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A pragmatic controller for a gantry crane

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Abstract. A gantry crane presents a control problem with ten state variables. The undamped swinging of the load has led earlier researchers to apply cumbersome control strategies. The essence of pragmatic control is gleaned from autopilot designs of half a century ago. The control is designed as a set of 'nested loops', where the innermost loop takes the form of a velocity loop wrapped around a motor to give crisp velocity control. Target values are derived from states in the outer loops, to be applied to a succession of inner loops. These target values are subjected to constraints. Thus in the case of the crane, the horizontal position of the load can be considered to be the two outermost variables. In this study, from the load position error, two target velocity components are calculated and subjected to limits. The velocity error leads in turn to a target acceleration of the load and subsequently, to the target displacement that takes place between the horizontal coordinates of the hoist and the load. In this paper, the pragmatic control technique is demonstrated with the aid of a JavaScript and MATLAB software programs using a state-space model.

1. Introduction

In many industrial applications, the operation of the crane system depends on a skilled operator using visual feedback. Control of an overhead gantry crane is complicated by the need to damp the swinging of the load. Appropriate movement of the hoist's position achieves this. The strategy has its foundation in the calculation of a demanded velocity for the load, so the hoist will follow a path to the target position. A limit is applied to that target velocity to keep it within the capability of the motors that move the hoist. Correction of the velocity error is achieved by applying an appropriate acceleration to the load. This acceleration results from the displacement of the horizontal hoist position relative to that of the load. Once again, a limit can be applied to the target acceleration. Thus, in calculating a target hoist position at each instant, the load velocity will be corrected and any swinging of the load will be damped in a dead-beat manner. Predictive control was produced in the 1950s by [1, 2]. The research on this technique continued for several years in Cambridge as in [3] and [4]. 'Pragmatic' control can be understood to involve a relatively simple strategy that can be understood easily. Examples include 'constrained nested control loops' and 'Logical Predictive Control'. However, classical proportional–integral– derivative PID control is often inadequate, but techniques that are computationally simple, such as Logical Predictive Control (LPC) or the method of 'cascaded constrained loops', can address many such problems. Being easy to understand, these techniques can be given the label 'pragmatic strategies'. The term 'pragmatic' also implies that the strategy can be implemented within a simple microcontroller, which gives a very fast real time response to the system as in [5]. The pragmatic strategy used a fast model of the plant that predicted the system behavior through straightforward simulation of plant dynamics. The control task is not quite as simple as it might appear, in that all three axes of the crane movement will have inertia and be of second order. Furthermore, the relationship between load acceleration and hoist displacement are inversely proportional to the length of the cable from hoist to load, adding further nonlinearity to the strategy. On the other hand, the acceleration required to move the trolley causes an undesirable load swing, which has negative consequences on system control and safety performance. Moreover, the delay of the crane's operation due to swinging, will lead it to spend more operation time, which decreases the efficiency of the crane. The pendulum motion of the load presents a serious risk of damage or injury to the material and personnel on site. It also acts as an impediment to efficiency; limiting the speed of load transportation from one place to another with accuracy. Its improvement is essential to increasing productivity in the workplace [6]. This paper proposes a pragmatic controller to control the position of the hoist of a two-dimensional gantry crane while minimizing the swing angle of the payload. The simulation results indicate that the proposed controller works well under different operating conditions.

2. Background

2.1. Gantry crane modelling

In recent decades, the control of cranes, especially the gantry crane, has led researchers to investigate a variety of control strategies. Crane systems have been considered to be difficult because they are nonlinear and contain unknown dynamics [7]. Most researchers have used the Lagrangian method for crane modelling and controller design such as in [8-12]. The method involves finding the kinetic and potential energies of the system and solving the Lagrange equation to obtain the mathematical equations representing of the system.

