Hardware-In-The-Loop Simulation (HILS) Based Design and Robustness Evaluation of an Intelligent Gantry Crane System

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Abstract: The use of gantry crane systems for transporting payload is very common in industrial application. However, moving the payload using the crane is not an easy task especially when strict specifications on the swing angle and on the transfer time need to be satisfied. To overcome this problem, this paper describes development of an intelligent gantry crane system based on the mechatronic design. A lab-scale gantry crane is designed and then its intelligent controllers are developed. Fuzzy logic controllers are adopted, designed and implemented for controlling payload position as well as the swing angle of the gantry crane. The performance of the intelligent gantry crane system is evaluated on a hardware-in-the-loop simulation (HILS) environment. Moreover robustness of the proposed system is also evaluated. The result shows that the intelligent gantry crane system designed based on the mechatronic design approach has better performance compared with the automatic gantry crane system controlled by classical PID controllers. Moreover simulation result shows that the intelligent gantry crane system is more robust to parameter variation than the automatic gantry crane system.

Keywords: Intelligent, controller, fuzzy, crane, hardware-in-the-loop simulation, robustness

1. INTRODUCTION

Gantry cranes are widely used in industry for transporting heavy loads and hazardous materials in shipyards, factories, nuclear installations, and high building construction. The crane should move the load as fast as possible without causing any excessive movement at the final position. However, most of the common gantry crane results in a swing motion when payload is suddenly stopped after a fast motion [1]. The swing motion can be reduced but will be time consuming i.e. reduce facility as well as productivity. Moreover, the gantry crane needs a skilful operator to control manually based on his or her experiences to stop the swing immediately at the right position. Furthermore to unload, the operator has to wait the load stop from swinging. The failure of controlling crane also might cause accident and may harm people and surrounding.

Various attempts in controlling gantry cranes system based on open loop system were proposed. For example, open loop time optimal strategies were applied to the crane by many researchers such as discussed in [2,3]. They came out with poor results because open loop strategy is sensitive to the system parameters (e.g. rope length) and could not compensate for wind disturbances. Another importance of open loop strategy is the input shaping introduced by Karnopp [4], Teo [5] and Singhose [6]. However the input shaping method is still an open-loop approach.

On the contrary, feedback control which is well known to be less sensitive to disturbances and parameter variations [7] is also adopted for controlling the gantry crane system. Recent work on gantry crane control system was presented by Omar [1]. The author had proposed PD controllers for both position and anti-swing controls. However, it is well known that controlling the position by using PD controller will cause higher steady state error and low sensitivity to disturbance. The PID controller was also proposed for controlling the gantry crane system [8]. However the performance of the controller degrades when the actuator saturates [8]. In addition, the classical PID controller has to be designed based on the model and parameters of the plant. It is well known that modeling and parameters identification are time-consuming processes.

To overcome the above-mentioned problem, an intelligent gantry crane system is designed based on the mechatronic design approach. The proposed intelligent gantry crane is realized by adopting fuzzy logic controllers. The proposed fuzzy logic controllers consist of position as well as anti-swing controllers. Fuzzy logic control was designed based on information of the skillful operators and without the need of crane model and parameters. The performance of the proposed intelligent gantry crane system is evaluated experimentally on hardware-in-the-loop simulation environment. Moreover robustness of the proposed intelligent gantry crane system is also evaluated through simulation. The evaluation result showed that the intelligent gantry crane system had produced good performances compared with the automatic crane system controlled by classical PID controllers. In addition, simulation results show that the proposed system is more robust to parameter variation than the automatic crane system controlled by classical PID controllers.

2. MECHATRONICS DESIGN APPROACH

The goal of a mechatronic approach is to take all advantages that can results from an integrated design combining mechanical, electronic and computer elements which is coordinated by a control algorithm. The concurrent design for mechatronic system consists of three phases [9] namely modeling, prototyping/testing and deployment. Fig. 1 shows the detail three phases of mechatronic design process. These three phases of mechatronic design process can be repeated until the results are satisfactory.

