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The Design of Inverted Pendulums as Learning Sources of Adaptive Control

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Abstract. Inverted Pendulum is a control application which is the basis of science in today's technologies such as missiles, aircraft, satellite control, etc. This inverted pendulum receives input then the parameters are determined and the system responds. This research aims to design an inverted pendulum as a source of learning adaptive control. The design process uses the RnD method with phases including requirements analysis, design, implementation, and evaluation. Inverted pendulum design includes mechanical, electronic and source code design.

1. Introduction

The demand of industrial revolution 4.0 has become an unavoidable challenge **[1]**. Minister of Research, Technology and Higher Education (MoRTHE), Mohamad Nasir, explains that based on the initial evaluation of the country's readiness in facing this current era 4.0, Indonesia has been predicted to have high potential **[2]**. Regarding to these circumstances, it is necessary to reorient the curriculum to be more relevant for a 21st-century world, especially with the massive technological developments [3]. The current technology is not just about turning on/off the machine power but more on controls that can adapt to the surrounding environment. For instance, [4] development of self-driving car or often called as smart car. This kind of vehicle has various automatic sensors that can detect the surrounding environment to operate as a human driver. It urges academicians and researchers to master up-to-date technology to have global competitiveness. To boost technological literacy, a proper model is truly used to represent this requirement.

Inverted Pendulum is one model that represents a simple adaptive control. To learn control in this model, it requires some innovation that involves mathematical functions. This control is commonly used in industries, such as Proportional Integral Derivative (PID) controller, and Sliding Mode Controller (SMC). This control system has been the basis of applications in present technology, like rockets, airplanes, unicycles (single-wheeled vehicles), modern motor vehicles, wheelchairs, satellite position control, games (Cubic Li) and others.

This study aims at designing an inverted pendulum as a learning source of adaptive control. The control in this Inverted Pendulum employes PID (Proportional Integral Derivative). PID was chosen because it became the basis of adaptive control so that students can learn the basic concepts of adaptive control in the form of simple modeling.

2. Literature Review

2.1. Inverted Pendulum

The Inverted Pendulum System is a non-linear control system that is unstable as a training module of theoretical control system and various control system experiments [5]. In the control system experiment of the Linear Inverted Pendulum, a pendulum with a center of mass above the pivot point is attached to a linear actuator and is moved to be in balanced condition. Figure 1 below is a general example in basic control system experiments with feedback especially in the design of control systems with PID (Proportional Integral Derivative) algorithm.

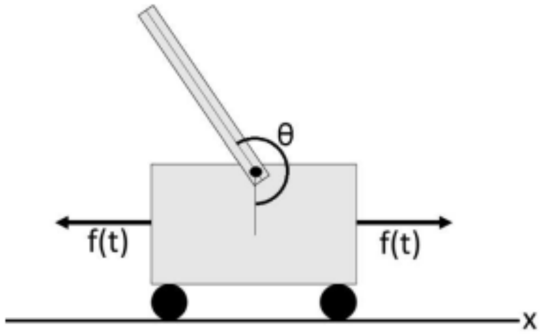


Figure 1. Linear Inverted Pendulum System

Inverted pendulum conditions that are unstable can be an interesting laboratory experimental objects and can be easily connected to real-world applications, such as rocket and missile control systems or electric vehicles with automatic balance systems [6].

There are several studies related to an inverted pendulum that has been done, such as Goegoes Dwi [7] by designing an inverted pendulum with a circular path. In this study, the Inverted Pendulum was designed as a circular or rotary inverted pendulum to eliminate the length limit of the path contained in the pendulum inverted with the transverse path. Another study is from Sudipta Chakraborty thesis [8] that examines the systems and hardware in the Inverted pendulum, system dynamics, state-space models, derivatives in the transfer of functions, and the strategy of making controls on the inverted pendulum. This thesis implemented 2 PID loops, PID + PI and LQR control that showed a satisfying response.