2.2. Control techniques

Researchers have applied cumbersome control techniques to the undamped swinging of crane loads. These techniques can be divided into the open loop and closed loop techniques. Among many methods that have been applied, there are some based on concepts such as open loop, optimal control and input shaping control techniques as [13,14]. The open loop technique has been widely used in crane system by many researchers because it easy to implement. However, the disadvantage of this technique is its sensitivity to external disturbances such as wind or ocean waves as in [15].These techniques tend to be extremely sensitive to parameter variations, changing conditions and external disturbances, decreasing the reliability of the system's performance. Closed loop control systems are also known as a feedback control systems. The closed loop technique uses feedback to maintain the demanded output condition by comparing it with the actual condition. Many researchers have used techniques such as PID to reduce the swing of the load and control the position [16-19]. Other researchers have used fuzzy logic technique such as in [20-23].These techniques have been successful in reducing swing and controlling the position of the crane. They are more robust than open loop techniques. However, the fuzzy set and the fuzzy rules are difficult to determine as in [24]. Other control strategies that have been applied to control the load positioning of the crane system include linear matrix inequalities (LMI) based control parameterization [25], also Model predictive control technique has been used by [26-28]. Furthermore, in [9], the authors used the feedback linearization technique and the decoupling strategy, but their design lacked three-dimensional modelling. The practicalities of these control strategies have remained to be further tested [29]. Regarding dynamic modelling of cranes, most researchers have used the Lagrange equation such as [19, 30]. In this paper, we present a pragmatic controller that achieves increased control performance. Specifically, the gantry crane model is derived using state space. Practical nested loop controllers will be proposed to position the load and suppress the load swing during load transference.

3. Dynamic modelling of gantry crane

The model for the gantry crane consists of a trolley that moves on a horizontal girder and the trolley that consists of a hoist system (rope and hook) to lift and lower the load. The girder motion is perpendicular to the trolley movement. It is essential to know what part of the crane dynamics should be included in the control design and what part can be neglected. Figure 1 shows the gantry crane structure.

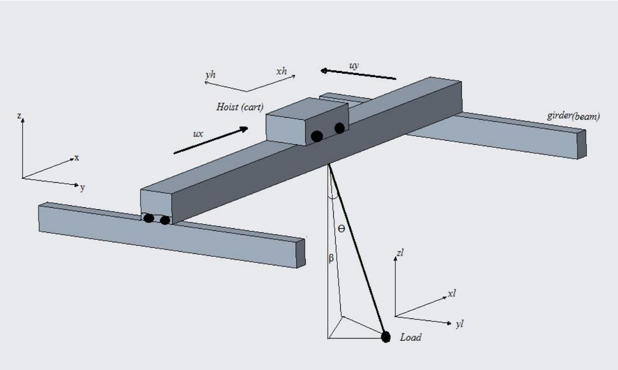

Figure 1. The structure of gantry crane system.

As shown in figure 1, the structure of gantry crane consists of:

(1) Two girders that are fixed either in the wall or on four columns with tires.

(2) A beam or rail mounted on the girder.

(3) A trolley that slides over the beam in a translational motion. (4) The second movement of the jib is either because the movement of the girders if it was fixed on columns with tires or the beam moves along the girder.

(5) A suspension system of cables and a hook. The length of the cable can be changed during load transportation or at least at the pickup and drop off points.

The combination of trolley and girder (beam) movement allows the load to reach the desired destination. Therefore, the acceleration of cart x and the acceleration of girder y are considered the inputs of the crane system. In this paper, the state space method is used to derive the mathematical model of the gantry crane system. Table 1 shows the crane parameters in use.

Table 1. Parameters of crane model.

Symbols	Description
l_x, l_y	Position of the load in x and y direction
h_x, h_y	Position of hoist (trolley) in x and y direction
v_{lx}, v_{ly}	Velocities of the load in x and y direction
v_{hx}, v_{hy}	Velocities of hoist (trolley)
$x_{target}\ y_{target}$	The demanded position of the load
v_{xldem}, v_{yldem}	The demanded velocities of the load in x and y direction
h_{xdem}, h_{ydem}	The demanded positions of the hoist in x and y direction
g	gravitational acceleration (9.81m/s2)
c	The length of cable= (5&10m)
dt	Time interval=0.01s

The following assumptions are considered:

i) The load and hoist are connected by a massless cable. That is, a pendulum motion of the load is taken into consideration;

ii) All frictional elements in the hoist motions can be neglected;

iii) The cable elongation is negligible.

The essence of the pragmatic law is designed as a set of 'nested loops', where the innermost loop takes the form of a velocity loop wrapped around a motor to give smooth velocity control. Target values are derived from states in the outer loops, to be applied to a succession of inner loops as shown in figure (2). These target values are subjected to constraints. The data on the hoist position and velocity in both axes, load position and velocity, the demanded positions of the hoist, the demanded position of the load, hoisting rope length and its time rate of change are assumed to be the main parameters of the design.

