that it can keep its equilibrium state when it directed upwards. Therefore, the study of mathematical model, dynamic model and algorithms in controlling the inverted pendulum plays very important role in controlling robot and spacecrafts. Stabilization controllers can be achieved by using Full State Feedback Controller [13], Fuzzy PD controller [14] and PID Controller [15] [16]. The swing up control can be attained using various strategies such as energy-based controller [14] and Cascade controller [19]. Then, the inverted pendulum is modelled and studied in Matlab or LabVIEW environment.

2.2 Present Applications of Inverted Pendulum

The principle of the stabilization can be found in many devices such as Segway PT, self-balancing hover board, self-balancing unicycle, automatic aircraft landing system and so on. Figure 2.1 shows the Segway PT which is self-balancing scooter that utilized the principle of stabilization to balance the human that stand on top of its platform. [2]

Figure 2.1: Scooter Segway PT [2]

Besides that, the rapid increase of the aged population in countries like Japan has prompted researchers to develop robotic wheelchairs to assist the infirm to move around. The control system for an inverted pendulum is applied when the wheelchair moved with a small step or road curbs as shown in Figure 2.2. [8]

Figure 2.2: Robotic wheelchairs [8]

2.3 Definitions of Terminologies

The control design process begins by defining the performance requirements. Control system performance is often measured by a step function as the set point command variable and then measuring the response of the process variable. Commonly, the response is quantified by measuring defined waveform characteristics. Rise time is the amount of time the system takes to go from 10% to 90% of the steady-state or final value. Percent overshoot is the amount that the process variable overshoots the final value, expressed as a percentage of the final value. Settling time is the time required for the process variable to settle to within a certain percentage (commonly 5%) of the final value. Steady state error is the final difference between the process variable and set point. The response of the system is useful to define the worst-case conditions in which the control system will be expected to meet these design requirements. Often times, there is a disturbance in the system that affects the process variable or the measurement of the process variable. It is important to design a control system that performs satisfactorily during worst case conditions. The measure of how well the control system will tolerate disturbances and non-linearities is referred to as the robustness of the control system. [5] Figure 2.3 shows the response of typical closed loop system.

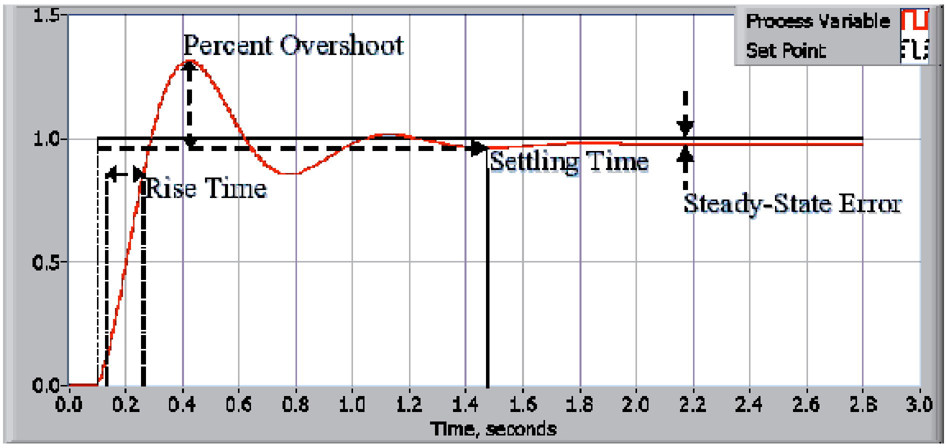


Figure 2.3: Response of a typical closed loop system [5]

2.4 System Design with Microcontroller

Raspberry Pi microcontroller is used as the platform to run the project. Raspberry Pi is popular for the electronic hobbyists as it is small and low-powered. [9] Raspberry Pi comes with a combination of the computer's small size and affordable price. Institutions, such as schools and universities can benefit from deploying a fleet of computers for a fraction of the cost of traditional towers. The small size makes for an easy-to-hide computer that saves power and can be mounted behind the display with an appropriate case. It operates as traditional desktop computer which is a complete Linux computer and could be useful for troubleshooting and researching solutions. [10] In this project, Raspberry Pi microcontroller is used as desktop computer together with monitor, keyboard and mouse that is cost savings method.

Arduino UNO is combined with Raspberry Pi microcontroller to perform the inverted pendulum function. Normally, the inverted pendulum needs almost real time response to estimate and correct the tilt angle. Hence, the development of board must provide a processing speed that is sufficiently fast to perform the processing tasks, including data acquisition, control computation and signal output.[11] Arduino UNO is a microcontroller board based on the ATmega328 which has 14 digital input/output pins and can simply wired to external electronics such as motor, encoder, Raspberry

Pi microcontroller and so on with just a USB cable.[12] The inverted pendulum's algorithms are programmed inside the Arduino UNO and Arduino can read high speed encoders easily without missing any count. Besides that, the Arduino is an open source programming which can easily access the algorithms that is available in Internet. It is convenient for the users to get any information from the Internet.