Modeling, which is the first phase in the mechatronic design approach, is to analyze the goal of the project and the technical environment in which system is integrated. Normally a block diagram is used to create intuitively understandable behavior models of the system. In this phase, a mathematical model of each component is derived and then used to analyze and predict the system performances. Software such as ACSL, SIMPACK, MATLAB/Simulink, VISIM and MATRIX-X is useful and valuable for allowing the designer to study the interaction of components and the variation of design parameters before manufacturing.

Unfortunately it is usually very difficult to build exact mathematical model for complex mechatronics systems including sensors and actuators. However, there is no single model which can ever flawlessly reproduce reality. There will always error called as unmodeled errors between behavior of a product model and the actual product. These unmodeled errors are the reason why so many model-based designs fail when deployed to the product.

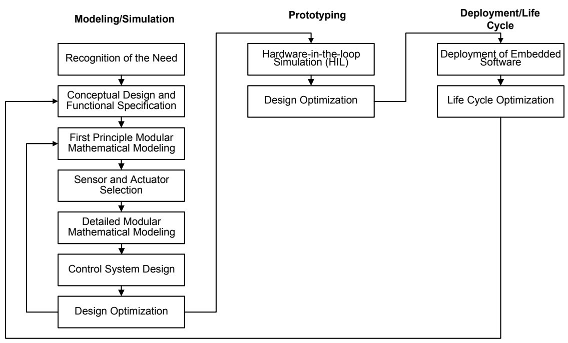


Fig. 1 Mechatronic design process

Table 1 Different configuration of HILS

Actual Hardware	Mathematical Model	Purpose
• Sensors • Actuators • Plant	• Control algorithm	Modify control system design subject to unmodeled errors and machinery errors.
• Sensors • Actuators • Controllers	• Plant	Evaluate validity of plant model
• Signal processing hardware	• Sensors • Actuators • Controllers • Plant	Evaluate the effects of the actual signal processing hardware.

In order to take into account the unmodeled errors in the design process, the mechatronic design approach includes prototyping phase. In this phase, actual hardware is used to replace part of the model of each subsystem. On-board diagnoses of the signal processing, controlling and translating subsystem should be made in this phase. Each subsystem can be built and tested individually by adopting the concept of HILS. Basically HILS refers to a computer simulation in which some of the components of the simulation have been replaced with actual hardware. The actual hardware used in the HILS depends on the purpose of prototyping as shown in Table 1 [9]. This approach increases the realism of the simulation with a lower cost compared with a fully built prototype. In addition, with a functional prototyping using HILS approach it will able to emulate the mechatronics system in real time, change and test quickly new algorithm and detect errors and bottlenecks in the system specification at an early design state.

Finally, the last phase of the mechatronics design approach is deployment in which the control code used on the embedded processor of the final product is coded and subsystems are connected to complete the full integrated mechatronic system.

3. SYSTEM DESCRIPTION

3.1 Lab-scale Gantry Crane

Fig. 2 shows the lab-scaled of gantry crane system. The physical system of the automatic gantry crane system consists of a mechanical sub-system, an actuation mechanism for transferring the payload, position and swing angle sensors, real-time control software/hardware. A DC motor and its driver are used to move trolley in which the payload is connected. The rack and pinion mechanism is adopted to allow the trolley guided by a shaft moving along working space. Two potentiometers are used to measure trolley position and payload swing angle. Then potentiometer outputs are used as feedback to controllers. The lab-scale gantry crane used only considers the planar movement of trolley with fixed load and length of the string. The hoisting mechanism used for lifting/unloading is also not considered.