2.2. Mathematics Model

Inverted pendulum systems include classical control problems with the non-linear processes and unstable [5]. Inverted pendulum systems generally have one input signal with several output signals. The main purpose of a linear system of inverted pendulums is to balance a pendulum stick vertically on a motor-driven cart.

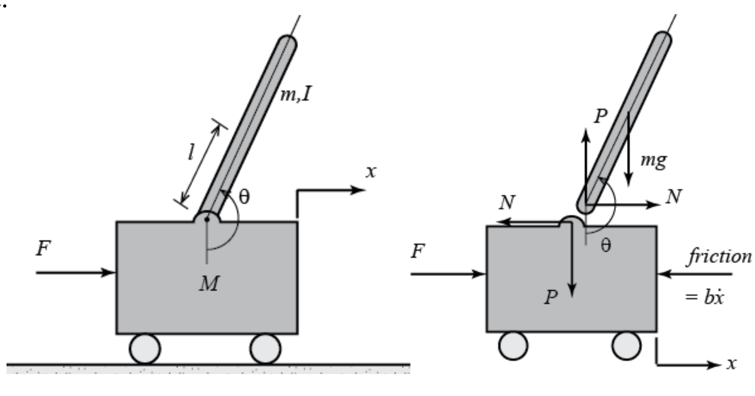


Figure 2. Physical Model of Linear Inverted Pendulum

Image 2 above is a Physical model of linear inverted pendulum system.
M : cart mass
m : pendulum mass
b : coefficient of friction cart
L : pendulum length
I : moment of pendulum inertia
F : given force on cart
x : cart position
θ : pendulum angle

2.3. PID Controller
The PID controller is a classic control that has been used in a variety of control system applications. The PID controller has a simple control structure that can be easily understood. The PID controller has the ability to optimize the performance of a control system by tuning the parameter values that involve Proportional (P), Integral (I) and Derivative (D). In a linear inverted pendulum control system, the use of PID controller can be described in the block diagram as follows.

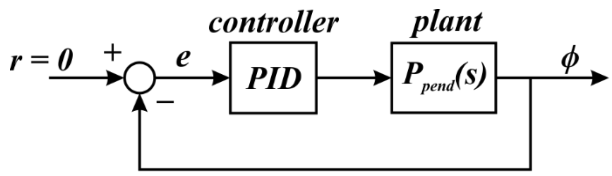


Figure 3. Block Diagram of PID Controller on Linear Inverted Pendulum

In the block diagram above, the inverted pendulum system has one input signal and one output signal. From the block diagram, a transfer function must be made to determine the characteristics of the control system contained in the linear inverted pendulum.

2.4. Learning Sources
Learning according to Oemar Hamalik [9] is a modification or reinforce behaviour through experience. According to this definition, learning is seen as a process or activity and it is not just as an outcome or a goal. It means learning can not be simply defined as remembering, but it is more providing meaningful experience. The outcomes of learning do not only in the form of content mastery but also behaviour change.

To make learning run well, it requires an object as a source of learning. Fatah Syukur NC [10], explains that learning resources are all things (environment, and experience) that can be used to support the learning process more effectively and efficiently. It should be available directly or indirectly whether concrete or abstract. According to Januszewski and Molenda [11] learning resources refer to all sources including messages, people, materials, tools, techniques, and settings that can be used by students both individually and in a group to facilitate their learning activities and improve their learning performance. Similarly, Seels and Richey explain that learning resources are all supporting sources for learning activities, such as supporting systems, materials and environment. Based on the various statements above, it can be inferred that a learning source is a learning object that can make students easier to understand the materials to achieve the learning objectives.

Learning resources are not only tools and materials used in learning, but also people, budgets, and facilities. It can include anything available to help someone to learn. According to Putu Sudira [12] how big the impact of education or learning is strongly influenced by how many students obtain their learning experience and it is influenced by several factors, i.e. teacher/lecturer performance, learning facilities and infrastructure, learning environment, and ICT support. Some research on learning resources, especially for the development of instructional media in engineering field by Eko Marpanaji et al. [13]

creates the PID Controller trainer using dual brushes controllers. Meanwhile, in this study PID Controller employed inverted pendulum.