2.5 Controller Design (Stable Upright Control)

The pendulum is manually held at a smaller angle target position and then the algorithm attempts to stabilize it and maintain the pendulum in upright position.

2.5.1 Full State Feedback (FSF) Controller based on Ackerman's Formula [13]

In modern control system, state x is used as feedback instead of plant output y and k indicates the gain of the system. To design an FSF controller, Ackerman's formula is used which is an easy and effective method to design a controller through pole placement technique. Figure 2.4 shows the block diagram of FSF controller of a system.

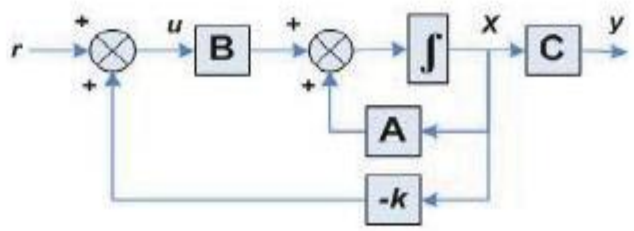


Figure 2.4: Block diagram of FSF controller of a system [13]

Ackerman's formula is represented as in Equation (2.1).

$$\mathbf{K}=[\mathbf{0} \dots \mathbf{01}]\boldsymbol{M_C^{-1}}\emptyset_{\boldsymbol{d}}(\boldsymbol{A})\dots\dots\dots\dots \quad (2.1)$$

$$M_C = \left[BAB \dots A^{(n-1)}B\right]$$

where M_C indicates the controllability matrix and $\emptyset_d(A)$ is the desired characteristics of the closed-loop poles which can be evaluated as s=A. The close loop transfer function is selected based on ITAE table and the value of frequency is taken as 10 rad/s. The controller matrix gain, K can be calculated using the MATLAB code. Using the matrix gain value and the control law u= - Kx, the system is stabilized around the linearized point (pendulum upright). In the plant model of inverted pendulum, the output theta θ is regulated by the input voltage (V). The theta has the responsibility to keep the inverted pendulum vertically upright where alpha will be zero. Figure 2.5 shows the block diagram controller in MATLAB Simulink.

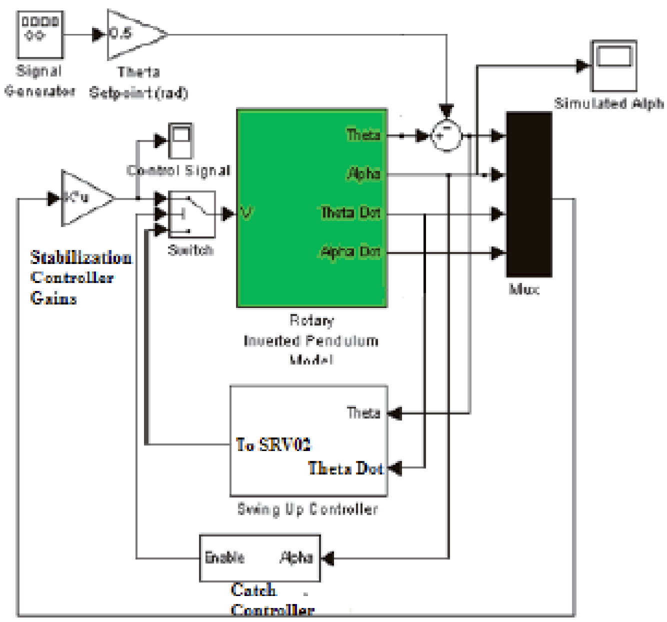


Figure 2.5: Block diagram controller (MATLAB Simulink) [13]

The pendulum starts from downwards position and whenever it comes to the upright mode, the FSF controller will maintain the pendulum in that position and make it stable.

2.5.2 Fuzzy PD controller [14]

The goal of stabilizing controller is to maintain the pendulum in upright position when it is almost there. The design of the fuzzy controller for the stabilization problem can be resumed to choosing and processing the inputs and outputs of the controller and designing its four component elements (the rule base, the inference engine, the fuzzification and defuzzification interfaces). The inputs to the fuzzy system are angle errorε_{∂} and the change of error cε_{∂}. The output from the system is the voltage u_m. The fuzzy controller implements a rule base made of a set of IF-THEN type of rules. The rule table is shown in Figure 2.7. The min-max inference engine was chosen, which for the premises, uses maximum for the OR operator and minimum for the AND operator. The conclusion of each rule, introduced by THEN, is also done by minimum final conclusion for the active rules is obtained by the maximum of the considered fuzzy sets. To obtain the crisp output, the centre of gravity (COG) defuzzification method is used. The crisp value is the resulting controller output. Figure 2.6 shows the block diagram of the controller.