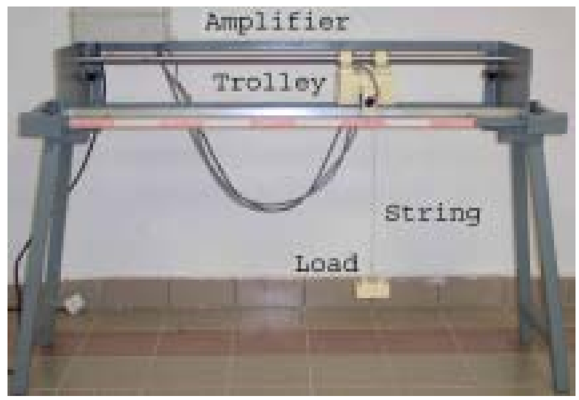


Fig. 2 Lab-scale gantry crane

3.2 Dynamic Model of Gantry Crane

The mathematical model of the lab-scale gantry crane was developed and its parameters are identified [10]. The developed gantry crane model is only used to design classical PID controller, which is used as a comparator, and to make simulation. The developed dynamics model of the crane is [10]

$$\frac{X(s)}{U(s)} = \frac{9.18}{s(0.0788s^2 + 0.9804s + 1)} \tag{1}$$

$$\frac{\Theta(s)}{X(s)} = \frac{-s^2}{40s^2 + 981} \tag{2}$$

where U(s), X(s) and Θ(s) are input voltage, trolley displacement and load swing angle respectively.

4. CONTROLLER DESIGN

4.1 Proposed Control Structure

The structure of the proposed controller for the gantry crane system is shown in Fig. 3. The proposed controller consists of fuzzy logic controllers for both position and anti-swing control respectively. The objective of the proposed fuzzy logic controllers is to control the payload position X(s) so that it moves to the desired position $X_{ref}(s)$ as fast as possible without excessive swing angle of the payload Θ(s). The design of fuzzy logic control is based on expert knowledge. For example the expert knowledge of skillful operator during the manipulation of gantry crane system is adopted in fuzzy logic controller design. It shows that fuzzy logic controller is a technique that can realize the skill of human operators and the design rules describe the subjective fuzziness of operators' experiences instead of the use of control theory based on mathematical model of the plant.

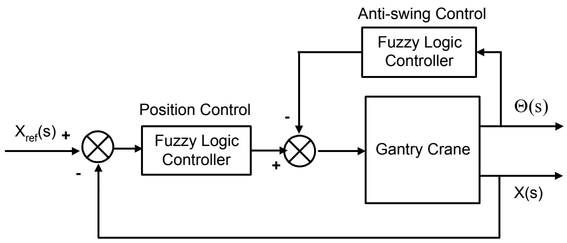


Fig. 3. Proposed fuzzy-based intelligent gantry crane system

Fuzzy logic controller is one of the recent developing methods in control that earned its popularities. The idea behind the fuzzy logic controller is to write the rules that operating the controller in heuristic manner, mainly in If A Then B format. In general, as shown in Fig. 4, fuzzy logic controller is constructed by the following elements [11]:

- *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**.**
- *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.
- *A fuzzification interface*, which converts controller input into information that the inference mechanism can easily being used to activate and apply rules.
- *A defuzzification interface,* which converts the conclusions of the inference mechanism into actual inputs for the process.

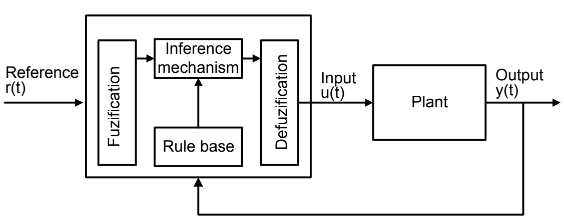


Fig. 4. Fuzzy controller structure

Another important part of fuzzy logic controller is linguistic variable. Linguistic variable plays the key role in many of its applications, especially in the realm of fuzzy expert systems and fuzzy logic control. Basically, a linguistic variable is a variable representing words or sentences in natural language. For example, in the fuzzy design controller for gantry crane the words 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. In brief, the linguistic variable is one of the important parts for tuning process of fuzzy logic controller to achieve the desired control process.

4.2 Design of Fuzzy Logic Controller

The main features of the fuzzy logic design process consist of the development of input and output of the membership functions, fuzzy rule base and defuzzification method. In the position control, error and error rate of position are taken into consideration as inputs. On the other hand, swing angle and swing angle rate are used as inputs for anti-swing control. Meanwhile, the voltage is taken as an output. Since there is no specific form to be used when designing fuzzy logic control [11], thus, the basic triangle and trapezoidal forms are chosen for input and output membership functions. In most cases, the performance of fuzzy control is minimally influenced by the shapes of memberships, but mainly by the characteristics of control rules [12].