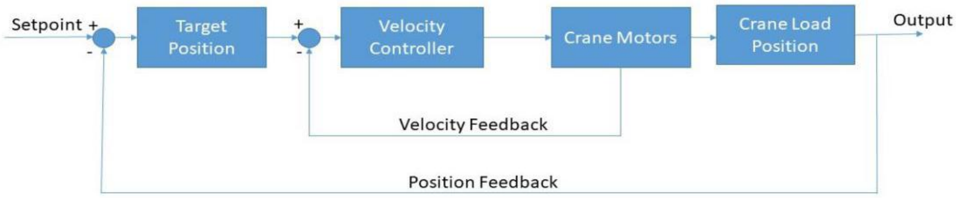

Figure 2. Block diagram of the system controller.

Although there are many possible configurations, we consider that the beam is lying in the y direction, with the rails conveying it in the x direction. The cable raises or lowers the load in the vertical z direction. Therefore, we define variables l_x, l_y and l_z for the three coordinates of the load, ignoring its tipping and twisting, h_x, h_y for the hoist, taking its z coordinate as zero. For the corresponding velocities of load and hoist, we take v_{lx} , v_{ly} , v_{hx} and v_{hy} . We take the cable length as c and its derivative as vc . The two motor inputs will be u_x and u_y , while the pairs of parameters that define their second order response are ax, bx , ay and by .

At first, we assume that the cable length is constant and that angles are small. We also assume that the inertia of the gantry motors is such that the effect of the swinging cable tension on their dynamics can be ignored. We then have the following eight state equations of the system, which can be expressed in the form of a matrix:

$$\frac{d}{dt}\begin{bmatrix} l_x \\ l_y \\ h_x \\ h_y \\ v_{lx} \\ v_{ly} \\ v_{hx} \\ v_{hy} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -g/c & 0 & g/c & 0 & 0 & 0 & 0 & 0 \\ 0 & -g/c & 0 & g/c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -bx & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -by \end{bmatrix} \begin{bmatrix} l_x \\ l_y \\ h_x \\ h_y \\ v_{lx} \\ v_{ly} \\ v_{hx} \\ v_{hy} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ ax*u_x \\ ay*u_y \end{bmatrix} \tag{1}$$

Later we can add two more equations, relating to the cable length, and include the effects of the cable tension on the hoist. We can simulate the solution to the equations with a simple Euler integration, with a time step of dt , such as;

$$l_x = l_x + v_{lx} * dt \tag{2}$$

$$l_y = l_y + v_{ly} * dt \tag{3}$$

where any desired accuracy can be achieved by making dt sufficiently small. Now to complete the strategy we need to define the demanded load velocities and the demanded hoist position v_{xldem}, v_{yldem}, h_{xdem} and h_{ydem} that will be used to reach the target at x_{target} and y_{target} . We can define:

$$v_{xldem} = \left(x_{target} - l_x\right) \tag{4}$$

Then limit it using

$$\begin{aligned} &if\,(v_{xldem} > v_{max})\{v_{xldem} = v_{max}\} \\ &if\,(v_{xldem} < -v_{max})\{v_{xldem} = -v_{max}\} \end{aligned} \tag{5}$$

Similar code will give v_{yldem}.

Now we set the target positions for the hoist axes by displacing them from the load coordinates with equation such as:

$$h_{xdem} = l_x + kh*\left(v_{xldem} - v_{lx}\right) \tag{6}$$

where, in later simulations, the gain parameter kh will be made to depend on cable length, which is a value of 2.5. Now we calculate the motor drives as a multiple of their position errors;

$$u_x = \left(h_{xdem} - h_x\right) \tag{7}$$

$$u_y = \left(h_{ydem} - h_y\right) \tag{8}$$

where u_x and u_y are then limited to the maximum proportion of full motor drive of 1. If necessary, additional velocity feedback can be applied to the motors to augment the self-damping bx and by that is assumed. Now having chosen the various control parameters the dynamics of the system can be computed by the equations below:

$$vxl = vxl + \left(xh - xl\right)*g*\frac{dt}{c} \tag{9}$$

$$vyl = vyl + \left(yh - yl\right)*g*\frac{dt}{c} \tag{10}$$

where v_{lx} and v_{ly} are the velocities of the load in x and y directions respectively. The new positions of the load at each instant are computed by previous equations (2) and (3).