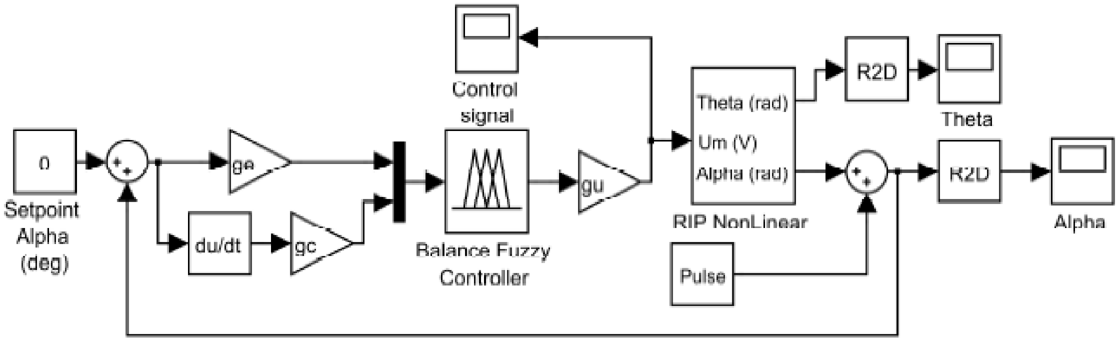


Figure 2.6: Simulink block diagram of the inverted pendulum stabilizing control [14]

e(kT) / c(kT)	NB	NS	Z	PS	PB
NB	PB	PB	PB	PS	Z
NS	PB	PB	PS	Z	NS
Z	PB	PS	Z	NS	NB
PS	PS	Z	NS	NB	NB
PB	Z	NS	NB	NB	NB

Figure 2.7: Fuzzy controller rule table [14]

2.5.3 PID Controller [15] [16]

The system is connected to PID controller where the proportional, integral and derivative parameters are set by the user. A signal generator provides a signal to the controller which in turn provides a control signal to the inverted pendulum. The control signal also depends on feedback from the system. Only one degree of freedom is assumed to perform the control action. The parameter fed back is angle of deflection of the pendulum. This is because the other parameter which is the angle of deflection of the rotary arm is considered to be automatically controlled by the voltage input. The continuous control signal, u(t), is defined as a function of the error, e(t)= signal reference r(t) – signal output y(t) by Equation (2.2).

$$\boldsymbol{u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt}} \textbf{.........(2.2)}$$

where K_p is the proportional constant, K_i is the integral constant and K_d is derivative constant. Figure 2.8 shows the Simulink block diagram of PID controller.

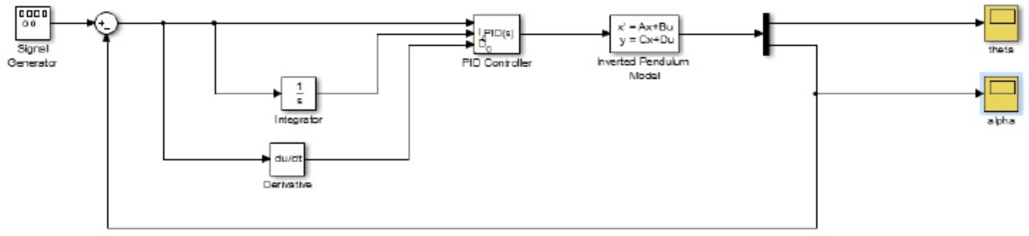


Figure 2.8: Simulink block diagram of PID controller [15]

In a PID controller, there are three control modes which are proportional, integral and derivative control that need to take in consideration. Each of the three modes reacts differently to the error. The amount of response produced by each control mode is adjustable by changing the controller's tuning setting. The proportional component depends only on the difference between the set point and the process variable. This difference is referred to as the error term. The proportional gain (K_c) determines the ratio of output response to the error signal. In general, increasing the proportional gain will increase the speed of the control system response and become unstable. The integral component sums the error term over time. The result is that even a small error term will cause the integral component to increase slowly. The integral response will continually increase over time unless the error is zero, so the effect is to drive the steady state error to zero. Steady state error is the final difference between the process variable and set point. The derivative component causes the output to decrease if the process variable is increasing rapidly. The derivative response is proportional to the rate of change of the process variable. Increasing the derivative time (T_d) parameter will cause the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response. [5] Figure 2.9 shows the PID control algorithm that made up of the sum of the proportional, integral and derivative control actions.

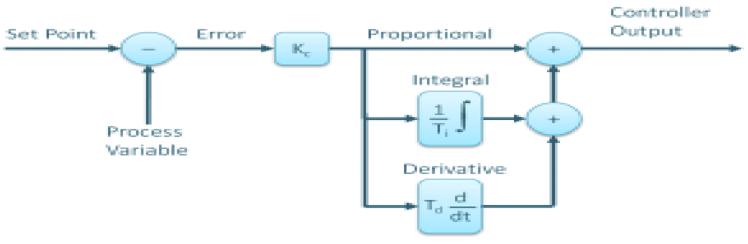


Figure 2.9: Block diagram of PID control algorithm [17]

2.5.4 Hybrid of PID and Fuzzy Logic Controller (FLC) [18]

In the hybrid controller design, the controller gains of PID controllers namely K_p, K_i and K_d are tuned by a Fuzzy Logic Tuner. When the system is simulated in real time, the output of the FLC constantly changes, thus giving variable gains for the PID controller. The PID gains that are obtained from the fuzzy output which is achieved through the rule-base designed to act on the error in the angle. Figure 2.10 shows the fuzzy PID controller scheme.