2.5. Adaptive Control
Adaptive control refers to a system control that is able to adaptively change the way it works according to environmental conditions and these changes are based on units of time [14]. This system can be basically applied to plants with a broader class, in this case if the system is applied then the controller will automatically adjust the system to ensure the plant operation in accordance with the designed parameters. The adaptive control in the inverted pendulum indicates that the system will make adjustments so that the pendulum shaft remains upright. It can be done by reading the rotary encoder sensor if more than 0 degrees then the system will move the slider to the right and left. This inverted pendulum stabilization is also needed as presented by Sekiguchi et al study [15] that the scope of the pendulum's movement in the form of horizontal and vertical should be taken into consideration. The stabilization of vertical and horizontal movements requires a dynamic addition.

3. Research Method
This research employed to research and development (R & D) models. Basically, this procedure was the stage in designing the inverted pendulum as a learning resource for adaptive control. This learning resource will be developed through validation both closed-model (in a small group) and experts judgments or called alpha testing. Beta testing was done afterward and revisions were made based on the suggestions before the real implementation. This development model refers to the Lee & Owens model below.

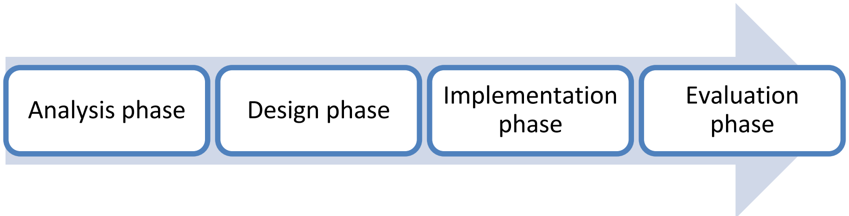


Figure 4. Lee & Bowyer Development Model

Descriptions of the pictures above were: 1) assessment phase, as the reinforcement of the objectives of this study. This phase consisted of need analysis regarding needs in the field and front-end analysis which aimed to bridge the gap between the existing goals and the objectives to be achieved 2) Design Phase, as the project planning so that it can run well 3) Implementation phase, as the realization of the previous phases. This phase involved the alpha and beta test process, 4) The evaluation phase as the stage to answer the core problem. In this phase, the level of accuracy, function, material content and instructions in using the module adaptive control were presented.

4. Finding and Discussion
4.1. Analysis Phase
The research aims at designing a learning model of adaptive control in the form of Linear Inverted Pendulum based on the following findings:

(1) The aadaptive control modelling so far had only been through the MATLAB software and can not be easily understood by students. It raised the importance of media as a source of learning
(2) The students who have studied control materials need a real practice model that had been undertaken, especially on adaptive control
(3) There is no learning model of Linear Inverted Pendulum as the basis for adaptive control learning.
(4) It can be the right momentum to introduce, understand and implement an up-to-date technology, such as control, instrumentation, and manufacturing.

4.2. Design Analysis
This phase consisted of designing both administrative and product design as presented below.

4.2.1. Administrative Design
This design contained the schedule of development activities, team, and provided mapping information.

4.2.2. Product Planning
The initial step before designing a tool was knowing the structure and the system model of the tool. It is important to make it easier to do testing, analysis, and troubleshooting if there are problems in the manufacturing process and tool operation. The overall block diagram of the linear inverted pendulum system is presented below.