The membership functions for error, error rate and voltage of the position control consist of Negative (N), Zero (Z) and Positive (P) as shown in Fig. 5. The universe of discourse is from -100 to 100 cm for error, -12.85 to 12.85 cm/s for error rate and -1.4 to1.4 for voltage. Meanwhile, membership functions for swing angle, swing angle rate and voltage of anti-swing control consist of Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB) as shown in Fig. 6. The universes of discourses of error, error rate and input voltage are from -1 to 1 rad, -2.5 to 2.5 cm/s and -1.4 to1.4 V respectively.

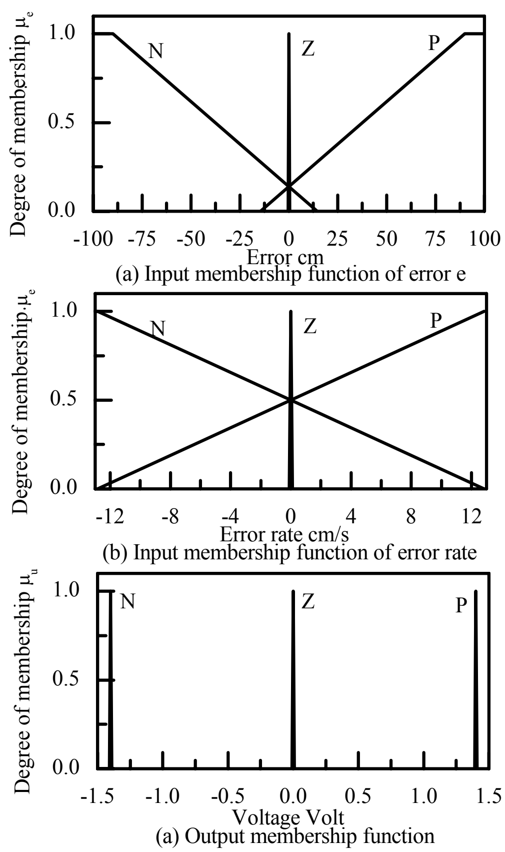


Fig. 5. Membership function of position control

The rules of fuzzy position and fuzzy anti-swing controls are adopted from operator's knowledge and experiences. Basically, the operator considers the target position, actual position and the crane speed during operation. Therefore, error and error rate are used in order to generate the rules. Tables 1 and 2 list the generated linguistic rules for position and anti-swing control respectively.

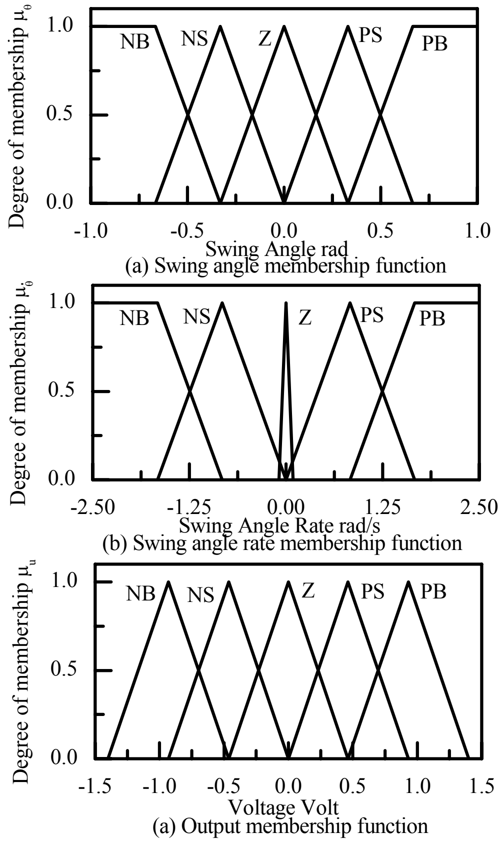


Fig. 6. Membership function of anti-swing control

Table 2. Fuzzy rule base of position control

Error \ Error Rate		Error rate $\dot{e}(t)$ P	Z	N
Error $e(t)$	P	P	P	P
	Z	N	Z	P
	N	N	N	N