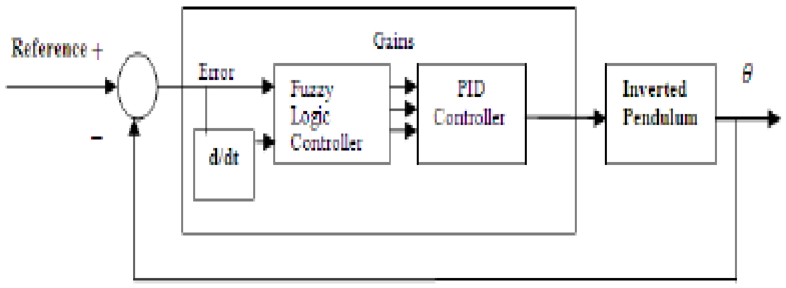


Figure 2.10: Fuzzy PID controller scheme [18]

2.6 Swing Up Control

Swing up controller will drive the position of the pendulum to get away from the stable, downward position. By supplying the dc motor and moving the arm back and forth strongly enough, the energy is gradually added to the inverted pendulum system, so the pendulum can be swung up to the unstable position and then aim to stabilize it. [14]

2.6.1 Conventional PD Cascade Controller [14][15]

In cascaded control, two PID controllers are used. The k_p, k_i and k_d values for both PID controllers are very different in Cascade controller. Conventional PD algorithm is used to minimize the swing up time. Swing up time can be significantly reduced by adding an impulsive control to the PD algorithm. Positive feedback PID controller is used because of its simple structure, effectiveness and easy tuning. The block control diagram consists of two loops. The inner loop performs the position control of the arm, while the outer loop specifies the desired trajectory for the arm angle to swing the pendulum to balancing position. Figure 2.11 shows two loops in the block diagram.

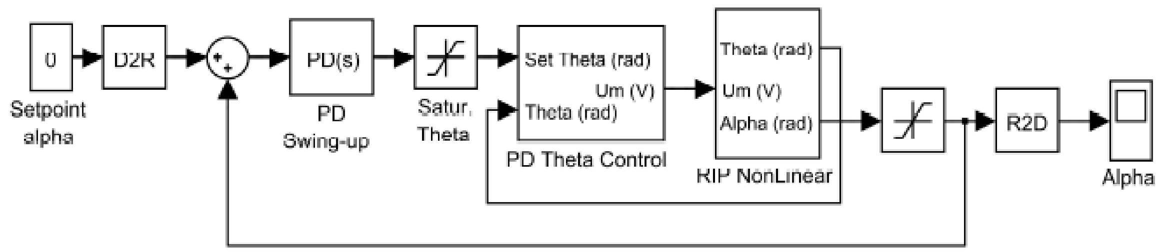


Figure 2.11: Simulink block diagram of the inverted pendulum swing-up control [14]

A negative feedback PD control is designed for the servo arm to track the desired position is shown in Equation 2.3.

$$\boldsymbol{u_m(t) = k_{p\theta} \times \varepsilon_\theta + k_{d\vartheta} \times \frac{d\varepsilon_\theta}{dt}}\text{...... (2.3)}$$

The position PD controller offers the voltage applied to the motor so that the angle θ tracks the desired position θ_d. In the outer loop, a positive feedback PD control loop was chosen. This positive feedback loop increases the energy provided to the pendulum and has a role of a destabilizing system because the downward position of the pendulum is stable. The proportional and derivative constants can be tuned to adjust “positive damping” in the system. Moreover, the command provided by the swing-up controller (desired angle of the pivot arm) must be limited within a range of ±180 degree to ensure that the arm does not reach a position that will cause a collision with other hardware. [14]

Figure 2.12 shows another example of Cascade controller by [15]. One loop is used to control angle of deflection of pendulum while the another loop controls angle of deflection of rotary arm. Each angle is fed back to the corresponding controllers through encoders in order to carry out the required control mechanism. [15] Figure 2.12 shows another block diagram using Cascade controller.