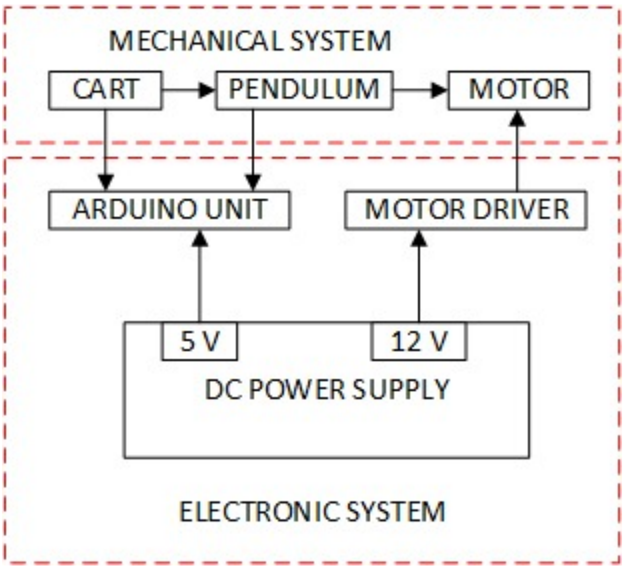


Figure 5. Block Diagram of the Linear Inverted Pendulum System

Based on the block diagram above, it can be seen that the linear inverted pendulum system consisted of two main parts, namely the mechanical and the electronic system. These two parts will be related to each other when the pendulum balancing process was in a vertical position.

4.2.2.1. Design
4.2.2.1.1. Mechanic System Design
In general, the mechanical system of a linear inverted pendulum consisted of three main parts, i.e. cart, pendulum, and motor. Besides these three main parts, there were other important components that make the mechanical system of the linear inverted pendulum can work properly. The following is a mechanical system construction design of a linear inverted pendulum.

(1) Pendulum shaft
(2) Rotary Encoder Sensor
(3) Cart or Slider line
(4) Supporting Legs
(5) Cart or Slider
(6) Belt and Pulley System
(7) Stepper Motor

4.2.2.1.2. Electronic System Design

The electronic system design of the linear inverted pendulum as a whole consisted of three main parts namely the Arduino Uno microcontroller, driver motor, and power supply. The microcontroller functioned as the brain which regulated the operation of the linear inverted pendulum. This microcontroller can be programmed with the PID algorithm to get a programmable control system that was reliable and easy to be operated. The input from this microcontroller was the data from the pendulum bar angle which was read by the sensor. The data from the angle reading will be then processed using PID algorithm in order to obtain the appropriate data to adjust the position of the cart so that the pendulum shaft remains balanced.

4.2.2.1.3. Coding

Software design was a program created to manage the workflow of the Arduino Uno microcontroller. This program will control the working system of the linear inverted pendulum according to the desired instructions. The important step in a program creation was making a flowchart of the program. The flowchart can show the explanation of the workflow of the running program within the linear inverted pendulum system. The following picture is a flowchart of the created program.

