Swing Stability and Control For Loaded Cranes

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Abstract – Cranes are mechanized industrial equipment used for a host of engineering applications that require handling and manipulation of heavy payloads. Payload oscillations are common during the normal operation of the crane. These oscillations may be due to large corrective control inputs on the part of the operator and/or external disturbances such as wind. Large undamped swing oscillations however pose a serious safety hazard to personnel and equipment. Typically, commercial cranes do not provide a feature for the automatic dampening of payload oscillations and as such operators are required to manually dampen the swing motion through input controls. This paper investigates the effectiveness of Fuzzy Logic and Gain Scheduling for the automatic control of swing oscillations inherent to boom crane operation. Fuzzy Logic and Gain Scheduling are popular non-linear control strategies that have been successfully utilized for a multitude of applications. The control strategies were implemented on a prototype boom crane and tested in order to develop preliminary conclusions and insight. The results demonstrated that both control strategies were effective in dampening the payload swing in the crane prototype. However, the Fuzzy Control method was far superior as it completely eliminated overshoot thereby aggressively minimizing hazardous crane swing. It also required significantly less design effort compared to the Gain Scheduled method. The results suggest that further work and development of Fuzzy Control for swing oscillation in Boom crane is merited, with implementation and testing on industrial and commercial boom crane as the next step in the research.

Keywords – Boom Crane, Fuzzy Logic Control, Gain Scheduling Control.

I. INTRODUCTION

Cranes are utilized for a host of engineering applications that require handling and manipulation of heavy payload. There are many variants of cranes each with unique mechanical structures. However, all crane types utilize levers which result in payload swings during normal operation that subsequently can result in damage to equipment and individuals nearby. To solve this problem, operators must manually actuate the crane so that the ensuing swing is dampened. This control method however requires an experienced operator and is limited by the operator's reaction time which may not be adequate when dampening payload oscillations are caused by external disturbances.

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In this paper, the effectiveness of Fuzzy Logic control and Gain Scheduling are in dampening the payload swing and solving this control problem is evaluated and compared. A primary reason for using these strategies is that both are popular forms of non-linear control, a necessary requirement due to the highly non-linear behavior of the payload swing. The control algorithms were also chosen due to their differing internal structures so as to allow for comparison of performance. Testing and implementation utilized a prototype of a boom crane. A boom crane was chosen for this study because it has two degrees of freedom hence the results of this study is applicable to a wide variety of cranes since most cranes typically have two degrees of freedom.

II. MODELING OF BOOM CRANE

The mathematical modeling of the boom crane is presented in this section.

Principle of Operation

A boom crane uses a single boom that pivots and rotates on a base at one end and suspends the payload at the other end. This crane has two degrees of freedom as the boom can rotate about a vertical and horizontal axis. Rotation about the vertical axis is known as slewing and rotation about the horizontal axis is known as luffing. Cables are often used to luff the boom and hoist the cranes' payload. The luffing cable usually runs from a motor on the base of the crane and then connects to the tip of the boom. The hoist cable is usually connected to the payload over a pulley at the end of the boom. This allows the payload to be hoisted up and down. The full mechanical structure inclusive of the main elements and angles can be viewed in [6]. However, for the prototype used in this study, the luffing movements were achieved using motors rather than cables. The prototype also lacked any hoisting capabilities to simplify the crane model and controller design.

Physical model

Figure 1 shows the 3-D model of the crane prototype.

FIGURE 1: 3-D MODEL OF CRANE

The boom length, hoisting cable length and payload mass of the prototype were chosen to be 0.2m, 0.1m and 1kg respectively. The crane dimensions were limited to the 3-d printer used.

Materials and Methods

Table 1 shows the hardware used in the crane assembly.

TABLE 1 PARTS LIST

Part	Part Number	Description
Arduino© Mega Micro Controller	ATmega2560	Used to implement the control algorithms and actuate the crane motors
Arduino© Nano Micro Controller	ATmega328	Used for measuring and recording the crane position and payload angle
Slewing Servo Motor	HiTEC© HS-85MG	Used to provide slewing movements. Motor time constant $\tau \approx 30\,ms$
Luffing Servo Motor	Tower Pro MG90S	Used to provide luffing movements. Motor time constant $\tau \approx 250ms$
2-axis Joystick	Adafruit Analog 2-axis Joystick ADA512	Used to provide slewing and luffing setpoints to the controller
Payload Swing Sensor	MPU6050 3-axis Gyro and Accelerometer	Used to measure the payload angle in real time

Mathematical Model

To simplify the modeling process, the crane prototype was categorized into three subsystems. They were the:

- Slewing Motor Subsystem
- Luffing Motor Subsystem
- Payload Swing Subsystem

Slewing and Luffing Motor Subsystems

For the actuation motors, the inputs were chosen as the write commands sent through software. These write commands were represented as impulses and signified a change in the position of the motor shaft. For example, a write command of +2 would be represented by an impulse of +2. This command would signal the motor to rotate its shaft 2 degrees in the positive direction.