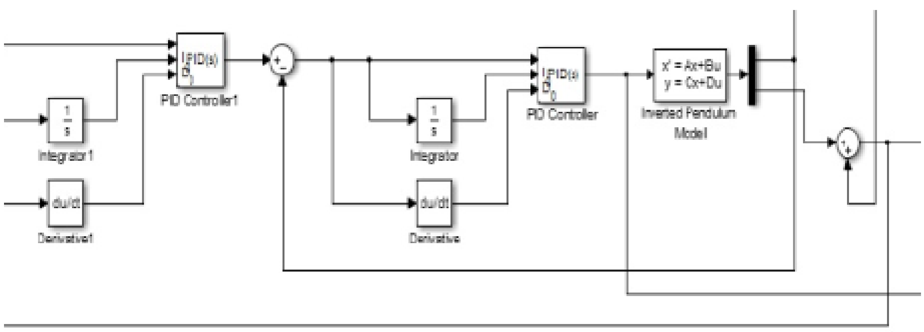


Figure 2.12: Simulink block diagram of Cascade controller [15]

2.6.2 Energy-Based Controller [19]

Swing up is attained using an energy controller. The energy-based approach attempts to swing the pendulum upright by utilizing the total energy of the system as a feedback quantity. The pendulum is controlled in such a way that its energy is driven towards a value equal to the steady state upright condition.

2.7 Comparisons in Results for Different Types of Controllers

2.7.1 Comparison between Cascade Controller and PID Controller [15]

The simulation shows that the control signal of Cascade controller gives more overshoots than PID controller after which it comes down to stable state. However, the settling time of the response is low as can be seen in Figure 2.14. After the settling time of the overshoot, the stabilized output seems to slightly elevate which shows that the speed of the rotary arm steadily increases after a certain angle. The stability can be maintained by providing a slight external force to keep the angle within range. The rise time and settling time of Cascade controller is lower compared to PID controller. The Cascade controller has given robust performance compared to the single PID controller in balancing the pendulum in inverted pendulum. Figure 2.13 and Figure 2.14 show the hardware response of the system by using PID and Cascade controllers.

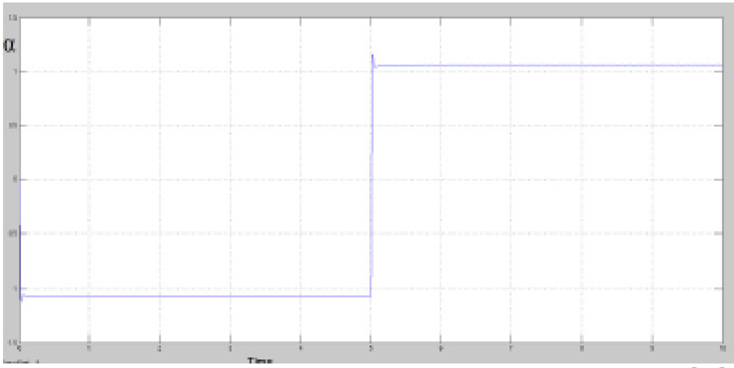


Figure 2.13: Response of PID controller in simulation [15]

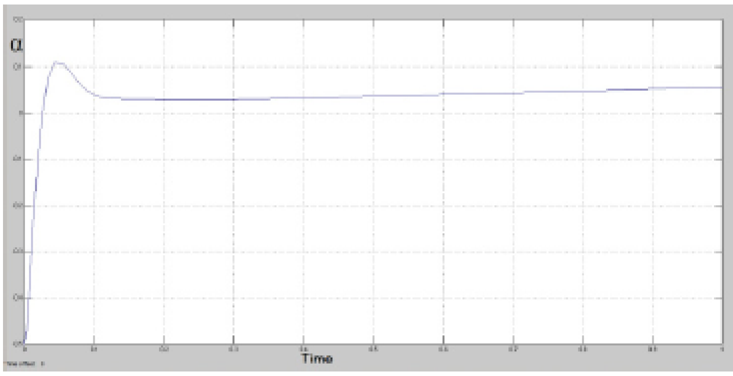


Figure 2.14: Response of Cascade controller in simulation [15]

2.7.3 Comparison in PD Controller and Energy Controller [19]

Energy based approach is found to swing up the pendulum much faster than the PD controller. Energy based controllers can swing up within 5 seconds while PD controller can only swing up after 25 seconds. Figure 2.15 shows the swinging up of the pendulum using PD and energy controller.

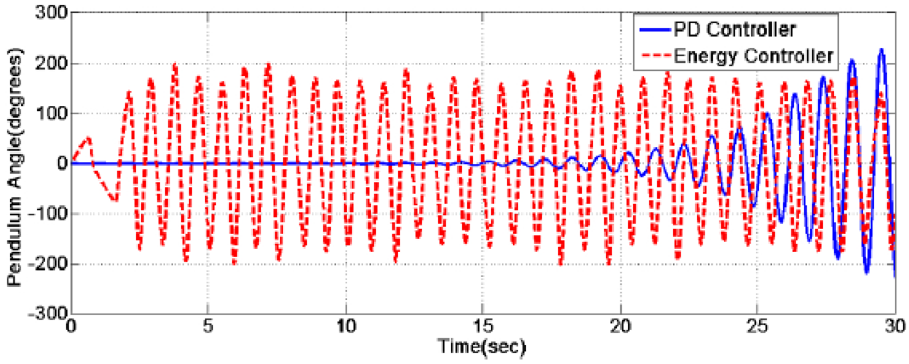


Figure 2.15: Swinging up of the pendulum using PD and Energy controller [19]

2.8 Strength and Weakness of Each Controller

Table 2.1 shows the strength and weakness of each controller after getting the analysis from the journals.

