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# NCTF-FL Controller for Pendulum Balancing System

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***Abstract***

*Pendulum Balancing of Linear Servo System consists of a cart driven by a DC motor, via a rack and pinion mechanism to ensure consistent and continuous traction. The cart is also equipped with a rotary joint to which a free turning rod (or pendulum) can be attached. This concept paper proposed a combination of Nominal Characteristic Trajectory Following (NCTF) and Fuzzy Logic (FL) to control the position of the cart and to balance the pendulum. The proposed controllers are expected to have a simple design method and achieved high performances.*

***Keywords**: continuous traction, fuzzy logic, NCTF, pendulum system*

## 1. Introduction

Pendulum Balancing of Linear Servo System is a challenging problem in the area of control systems. It is very useful to demonstrate concepts in linear control such as the stabilization of unstable systems. Besides, as a typical unstable nonlinear system, this system is often used as a benchmark for verifying the performance and effectiveness of a new control method because of the simplicities of the structure. Pendulum balancing of the linear servo system consists of a cart driven by a DC motor, via a rack and pinion mechanism to ensure consistent and continuous traction. The cart is also equipped with a rotary joint to which a free turning rod (or pendulum) can be attached (see Figure 1).

The control strategy of this system is composed of the swing-up control of the pendulum and the stabilizing control of the whole system that consists of angular control of the pendulum at upright position and position control of the cart at the origin of rail. First, swing up control is to bring the pendulum from the downwards position to the upright position. This is achieved when the motor is given voltage in the appropriate direction and magnitude to drive the cart back and forth along the extremely limited track length repeatedly until the pendulum is close to the upright position. Thereafter, stabilizing control is to balance the pendulum in the upright position.

When the pendulum leans in one direction, the control algorithm will try to move the cart under it with appropriate speed and direction. In this case, the algorithm will take the inputs, i.e. the pendulum angle and cart position measured by encoders, then tell the cart which way and how fast to move.

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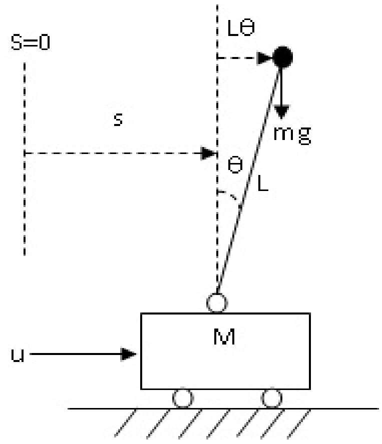



Figure 1. Inverted pendulum on a carriage

Until now, a lot of intelligent approaches about the swing-up and stabilizing control of the inverted pendulum system have been proposed [1]. The system is designed in such a way so that various controllers such as PID, Fuzzy Logic, as well as Neural Networks, adaptive and nonlinear controllers can be implemented and evaluated via feedback strategies. Since many controllers can be implemented in this system in order to control the position and swing angle, the implementation of a practical controller must be investigated.

The objective of the study is to investigate and propose a practical control method for pendulum balancing of the linear servo system as follows:

i. To control the position of cart by using the Nominal Characteristic Trajectory Following (NCTF) controller
ii. To control the balancing of pendulum by using Fuzzy Logic (FL) controller.

**2. NCTF Controller**

The structure of the NCTF control system is shown in Figure 2.