Table 2. Fuzzy rule base of anti-swing control

Swing angle \ Swing angle rate		Swing angle rate $\dot{\theta}(t)$ PB	PS	Z	NS	NB
Swing angle θ	PB	PB	PB	PB	PB	PB
	PS	PB	PS	PS	PS	PS
	Z	PB	PS	Z	NS	NB
	NS	NS	NS	NS	NS	NB
	NB	NB	NB	NB	NB	NB

The fuzzy inference for position control has adopted the Mamdani's Min-Max method which the fuzzy control output μ_v for the input μ_e and $\mu_{\dot{e}}$ is computed as

$$\mu_u = \vee[\mu_e \wedge \mu_{\dot{e}}] \quad (3)$$

where $\vee$ and $\wedge$ denote the maximum and minimum operators respectively while μ_e, $\mu_{\dot{e}}$ and μ_u denote degree of memberships of the error, error rate and voltage control action respectively. Meanwhile, for the anti-swing control, the same technique is used for fuzzy inference. The Mamdani's Min-Max method which the fuzzy control output μ_u for the input μ_θ and $\mu_{\dot{\theta}}$ is computed as

$$\mu_u = \vee[\mu_\theta \wedge \mu_{\dot{\theta}}] \quad (4)$$

where μ_θ and $\mu_{\dot{\theta}}$ denote degree of memberships of the swing angle and swing angle rate respectively.

Furthermore, in order to convert the fuzzy value to the crisp value of fuzzy position and anti-swing control, the centre of area of defuzzification method is used.

$$u = \frac{\int_u \mu_u(u) u du}{\int_u \mu_u(u) du} \quad (5)$$

where u is control input voltage obtained using Centre of Area (COA) defuzzification method.

5. HARDWARE-IN-THE-LOOP SIMULATION

Following the mechatronics design approach illustrated in Fig. 1, finally, the prototyping phase based on the HILS concept is done. Fig. 7 shows the HILS environment of the developed automatic gantry crane system. The HILS environment shown in Fig. 7 consists of the lab-scale gantry crane, two computers and interfacing circuit. The actual hardware part is the lab-scale gantry crane including sensors and actuator while the mathematical model part is the controllers (PID controllers or fuzzy logic controllers) which are located in the Target PC. Another computer called as Host PC is needed for generating the controller algorithms. This arrangement is done since the main purpose of the prototyping phase is to evaluate the controller performances in the real plant. In order to interface between controllers located in the Target PC and the lab-scale gantry crane, an analog-to-digital/digital-to-analog PCI-6024-E from National Instrument is used.

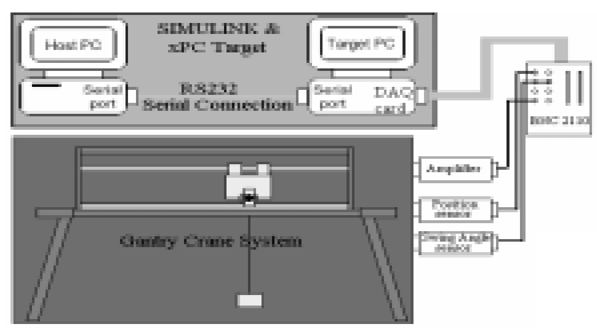


Fig. 7 Prototype of the intelligent gantry crane system

Furthermore, the MathWork's MATLAB/Simulink tool is used not only for designing the PID controllers but also for simulating the controllers in the HILS environment through RTW and xPC Target. The RTW environment provides a real-time operation using personal computers and multifunction I/O boards. However, the use of RTW still requires the development of custom interface programs for correct communication with multifunction I/O boards. To overcome this problem, xPC Target is included in the software configuration.