The actuation motors used in the prototype were first order systems. However, a general first order transfer function could not be used to describe them because its impulse response always asymptotically approaches zero. If the transient response of the motor is subtracted from the steady state value of the motor shaft a satisfactory transfer function is obtained. Therefore, the transfer function describing the actuation motors is:

$$H(s) = \frac{(\tau - K)s + 1}{\tau s^2 + s}$$

Where:
τ – motor time constant
K – steady state gain

Payload Swing Subsystem

According to [9], the payload swing in boom cranes is governed by the following system of differential equations:

$$\ddot{\beta} = -2\dot{\theta}\dot{\phi} - \left(-\dot{\theta}^2 - \frac{rsin(\gamma)\ddot{\gamma}^2}{l} + \frac{rcos(\gamma)\ddot{\gamma}}{l} + \frac{g}{l}\right)\beta - (\dot{\theta}p)\phi - \frac{rcos(\gamma)\dot{\theta}p}{l} + \frac{2rsin(\gamma)\dot{\theta}\dot{\gamma}}{l} \dots (1)$$

$$\ddot{\phi} = 2\dot{\theta}\dot{\beta} - (-\ddot{\theta})\beta - \left(-\dot{\theta}^2 - \frac{rsin(\gamma)\dot{\gamma}^2}{l} + \frac{rcos(\gamma)\ddot{\gamma}}{l} + \frac{g}{l}\right)\phi + \frac{rcos(\gamma)\dot{\theta}^2}{l} + \frac{rcos(\gamma)\dot{\gamma}^2}{l} + \frac{rsin(\gamma)\ddot{\gamma}}{l} \dots (2)$$

Where:
β – tangential component of the payload swing
ϕ – radial component of the payload swing
l – length of the cable suspending the payload
r – boom length
θ – slewing angle
γ – luffing angle
p – mass of the payload
g – acceleration due to gravity

III. CONTROL STRATEGIES

From the mathematical model it is clear there are two components in the payload swing: tangential component β and the radial component ϕ. As such two degrees of movement are required to dampen the payload swing completely. It can be noted also that the slewing movement has a greater influence on the tangential swing than luffing movement. Similarly, the luffing movement has a greater influence on the radial swing than the slewing movement. Subsequently, two separate control loops were used in both the fuzzy control scheme and the gain scheduling control scheme such that one dampens the tangential swing via slewing movements, and the other dampens the radial swing via luffing movements.

Fuzzy Control

Fuzzy Logic Control is a linguistic form of control based on the human reasoning process, and can be used when a plant cannot be modeled mathematically [10]. Instead of a traditional mathematical model, fuzzy systems use "expert knowledge" to describe the behavior of a system. This expert knowledge is acquired via experimentation or trial and error. Humans often use expert knowledge about various systems to control them without the help of closed loop control. Expert knowledge cannot be used in conventional mathematical control strategies; however, it is one of the biggest advantages of fuzzy systems. There are two types of fuzzy systems, 'Takagi Sugeno' and 'Mamdani'. In this study, Mamdani Fuzzy systems were used to minimize the payload swing. Figure 2 shows the control topology that was used when implementing this fuzzy control system.