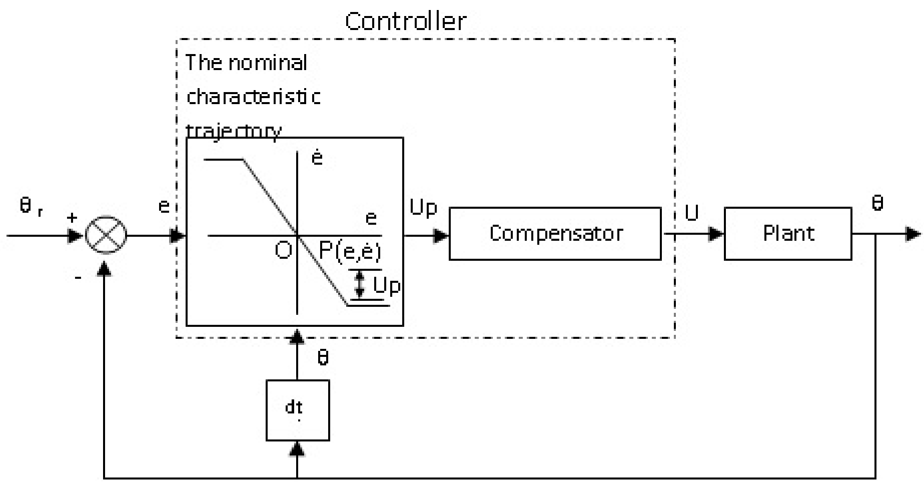



Figure 2. NCTF controller

The NCTF controller consists of a nominal characteristic trajectory (NCT) and a compensator [2]. The NCTF controllers works under these two following assumptions:

i. A DC or an AC servomotor is used as an actuator of the object.

ii. PTP positioning systems are discussed, so $\theta_r$ is constant and $\dot{\theta}_r \equiv 0$.

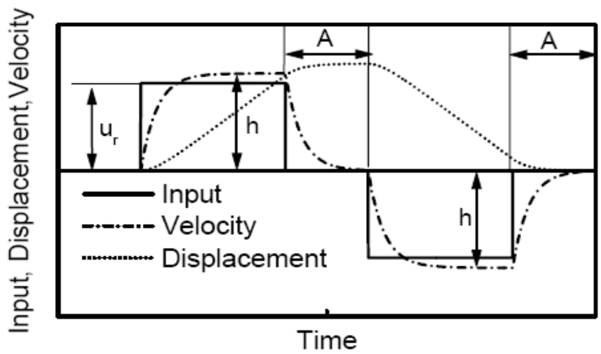
Here, the objective of the NCTF controller was to make the object motion follow the NCT and end at the origin of the phase plane (e,ė).

The NCTF controller design is based on a simple open loop experiment of the plant as follows:

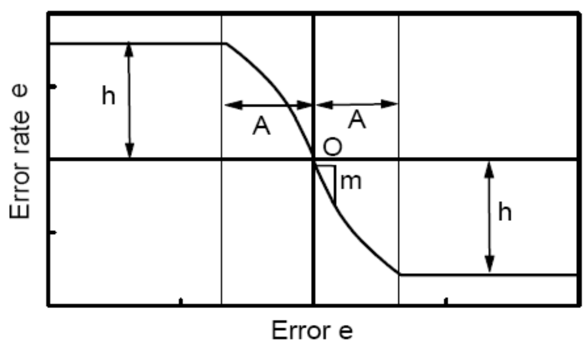
i. Open-loop-drive of the plant with stepwise inputs and measurement of the displacement and velocity responses of the plant: Figure 3(a) shows the stepwise inputs, and the velocity and displacement responses due to the stepwise inputs. In this paper, the rated input to the actuator $u_r$ is used as height of the stepwise inputs.
ii. Construction of the NCT by using the plant responses: The velocity and displacement responses are used to determine the NCT. Since the main objective of the PTP positioning system is to stop a plant at a certain position, a deceleration process (curve in area *A* of Figure 3(a)) is used. Variable *h* in Figure 3 is the maximum motion velocity. From the curve in the area *A* and *h* in Figure 3(a), the NCT in Figure 3(b) is determined. Since the NCT is constructed based on the actual responses of the plant, the NCT includes nonlinearity effects such as friction and saturation.

$$K = -\frac{h}{u_r} \tag{1}$$

$$\alpha = -m \tag{2}$$



(a) Stepwise inputs and responses



(b) Nominal characteristics trajectory (NCT)