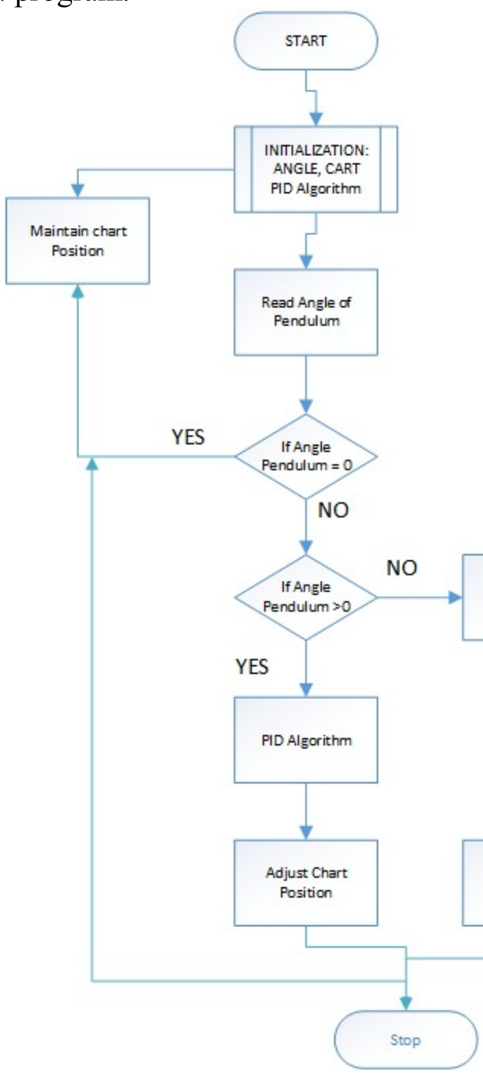
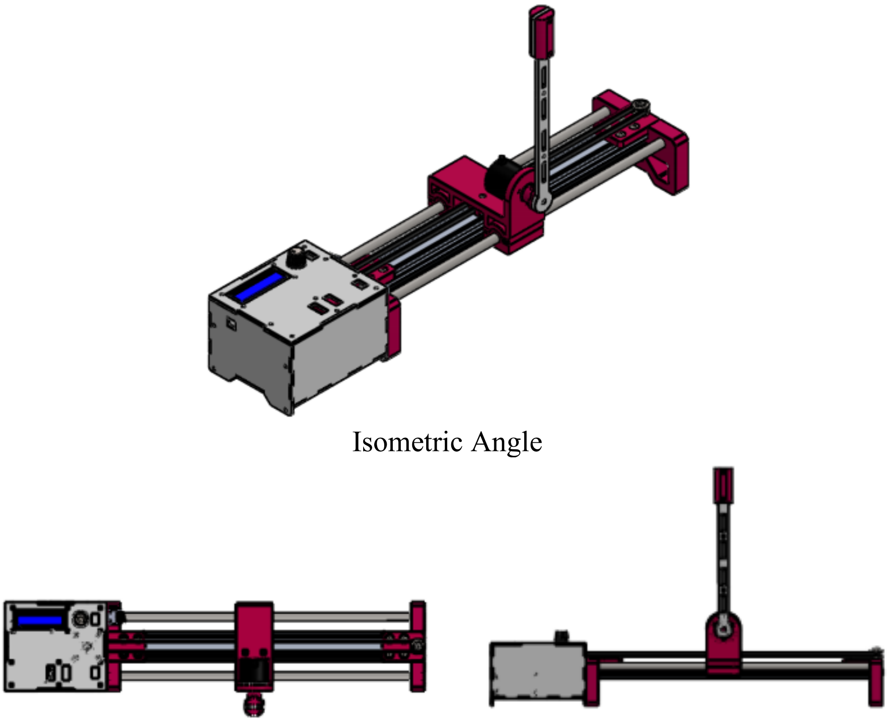


Figure 6. Flowchart of Linear Inverted Pendulum System

4.2.2.2. Planning Results

The results of the planning design of Linear Inverted Pendulum



Isometric Angle

Top angle Front angle

Figure 7. Design of Linear Inverted Pendulum

4.3. Implementation Phase

This phase is realizing the design in the tangible form including pre-production, production, post-production and quality review. These stages began with the preparation of manufacturing, mechanical manufacture, electronics, and coding in order to match the tool purpose. Moreover, additional practice guidelines were needed to support the learning process. Then, it was necessary to perform a performance test to determine overall performance. After the performance was fulfilled the desired target, a quality review was held.

4.4. Evaluation Phase

In this phase, the alpha and beta tests were done. The alpha testing was done by testing the products through expert judgment from the material and media experts. After the trial, there were some revisions and improvements. After going through an alpha test, then it was through the beta test where the product was tested on two students who have received adaptive control courses. The beta test was then ended by trying out a group of students to reveal the practicality level of the learning resources.

5. Conclusions and Suggestion

Based on the research findings, some conclusions and suggestions can be drawn as follow.

(1) It is necessary to provide the tangible forms of the learning sources for adaptive control material

(2) The design of an Inverted pendulum as a learning source of adaptive control had been through several stages, i.e. Needs analysis, design, implementation, and evaluation.

(3) Inverted Pendulum design consists of mechanical, electronic and program design.

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