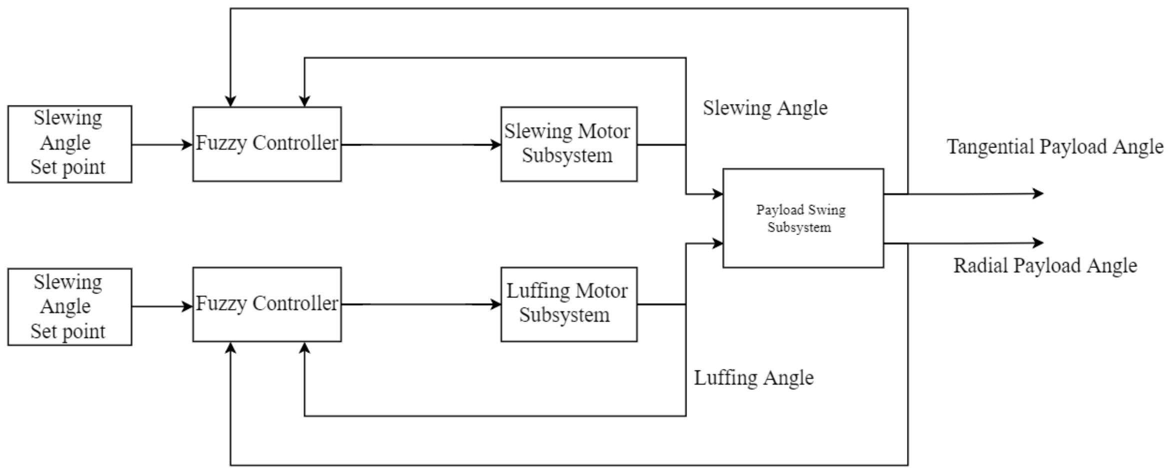

FIGURE 2 FUZZY SYSTEM CONTROL TOPOLOGY

Controller Fuzzy Sets

For the purpose of this study, a fuzzy controller was used to provide accurate position control in its designated degree of freedom as well as eliminate the corresponding component of the payload swing. Two error signals were used as the fuzzy controller inputs. They were the position error (i.e. how far away the crane position is from its desired value) and the payload angle error (i.e. how far away the payload angle is from 0°). Hence the linguistic variables for the fuzzy controller inputs were chosen to be "Position Error" and "Payload Angle Error".

For "Position Error", the effective universe of discourse was chosen to be $[-180, 180]$. This universe of discourse assumes that the crane can only move $180°$ in all its degrees of freedom. Similarly, with "Payload Angle Error" the effective universe of discourse was chosen to be $[-90, 90]$. This assumes that the payload angle will never be greater than $90°$ or less than $-90°$.

The fuzzy sets used to describe the input linguistic variables of each controller can be seen in figures 3 and 4.

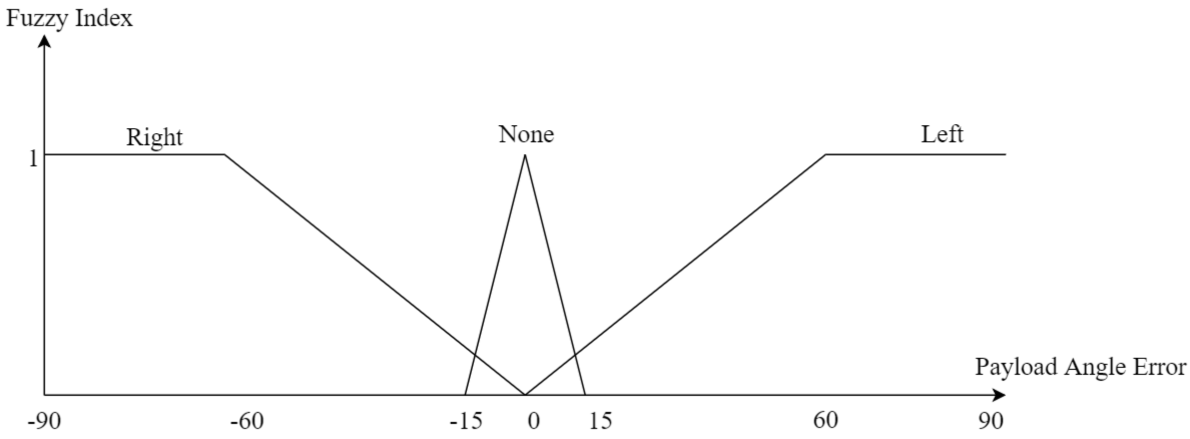

FIGURE 3 PAYLOAD ANGLE ERROR FUZZY SETS

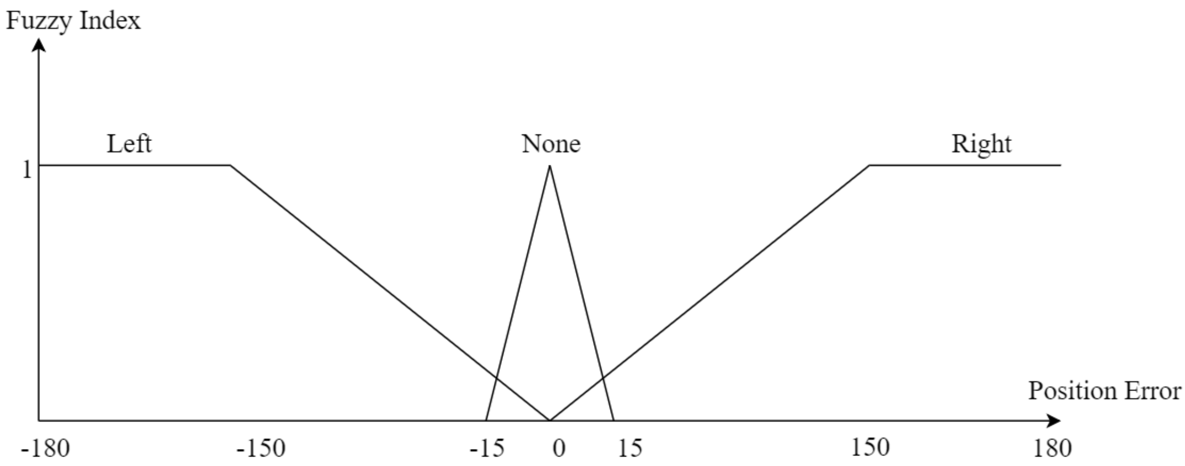

FIGURE 4 POSITION ERROR FUZZY SETS

Triangular and trapezoidal fuzzy sets were used in the modeling process of the controller inputs to simplify controller design; however, any shape of fuzzy set could be used providing that it accurately describes the system variables. Additionally, more complex fuzzy sets may reduce controller performance as microcontroller calculation and processing time may increase [3].