Figure 3. NCT determination

iii. Design the compensator based on the NCT information. Here, the following PI compensator is adopted due to its simplicity:

$$u = K_p u_p + K_i \int u_p dt \tag{3}$$

Where $K_p$ and $K_i$ are proportional and integral gains respectively. Using the PI compansentor parameters $K_p$ and $K_i$ and the NCT characteristics near the origin (see Figure 5(b)), the transfer function of the closed-loop positioning system controlled by the NCTF ontroller can be approximated as follows:

$$\frac{X(s)}{X_{ref}(s)} = G(s) = G_1(s)G_2(s) \tag{4}$$

Where,

$$G_1(s) = \frac{\alpha}{s+\alpha} \tag{5}$$

$$G_2(s) = \frac{2\xi\varpi_n + \varpi^2{}_n}{s^2 + 2\xi\varpi_n + \varpi^2{}_n} \tag{6}$$

$$K_p = \frac{2\xi\varpi_n}{K\alpha} \tag{7}$$

$$K_i = \frac{\varpi^2{}_n}{K\alpha} \tag{8}$$

Where $\alpha$ is the simplified object parameters, $\zeta$ is the damping ratio and $\varpi_n$ is the natural frequency.

When $\zeta$ and $\varpi_n$ are large enough, G(s) becomes nearly equal to $G_1(s)$, which represents the condition when the object motion follows the NCT as the objective of the NCTF control system. Moreover, large $\zeta$ and $\varpi_n$ also make the close-loop system robust to friction or inertia variation of the object in continuous systems [2]. Finally, by using $\zeta$ and $\varpi_n$ as design parameters, the PI compensator parameters are designed as follows [3]:

$$K_p = \frac{2\xi u_r}{mh} \tag{9}$$

$$K_i = \frac{\varpi^2{}_n u_r}{mh} \tag{10}$$

## 3. FL Controller

Fuzzy logic (FL) controller is one of the most successful applications of fuzzy set theory [4]. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in natural language (such as small and large), may be represented by fuzzy sets. The idea behind the fuzzy logic controller is to write the rules that operate the controller in heuristic manner, mainly in "If A Then B" format [5].

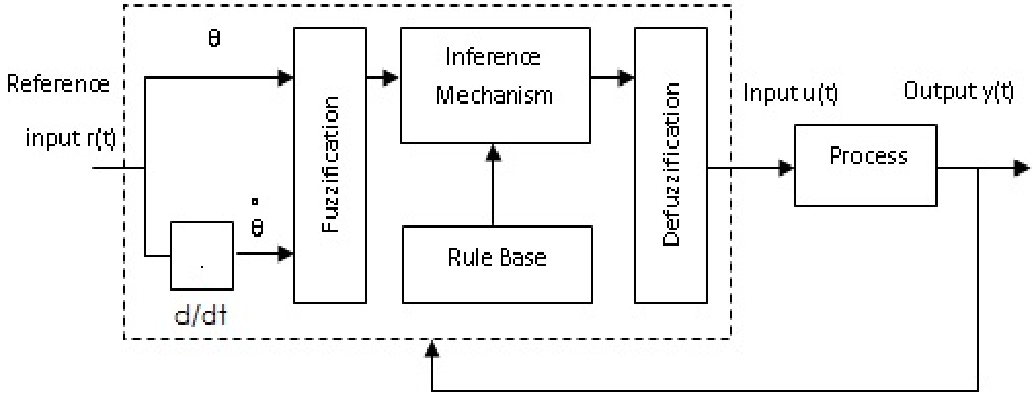



Figure 4. FL controller

In general, as shown in Figure 4, FL controller was constructed by the following elements:

i. *A rule base* (a set of "If-Then" rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control**.**
ii. *An inference mechanism* (also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.
iii. *A fuzzification interface,* which converts controller input into information that the inference mechanism can easily use to activate and apply rules.
iv. *A defuzzification interface,* which converts the inference mechanism results into actual inputs for the process.