By combining RTW and xPC Target, there is no need to write a low level programming language for realizing a controller and/or accessing other components such as DAQ boards. The controllers are developed in Simulink using its blocks, and then it is built so that C code is generated, compiled and finally a real-time executable code is generated and downloaded to the Target PC. In particular, the xPC Target software supports and provides built-in drivers for many industry standard DAQ card including the PCI-6024E DAQ card by National Instrument which is used in the prototype of the automatic gantry crane system. This combination of devices provides a unique and complete HILS environment for rapid prototyping and testing.

The Target PC is another personal computer which is booted using xPC boot floppy disk that loads the xPC Target real-time kernel. Subsequently, the generated real-time executable code is downloaded to the Target PC via selected communication protocol without writing any low-level code. The connection between the Host PC and Target PC is accomplished either through serial (RS-232) or network (TCP/IP) communications. The communication interface have to be defined during xPC setup process in the MATLAB since the communication protocol definition is required in creating the xPC boot floppy disk for the Target PC. In the proposed system, serial communications is used since it is inexpensive, easy to install and requires only a cable for connecting serial ports of the Host PC and Target PC.

6. PERFORMANCE EVALUATION

Finally the developed intelligent gantry crane system is tested and compared with the automatic gantry crane controlled by classical PID controllers. The PID controllers were designed and optimized by using the NCD blockset of MATLAB and the PID controller parameters are listed in Table 3 [9]. Fig. 8 shows the responses of gantry crane controlled by the proposed controllers as well as the classical PID controllers when the 70 cm step input reference was used. The detailed performance comparisons are shown in Table 4 for position control and Table 5 for anti-swing control. Here, the performances of position control system were evaluated based on overshoot, settling time and steady state error. On the other hand, anti-swing control was based on maximum swing amplitude and settling time.

Table 3 PID controller parameters

Controller	Parameters		
	K_p	K_i	K_d
Position Control	2.54	$7.80\text{x}10^{-4}$	0.88
Anti-swing control	63		4.2

The results show that the fuzzy logic controller for position control gave smaller overshoot, shorter settling time and smaller steady-state error than the PID controller. Therefore it can be concluded that, the proposed fuzzy position control system is better than the classical PID controller. Moreover, as shown in Fig. 8(b), the fuzzy logic controller for anti-swing control gave faster settling time than the PD controller. Although the maximum swing amplitude due to the fuzzy logic controller was slightly higher then due to PD controller, it was still small enough. In general, the results confirmed that the fuzzy logic controllers were successfully controlled the swing angle better than the PD controller. As the proposed fuzzy logic controllers give a better performance than the classical PID controller for both position and anti-swing controllers. Hence it can be concluded that the proposed fuzzy-based intelligent gantry crane system is better than classical automatic gantry crane system.