Since servo motors were used to actuate the plant, the fuzzy controller output was designed to change the motor shaft position. That is, the controller output would determine how much the motor shaft moves from its current position. As such, the linguistic variable assigned to the controller output was “Change in Position”. The universe of discourse chosen was $[-10, 10]$. By doing this the motor was limited to a 10° movement in any direction per controller cycle.

For “Change in Position”, three fuzzy sets were imposed onto the universe of discourse. Singleton membership functions were used for each fuzzy set. This allowed a simplified controller design and made the determination of the controller output by microcontroller less computationally intensive. Figure 5 shows the fuzzy sets used to describe the output linguistic variable.

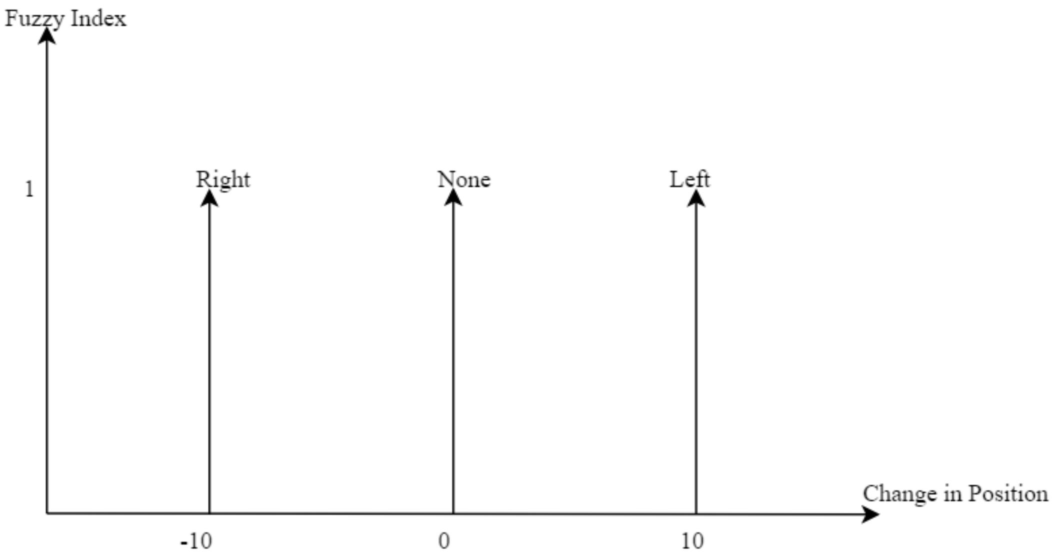

FIGURE 5 OUTPUT FUZZY SETS

Controller Rule Base

It is known that a mass suspended from a cable will oscillate if a force is applied to it. To dampen these oscillations, a force opposing the direction of swing must be introduced into the system. This method is used by crane operators to dampen the oscillations of the payload when a crane moves. This was used as the “expert knowledge” in the fuzzy system. By using the defined fuzzy sets and expert knowledge, the following rule base was designed to control the plant:

If Position Error *is* none *and* Payload Angle Error *is* none *then* Change in Position *is* none
If Position Error *is* none *and* Payload Angle Error *is* right *then* Change in Position *is* right
If Position Error *is* none *and* Payload Angle Error *is* left *then* Change in Position *is* left
If Position Error *is* right *and* Payload Angle Error*is* none *then* Change in Position *is* left
If Position Error *is* right *and* Payload Angle Error *is* right *then* Change in Position *is* right
If Position Error *is* right *and* Payload Angle Error *is* left *then* Change in Position *is* left
If Position Error *is* left *and* Payload Angle Error *is* none *then* Change in Position *is* right
If Position Error *is* left *and* Payload Angle Error*is* right *then* Change in Position *is* right
If Position Error *is* left *and* Payload Angle Error *is* left *then* Change in Position *is* left

FIGURE 6 GAIN SCHEDULED CONTROL TOPOLOGY

Fuzzy Controller Tuning

Preliminary simulations identified that gain amplification was required for the fuzzy controller since the response was not appropriate

Gain Scheduling Control

The gain scheduling approach to controlling a non-linear system entails deconstructing a non-linear plant into several linear systems evaluated about equilibrium points. This allows linear design methods to be applied to non-linear systems [8]. After the plant has been deconstructed into its linear models, controllers are designed for each model. Therefore, a gain scheduled controller consists of a family of linear controllers, so that each controller regulates the plant within a region of operation. Some applications of Gain Scheduling Control include magnetic levitation systems [4] and driver assistance trajectory following algorithms [12].