Linguistic variable is another important part of fuzzy logic controller. Basically, a linguistic variable is a variable representing words or sentence in natural or artificial language. For example, in the fuzzy design controller for balancing pendulum system the word Negative Big (NB) for error may correspond to the Positive Big (PB) or Positive Small (PS) of the voltage whereby the actual Negative Big of error represents specific range value between -1 to 1in radians and etc. In brief, the linguistic variable is one of the important parts for tuning process of fuzzy logic controller to achieve the desired control process.

## 4. Method

In order to achieve the objectives of this research, the following procedures were considered:

i. The research started with the understanding of pendulum balancing background, analyzed its problems and investigated control theory which has been applied to the pendulum balancing of linear servo system.
ii. Investigate the application of a NCTF controller in the pendulum balancing of linear servo system which is also based on non-mathematical model.
iii. Investigate the application of fuzzy logic controller in the pendulum balancing of linear servo system, which is designed based on non-mathematical model.
iv. Real time implementation of the control algorithm was carried out by MATLAB.
v. Tested the controller performances by experiments and analyzed the result.

### 4.1. Experimental Setup

This system consists of a single rod mounted on an IP02 linear cart, whose axis of rotation is perpendicular to the direction of motion of the cart. The pendulum rod is free to swing along the cart's axis of motion. The IP02 is connected to the computer software as shown in Figure 5. The IP02 is connected to the computer as controller. The PID control algorithms were implemented on a computer using Simulink and WinCon. The data acquisition card (DAQ) MultiQ PCI is used to acquire the analog signal from IP02. Both of the hardware was used in converting analog to digital signal and vice versa.

The IP02 is a solid aluminium cart and is driven by a rack and pinion mechanism using 6-V DC motor, ensuring consistent and continuous traction. The cart position is measured using an incremental encoder, which meshes with the rack via an additional pinion. The second incremental encoder on the IP02 is placed on an instrumented pendulum hinge, which is mounted on top of the cart. It measures the angle of the pendulum rod suspended in the front of the cart assembly. The pendulum is free to swing and is able to rotate through the full 360˚ range, along the cart's axis motion. The MathWork's MATLAB/Simulink is used for real-time controller implementation through WinCon.

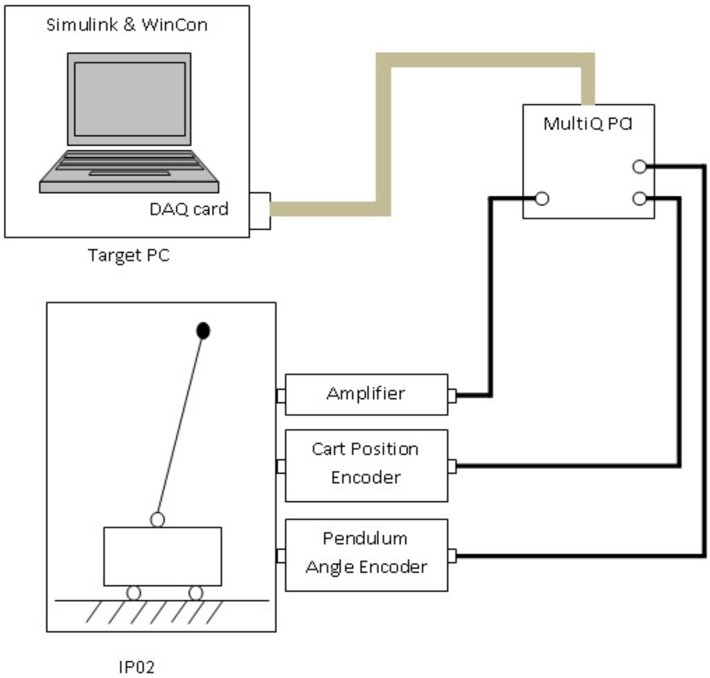



Figure 5. Serial connection between host and target computer to the pendulum system (IP02)

### 4.2. Benchmark Controller

The proposed control method is evaluated and compared to popular methods namely classical PID controller. This controller is chosen as benchmark due to fact that the PID controller represents a well-known model-based controller. The structure of the PID control for the pendulum balancing of linear servo system is shown in Figure 6.