Table 2.1: Strength and weakness of each controller

Types of Controllers	Strength	Weakness
PD Controllers	-To minimize the swing up time.	- Not the optimum techniques as the steady state error is not minimized.
Fuzzy controller	-Deal with uncertainties and non-linearities system	-Involves too much mathematical modelling formula.
PID controller	-Give less noise -Suitable for educational level as it is easily understandable -Can use in wide range of applications for industrial process control	-Challenging task as highly non-linear and open loop unstable characteristics -More suitable to linearlized model.
Cascade controllers	-Improved rise time and settling time. -Give robust performance	-

2.9 Summary

In this project, PID controller is chosen to control the inverted pendulum system in both swing up control and balance upright control. It is because it is suitable for undergraduate to apply on the projects as it is easier to understand. Besides that, it also can be used in wide range of applications for industrial process control and did not involve complex mathematical calculations.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Overview

This chapter will cover the explanation of methodology that is being used in detail to achieve the aim of project. A systematic methodology flow has been outlined in order to ensure the progress of the project able to run smoothly and can be completed on time. Figure 3.1 shows the methodology of this project.

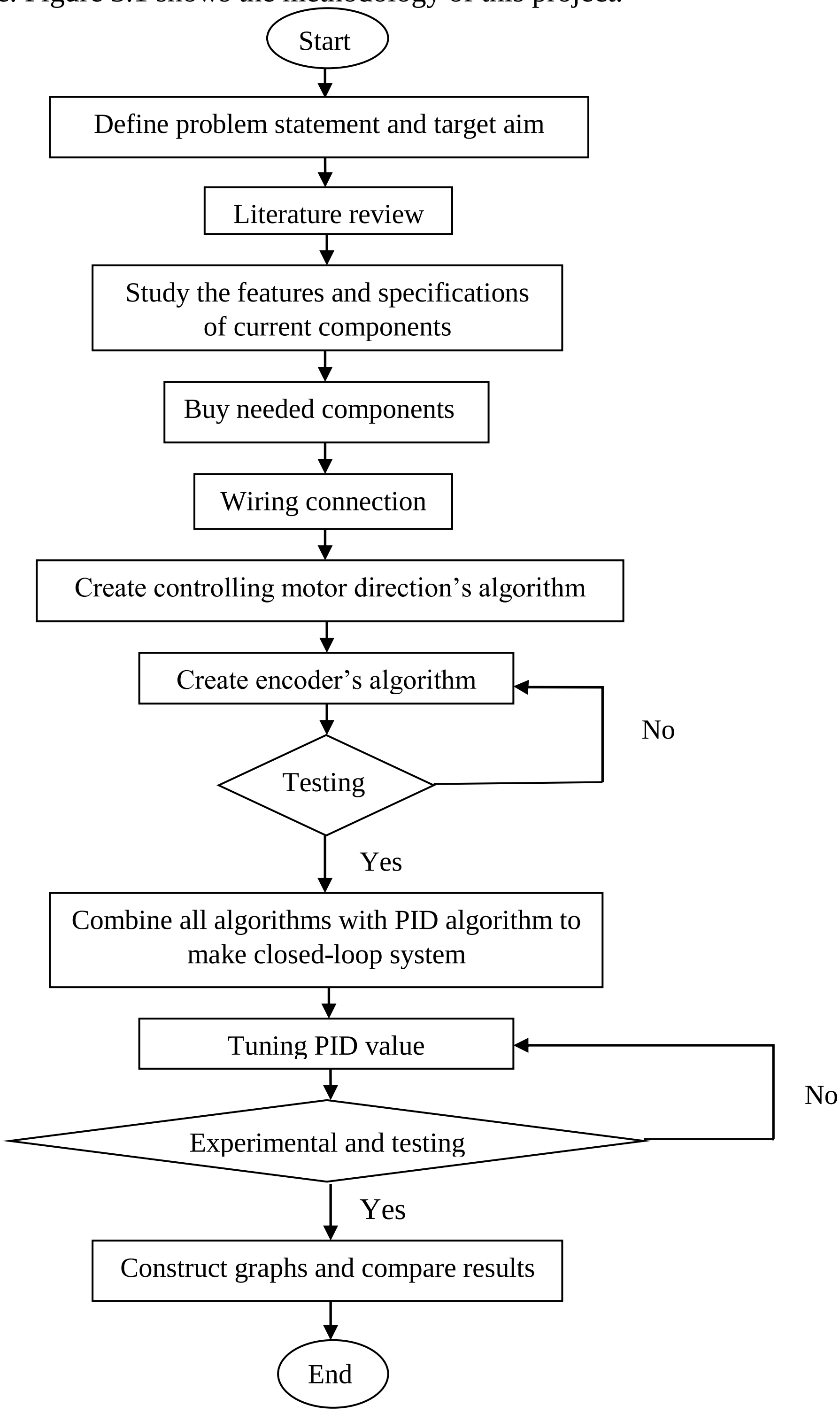


Figure 3.1: Flow chart of the project

First, the problem statement and overall aim of the project are defined through the understanding on the topic given. Then, the journal regarding the different approaches to perform inverted pendulum project are studied to understand on how the scientists perform the project. Next, the features and specifications of the inverted pendulum model that are existed in laboratory are studied to know how they work. Some needed hardware such as Raspberry Pi microcontroller, Arduino UNO and motor driver are brought from Cytron Technologies and Lazada which are compatible to the inverted pendulum system. The amplifier unit is eliminated as it is too big and heavy. Then, all components are connected to Arduino UNO with correct positive and negative sign to make sure there is no damage on the components.

For this project, creating the algorithm is the most important part as the algorithms will control the inverted pendulum system whether it can perform the correct function. The encoder for the pendulum is the most critical part as it will provide continuous feedback to the desired setpoint to alter the error. Therefore, the reading from the encoder must be accurate to prevent the inconsistent reading. Testing must be carried out to ensure that one revolution of the encoder is 4096 pulses with the used of interrupt function in the coding without any missing count. Then, the algorithms of PID formula and PWM motor are constructed and combined with the pendulum's algorithm to make a full closed-loop system. Continuous experimental and testing were carried out by tuning the K_p, K_i and K_d parameters for swing up control and upright balance control to make sure the pendulum can perform good motion. At last, the performance analysis of different tuning parameters are plotted and discussed.