The mathematical model of the payload swing subsystem showed that the swing is dependent upon on the slewing angle velocity and acceleration as well as the luffing angle, luffing velocity and luffing acceleration. To simplify controller design, the luffing angle was kept constant at 45° and all the slewing and luffing accelerations were assumed to be zero. As a result, the oscillations in the payload were assumed to be dependent only on the slewing angle velocity. By placing these restrictions and making the stated assumptions, the number of linear models required to describe the plant was reduced significantly. Since the luffing angle is constant, a degree of freedom is lost and the radial swing cannot be dampened. A PID control algorithm was used when implementing this control strategy. Figure 6 shows the gain scheduled control topology with the assumption being made that the crane has all its degrees of freedom.

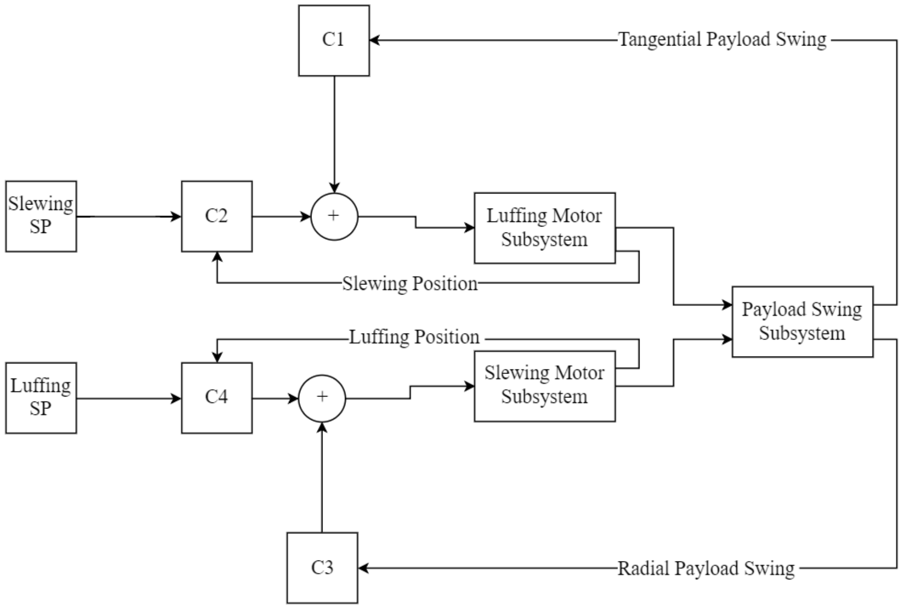

FIGURE 7 GAIN SCHEDULED CONTROL TOPOLOGY

Similar to the fuzzy system, there are two control loops. Each having two controllers in parallel. Since each controller is SISO, and there are four control variables, four controllers are necessary in this control algorithm. However, because the slewing and luffing motors are linear systems only the controllers responsible for dampening the payload swing are gain scheduled. Hence, four controllers were required but only controllers 'C1' and 'C3' were gain scheduled.

Linearizing the Plant

Jacobian Linearization [11] was only used to linearize the payload swing sub-system since the slewing and luffing motors were both linear.

The linear models describing the payload swing subsystem were put into the following general state space form:

$$\begin{bmatrix}\dot{\beta}\\ \ddot{\beta}\\ \dot{\phi}\\ \ddot{\phi}\end{bmatrix} = A * \left(\begin{bmatrix}\beta\\ \dot{\beta}\\ \phi\\ \dot{\phi}\end{bmatrix} - X_0\right) + B * \left(\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\\ \gamma\\ \dot{\gamma}\\ \ddot{\gamma}\end{bmatrix} - U_0\right)$$

$$Y = C * \left(\begin{bmatrix}\beta\\ \dot{\beta}\\ \phi\\ \dot{\phi}\end{bmatrix} - X_0\right) + D * \left(\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\\ \gamma\\ \dot{\gamma}\\ \ddot{\gamma}\end{bmatrix} - U_0\right)$$

Where X_0 and U_0 are the equilibrium point and equilibrium input respectively. The Jacobian Matrices are:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0\\ A_{21} & 0 & -\dot{\theta}p & -2\,\dot{\theta}\\ 0 & 0 & 0 & 1\\ \ddot{\theta} & 2\dot{\theta} & A_{43} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0\\ B_{21} & 0 & B_{23} & B_{24} & B_{25}\\ 0 & 0 & 0 & 0 & 0\\ B_{41} & x_1 & B_{43} & B_{44} & B_{45} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Where:

$$A_{21} = \left(\dot{\theta}^2 + \frac{r}{l} sin(\gamma)\,\ddot{\gamma}^2 - \frac{r}{l} cos(\gamma)\,\ddot{\gamma}\right)$$

$$A_{43} = \left(\dot{\theta}^2 + \frac{r}{l} sin(\gamma)\,\dot{\gamma}^2 - \frac{r}{l} cos(\gamma)\,\ddot{\gamma} - \frac{g}{l}\right)$$