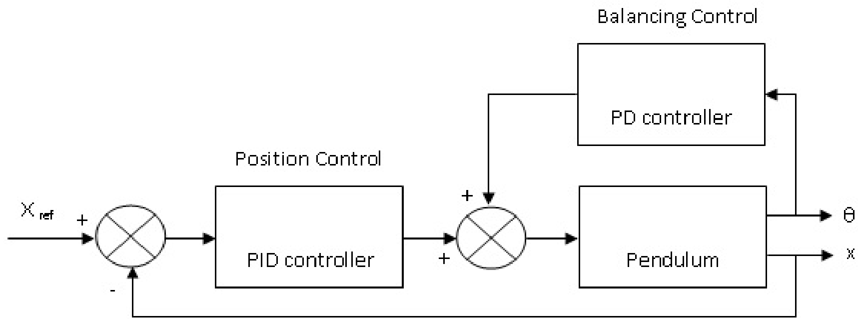



Figure 6. PID controller based pendulum balancing of linear servo system

#### 4.3. Proposed Controller

The controllers that are proposed are known as NCTF-FL, as shown in Figure 7:

i. A NCTF controller to control the position of the cart, while
ii. A FL controller is implemented to suppress or balance the pendulum.

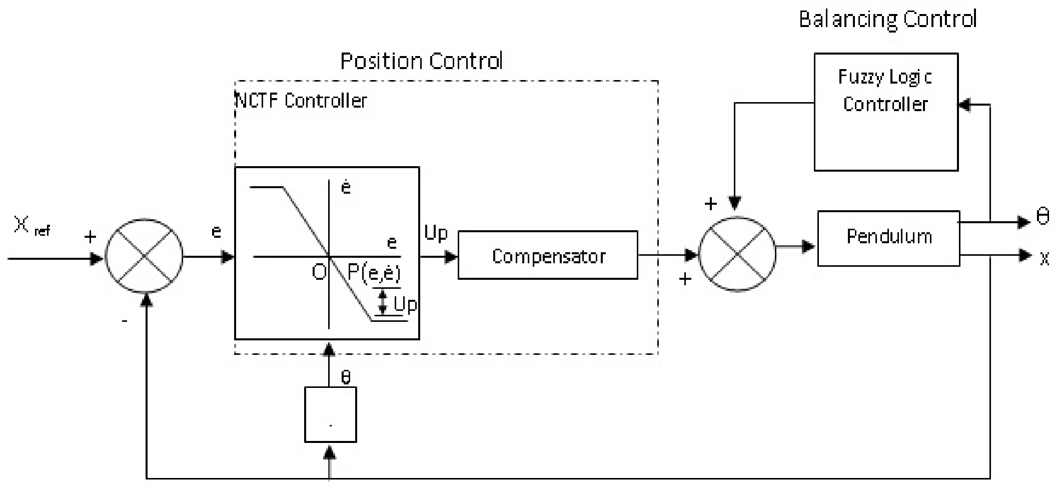



Figure 7. Proposed practical controller structure

The aim of this study is to investigate the appropriate control method for the pendulum balancing for linear servo system. The main expected results are as stated below:

i. The effectiveness of non-model based method of fuzzy logic controller for pendulum balancing control should be better than PD controller.
ii. The effectiveness of non-model based method of NCTF controller for position control of the pendulum balancing system should be better than PID controller.

## 5. Conclusion

The proposed controller is expected to have a simple structure, to be easy to design and adjust the controller without more knowledge of the classical control theory, and higher performance than conventional PID controller.

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