3.2 Description of the Inverted Pendulum System

The inverted pendulum system consists of RS-263-6011 DC motor which rotate a rotary arm which in turns affects the motion of inverted pendulum. There is only one encoder used in the system. The arm is connected to a pendulum at the other end which can freely rotate about the axis of the arm. The encoder is installed together with the pendulum and used to measure the deflection angle of the pendulum. The E30S4-1024-6-L-5 encoder has a total 1024PPR. The values sensed by the encoders are fed back into the system in order to control the duty cycle of the motor. The parts included in the system are shown in the Table 3.1.

Table 3.1: Parts in the inverted pendulum system

Parts	Functions
Encoder of pendulum	Measure the deflection angle of the pendulum
Motor	To rotate the arm
Pendulum	The freely rotating part
Rotary arm	Controlled by motor with one end supporting to the pendulum

As the voltage is supplied to the motor, it rotates which in turn imparts motion to the rotary arm. As the arm moves, the pendulum also starts to oscillate and the swing up control will swing the pendulum up till it reaches the region at which the balance upright control take place to stabilize the pendulum in upright position.

When the pendulum arm is moving in clockwise direction, positive voltage is applied to the motor and when it is moving in anticlockwise direction, negative voltage is applied. When the pendulum reached the desired position, balance control takes over. Now as pendulum angle deviates from zero to positive angle, rotary arm moves in clockwise direction (positive voltage is supplied to motor) to bring the angle back to zero. It is same as in anticlockwise direction.

The system is interfaced by Arduino UNO programming. The pendulum has two states which are stable and unstable. At the stable state, the pendulum is vertical and pointing down and the pendulum is needed to oscillate until it reaches the region at which the stabilization area takes place while an unstable state is the point where the pendulum is vertical and pointing up in inverted position. Figure 3.2 shows the full set of inverted pendulum with desktop computer that used in Automatic Control laboratory.

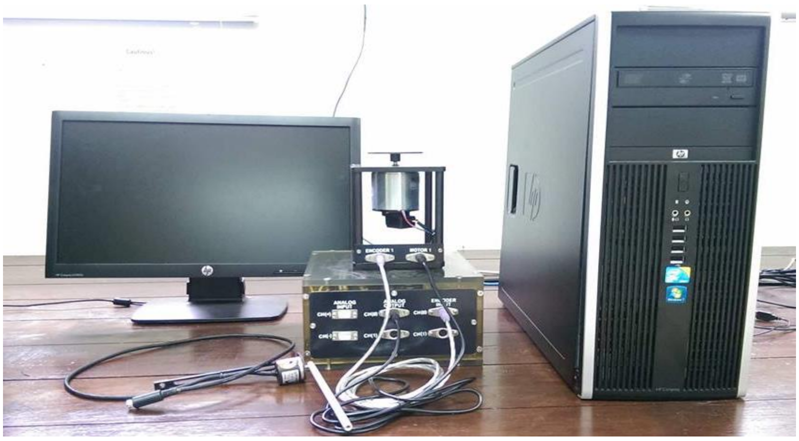


Figure 3.2: Full inverted pendulum with desktop computer

3.3 Selection on Motor Driver

The control unit that used in the laboratory is too big and complex. It is quite difficult to figure out the internal features of the control unit and needs a lot of time to create the algorithms to control the whole inverted pendulum system. Therefore, a new motor driver was bought to replace the existing inverted pendulum's control unit and amplifier which including data acquisition card. A new motor driver that is more economical is bought to support the voltage and current of the DC motor. Table 3.2 shows the comparisons in the features and specifications of motor driver whether which one is more suitable for the inverted pendulum system.