$$B_{21} = -2x_4 + 2x_1\dot{\theta} - px_3 - \frac{r}{l}\cos(\gamma)\,p + \frac{2r}{l}\sin(\gamma)\,\dot{\gamma}$$

$$B_{23} = \frac{r}{l}\cos(\gamma)\,\ddot{\gamma}^2 x_1 + \frac{r}{l}\sin(\gamma)\,\ddot{\gamma} x_1 + \frac{r}{l}\sin(\gamma)\,\dot{\theta} p + \frac{2r}{l}\cos(\gamma)\,\dot{\theta}\dot{\gamma}$$

$$B_{24} = \frac{2r}{l}\sin(\gamma)\,\dot{\theta}$$

$$B_{25} = \frac{2r}{l}\sin(\gamma)\,x_1\dot{\gamma} - \frac{r}{l}\cos(\gamma)\,x_1$$

$$B_{41} = 2x_2 + 2x_3\dot{\theta} + \frac{2r}{l}\cos(\gamma)\,\dot{\theta}$$

$$B_{43} = \frac{r}{l}\cos(\gamma)\,\dot{\gamma}^2 x_3 + \frac{r}{l}\sin(\gamma)\,\ddot{\gamma} x_3 - \frac{r}{l}\sin(\gamma)\,\dot{\theta}^2 - \frac{r}{l}\sin(\gamma)\,\dot{\gamma}^2 + \frac{r}{l}\cos(\gamma)\ddot{\gamma}$$

$$B_{44} = \frac{2r}{l}\sin(\gamma)\,\dot{\gamma} x_3 + \frac{2r}{l}\cos(\gamma)\,\dot{\gamma}$$

$$B_{45} = -\frac{r}{l}\cos(\gamma)\,x_3 + \frac{r}{l}\sin(\gamma)$$

The payload swing subsystem was linearized in $10°\ per\ second$ intervals in the range $-100 \leq \dot{\theta} \leq 100$ and the scheduling variables used were the tangential and radial swing angles as well as the slewing velocity. Each linear controller was designed using MATLAB and its PID tuning tool.

IV. RESULTS

The results obtained from the experimental studies conducted are presented in this section.

Simulation

This section shows the results obtained from the simulation of the open loop system as well as the closed loop system implementations of the Fuzzy Control algorithm and Gain Scheduling Control algorithm

Open Loop System Simulation

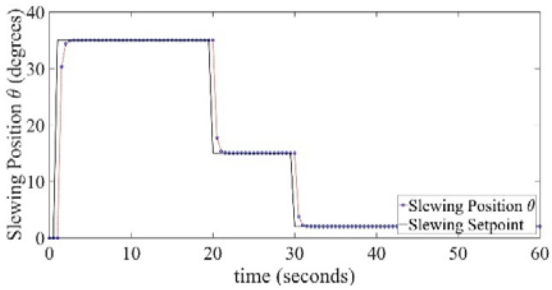

FIGURE 8 SLEWING POSITION

Figure 7 shows a plot of slewing position against time. The black trace shows the setpoint for the slewing angle and the blue trace shows the open loop slewing position response.

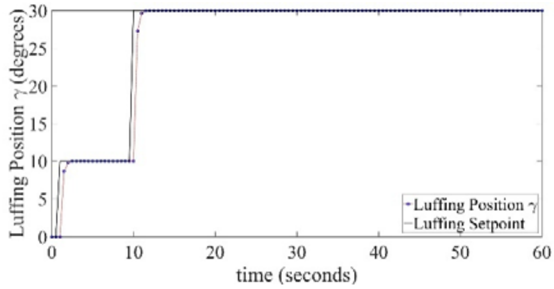

FIGURE 9 LUFFING POSITION

Figure 8 presents the luffing position against time. The black trace shows the setpoint for the luffing angle and the blue trace shows the open loop luffing system response.

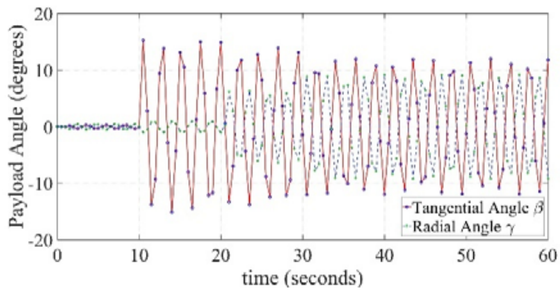

FIGURE 10 PAYLOAD SWING

Figure 9 shows the resulting payload swing for the slewing and luffing movements in figures 7 and 8. The red trace shows the tangential swing against and the green trace shows the radial swing against time.

From the open loop system performance, the crane has a fast slewing and luffing rise time however, the payload swing is large. With the peak tangential swing component being 15° and the peak radial swing component being 10°.