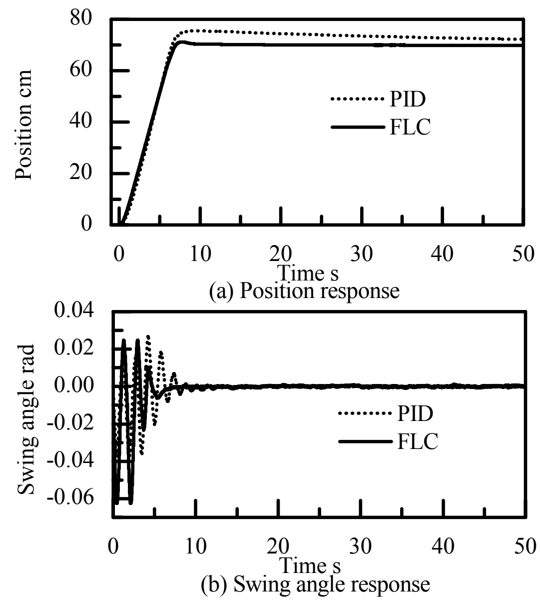


Fig. 8 Experimental responses to a 70 rad step input

Table 4 Positioning performances

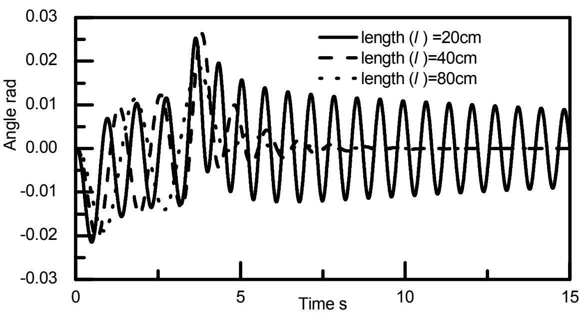
Controller	Performances		
	Overshoot	Settling Time	Error
PID/PD	7.92 %	> 50 sec	-2.19 cm
Fuzzy/Fuzzy	1.71 %	6.73 sec	0.158 cm

Table 5 Positioning performances

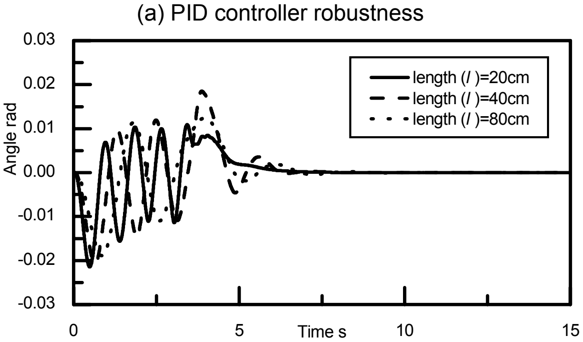
Controller	Performances	
	Max Amplitude	Settling Time
PID/PD	0.04 rad	12.7 sec
Fuzzy/Fuzzy	0.06 rad	6.73 sec

7. ROBUSTNESS EVALUATION

Physical system in general and crane system particularly are often characterized by uncertainties of parameters. Parameter estimation error and/or parameters variations contributed to these uncertainties. In the gantry crane system, one of the major contributing factors to the uncertainty was the length variation of the string. Hence robustness of the controller is an important requirement to retain performance of the gantry crane system. The controller was robust when it has small changes in performance due to the model changes or inaccuracies. Hence, the robustness of the proposed controller has to be analyzed in order to examine its performance due to the length variation. Here, the robustness of proposed and PD controllers were examined by testing the effect of string length (ℓ) on the performance of the gantry crane system. Three different lengths, i.e. ℓ =20, 40, and 80 cm, were tested through simulation and the results are shown in Fig. 9**.** Table 6 and 7 showed the performances changes due to the length variation. Fig. 9(a) showed that the PD controller had small effect on the settling time and amplitude if the longer length of the string was used. However, the response became worse as soon as the shorter length of the string was used. The settling time due to the shorter length became longer even though there was small effect on the amplitude. On contrary, Fig. 9(b) showed that the fuzzy logic controller had small effect on the settling time and amplitude if the length of the string was varied compared with the PID controller. Therefore, it showed that the fuzzy logic controller was more robust to the length variations than the PID controller.



(a) PID controller robustness



(a) Fuzzy controller robustness

Fig. 9 Robustness Evaluation

Table 6. PID control robustness evaluation

Length	Length variations	Performance changes	
		Settling time	Max amplitude
40 cm	1 times	1 times	1 times
20 cm	0.5 times	3.9 times	1 times
80 cm	2 times	0.8 times	0.67 times

Table 7. Fuzzy control robustness evaluation

Length	Length variations	Performance changes	
		Settling time	Max amplitude
40 cm	1 times	1 times	1 times
20 cm	0.5 times	0.98 times	1 times
80 cm	2 times	1.15 times	1 times

8. CONCLUSIONS

The mechatronic design approach has been used for designing the intelligent gantry crane system. Fuzzy logic controllers were adopted and designed for realizing the intelligent gantry crane system. The performance of the designed intelligent gantry crane system is evaluated on a Hardware-In-The-Loop Simulation (HILS) environment and is compared with the automatic gantry crane controlled with the classical PID controller. The result shows that the intelligent gantry crane system has better performance compared with the automatic crane system. Moreover, the simulation result also showed that the intelligent gantry crane was more robust to parameter variation than the automatic gantry crane.

ACKNOWLEDGMENTS

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