Table 3.2: Comparison between MD10C and L298N motor driver

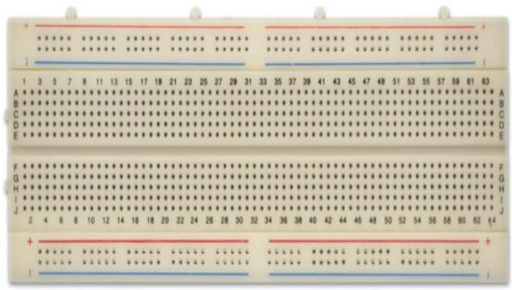
Name	**10Amp DC Motor Driver [20]**	**SD02C Stepper Motor Driver 2 Amp [21]**
Diagram		
Specification	• Bi-directional control for 1 brushed DC motor • Support motor voltages up to 30V. • Solid state components provide faster response time and eliminate the wear and tear of mechanical relay. • Fully NMOS H-Bridge for better efficiency. • Support both locked-anti phased and sign-magnitude PWM operation.	• Able to drive unipolar or bipolar stepper motor. • Bi-directional control • Support up to 1.8A(peak) per phase, 1A (continuous) per phase. • Able to drive from 6V to 20V. • 5V logic level compatible inputs.
Price	RM55.00	RM90.10
Reason of choosing	MD 10C is chosen because the price is cheaper than SD02C. H-bridge in MD10C can easily change the direction of motor. Besides that, it can provide faster response time to the motor. SD02C can only drive the motor to 20V which is not enough to run the motor effectively, so MD10C is chosen.	

3.4 Components Used in the Project

There are several components that are existed for the inverted pendulum system. Research had been made to understand the whole mechanism of the inverted pendulum. It is very important to know the complete mechanism before starting the project. Some details on the hardware of the rotary inverted pendulum are tabulated to know its specifications and understand their working principles. The development of all algorithms is done by interfacing the hardware using Arduino programming. Table 3.3 shows the components list that used for the inverted pendulum project.

Table 3.3: Components List

Components	Diagram
Raspberry Pi Microcontroller 3 [22] **Model: Model B**	
Arduino UNO board [23] **Model: ATmega 328P**	
Incremental 30 mm shaft type rotary encoder [24] **Model: E30S4-1024-6-L-5**	
Cytron 10Amp motor driver [20] **Model: MD10B**	

RS Pro 30W DC motor [25] **Model: RS263-6011**	
Programmable Dual-Range DC Motor Supply [26] **Model: Instek PSM-3004**	
Breadboard	
Jumper wire (Male-to-female, male-to-male)	
Monitor [27]	

Keyboard [28]	
Mouse [29]	

Figure 3.3 shows the control plants and its components that used in FYP.

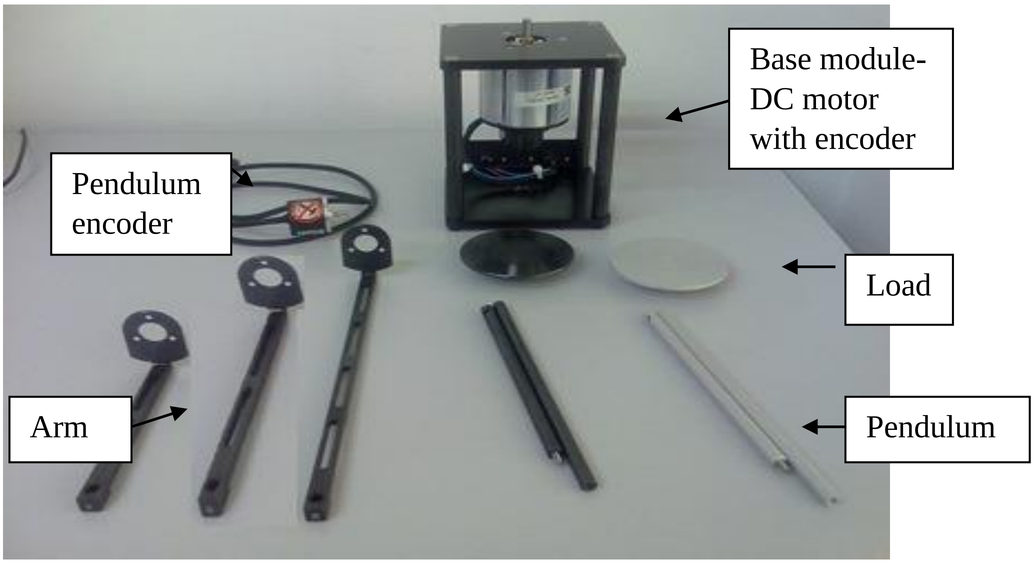


Figure 3.3: Control plants and components

Figure 3.4 shows the usage of current inverted pendulum system that used with monitor only without using the desktop computer.