Fuzzy System Simulation

The following results were obtained by using a slewing position error gain of 4, tangential angle error gain of 2, slewing controller output gain of 0.2, luffing position error gain of 4, radial angle error gain of 8 and a luffing controller output gain of 0.1.

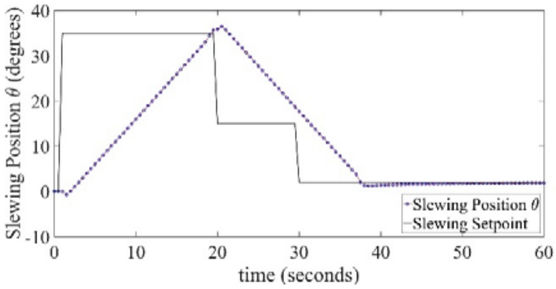

FIGURE 11 SLEWING POSITION

Figure 10 shows a plot of the slewing position against time. The black trace shows the setpoint for the slewing position and the blue trace shows the slewing position response under fuzzy control.

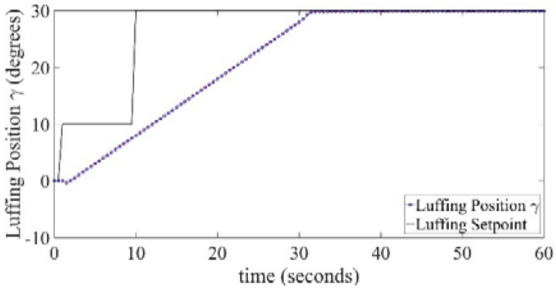

FIGURE 12 LUFFING POSITION

Figure 11 shows the luffing position against time. The black trace shows the setpoint for the luffing angle and the blue trace shows the closed loop fuzzy system response for the luffing position.

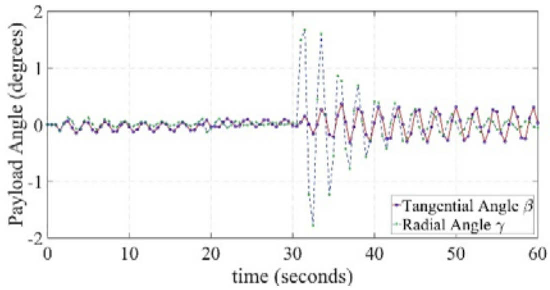

FIGURE 13 PAYLOAD SWING

Figure 12 shows the resulting payload swing for the slewing and luffing movements in figures 10 and 11. The red trace shows the tangential swing against time and the green trace shows the radial swing against time.

From the simulation it was observed that accurate setpoint tracking was achieved in all degrees of freedom, however, the slewing and luffing rise times were increased significantly. As a result, the payload swing was reduced drastically such that the closed loop system achieved a peak tangential swing of 0.25° and a peak radial swing of 1°.

__Gain Scheduled System Simulation__

For the gain scheduled system, only the slewing position and tangential angle response were analyzed, because the luffing angle was kept constant. Due to this restriction, luffing set point tracking and dampening of the radial payload swing could not be realized.

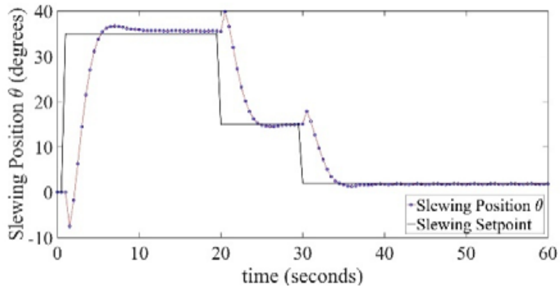

FIGURE 14 SLEWING POSITION

Figure 13 shows a plot of the slewing position against time. The black trace shows the setpoint for the slewing position and the blue trace shows the slewing position response under gain scheduling control.

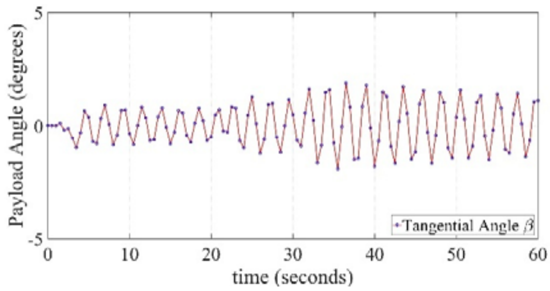

FIGURE 15 PAYLOAD SWING

Figure 14 shows the resulting tangential payload swing for the slewing movements in figures 13.

From the simulation it was observed that the gain scheduling control strategy can dampen the tangential swing while providing accurate slewing position control. However, the settling time of the payload oscillations was long and the slewing position response had some overshoot which was not desirable.

__Measured Results__

The built crane prototype was not capable of luffing movements because of limitations of the servo motors used. As a result, luffing position control could not be achieved and the radial payload swing could not be dampened. The following shows the closed loop fuzzy system response. The purple trace shows the slewing position setpoint, the orange trace shows the slewing position response and the blue trace shows the tangential payload swing.

FIGURE 16 OPEN LOOP SYSTEM RESPONSE

Figure 15 shows that under open loop conditions, the prototype is capable of accurate slewing position control, however, large tangential payload oscillations are present.

FIGURE 17 TUNED FUZZY SYSTEM RESPONSE

Figure 16 shows the closed loop fuzzy system response. It is observed that the slewing position rise time is significantly longer than the open loops systems' however, there is no tangential payload swing and accurate slewing position control is still achieved.

FIGURE 18 SYSTEM DISTURBANCE REJECTION WITHOUT SWING CONTROL

Figure 17 shows the open loop system response when an external disturbance applied to the payload. Note, the open loop system is not capable of dampening such disturbances, as the payload oscillates for a substantial amount of time.

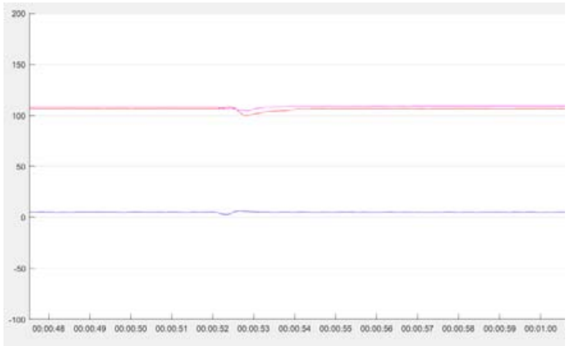

FIGURE 19 SYSTEM DISTURBANCE REJECTION WITH SWING CONTROL

Figure 18 shows the closed loop fuzzy system response to external disturbances. The closed loop system responds by slewing the crane in such a manner as to dampen the effects of the disturbance. The result is an initial inflection in both the payload swing and slewing position, however after this short transient period no payload oscillations are observed and the slewing position returns to its desired position.

From the measured results the fuzzy control system could provide accurate slewing position control while dampening the tangential payload swing. Figure 18 also shows that the system could respond to disturbances in the payload angle.

Results for the gain scheduled control strategy were not obtained because this control strategy could not have been implemented due to limitations of the microcontroller and hardware used.

V. DISCUSSION

The results suggest that both fuzzy control and gain scheduled control were capable of dampening payload oscillations during sudden crane movements and disturbances. However, the gain scheduled controller requires significantly more design effort which was disadvantageous.

The additional design effort incurred in utilizing the gain scheduled controller severely demerits this approach since the fuzzy control system response offered a more desirable system behavior, that is, the fuzzy system had no overshoot. This observation was in line with expectation given the general trend of fuzzy controllers outperforming PID controllers [10]. This result also concurs with the study conducted by Bruins [5], where it was shown fuzzy logic was superior to PID control when dampening oscillations in a gantry crane.

It was also observed that the models obtained from the Jacobian Linearization process were similar. This is a result of the initial constraints placed on the system. The gain scheduled controller was designed assuming that the luffing angle was constant and all angular accelerations in the system were negligible. With these assumptions in mind the payload angles were only dependent upon the slewing angle velocity. Due to these model simplifications, system's nonlinearities were not as prevalent, therefore, a gain scheduled controller was not necessary.

If the plant has the capability to move within all its degrees of freedom and the motor accelerations are not neglected, the models obtained from the linearization process will no longer be similar. Under these conditions, it is expected that a gain scheduled controller would be more appropriate. However, it would involve obtaining more linear models of the plant due to the increased range of operation.

Finally, whilst the fuzzy system required significantly less design effort, the gain scheduled control method allowed for more accurate setpoint tracking. Fuzzy systems inherently tend to have large steady state errors because of their inference mechanism. These steady state errors can be reduced by amplifying the controller inputs, however, these errors will never decrease to zero. This can be a problem when very accurate set point tracking is required.

VI. CONCLUSION

In this work, fuzzy control and gain scheduling control were evaluated for dampening the inherently oscillations due to crane operation. The control strategies were evaluated both in simulation and with the use of a representative miniature hardware prototype. The crane prototype was limited to slewing movements as the actuation motors used were not capable of moving the boom. Hence using a prototype which can move in all its degrees of freedom should yield more substantial results as all the components of the payload swing will be dampened and position control in all the crane's degrees of freedoms can be realized.

The results demonstrate that the fuzzy control strategy is superior to the gain scheduled control strategy. It provided a more desirable closed loop system response and required significantly less effort to design. However, these results are based on model assumptions that the system luffing angle was constant and that angular accelerations were zero. Further work could be done to investigate the case where these model assumptions are violated. Future work can also consider the use of more advanced approaches to controller design. For example, implementation of an ANFIS (Adaptive Neuro Fuzzy Inference System) will result if better closed loop performance when changes in the system arise.

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