The essence of this law is designed as a set of 'nested loops', where the innermost loop might take the form of a velocity loop wrapped around a motor to give smooth velocity control. Target values are derived from states in the outer loops to be applied to a succession of inner loops. These target values are subjected to constraints. The data on the swing angle, hoist position and velocity in both axes, load position and velocity, hoisting rope length and its time rate of change, are assumed to be known.

4. Simulation and results analysis

In this section, the proposed pragmatic control technique is implemented and tested with the aid of JavaScript and MATLAB. The simulation of the gantry crane is carried out to verify the performance of the proposed technique. The parameters that have been used to simulate the gantry crane model are shown in table 1. The simulation is based on a state matrix, which is shown in equation (1). The simulation of the system dynamic is executed with control inputs of u_x and u_y equations. Several simulation studies have been performed to study the behaviors of the proposed technique. As mentioned in the previous section, the hoist (trolley) runs across horizontal beam and we can consider it lying on the y direction, with the rails conveying it in the x direction. Figure 3 shows the behavior of load and hoist during travelling with a 5-meter cable length.

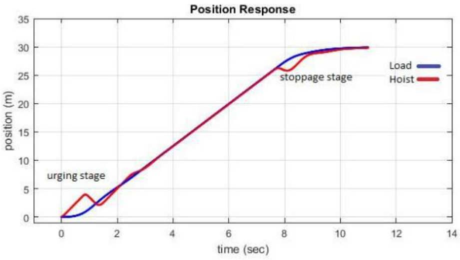

Figure 3. Trolley and load moving with 5-meter cable length.

To accelerate the load, the hoist moves ahead to give a horizontal component of the cable tension. When the load has reached the desired velocity, the hoist can travel immediately above the load, only deviating to compensate for disturbances such as wind gusts. As the target position is approached, the desired velocity falls, so the hoist ‘hangs back’ to decelerate the load and finally brings it to a halt; where once again it takes up a position that is immediately overhead. Further test have been undertaken to validate the reliability of the proposed technique. A ten-meter cable length was chosen to test the controller reliability, as shown in figure 4.

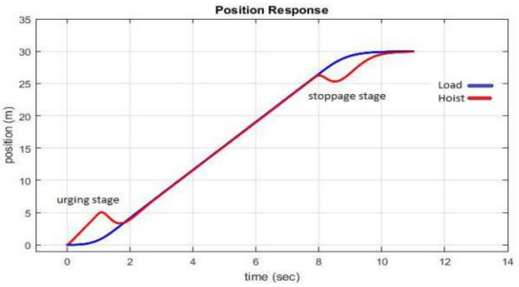

Figure 4. Trolley and load moving with 10-meter cable length.

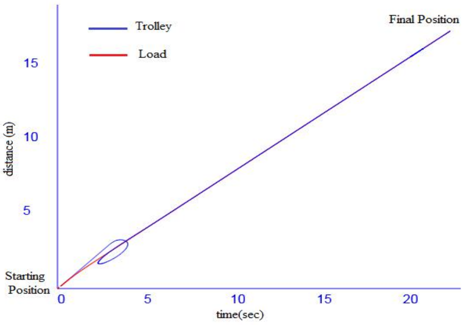

Figure 5. Crane movement with 45° slew motion.

Figure 5 shows a 2D motion of the crane system using JavaScript. Commands were generated to move the hoist from its position to the demanded position through 45° of slew from the original position of the crane. At the starting position, acceleration causes the trolley to move to the demanded position that results in an elliptic or circular shaped movement to cope with an undesired swing of the load, causing the loop to become excited. Usually, the crane’s acceleration generates a conical swing of the load.

However, the controllers tried to correct the position of the crane’s trolley to reduce the swing that was generated due to acceleration. Figures 3 and 4 show almost the same results except of a slightly larger deviation of the trolley when the cable length is longer, with the load swing being noticeable.

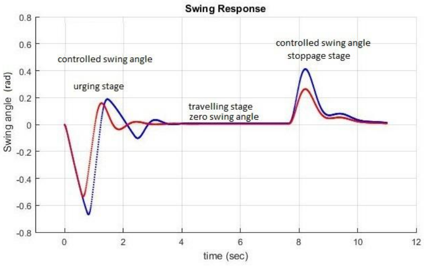

Figure 6. Schematic of swing angle with 5-meter cable length.

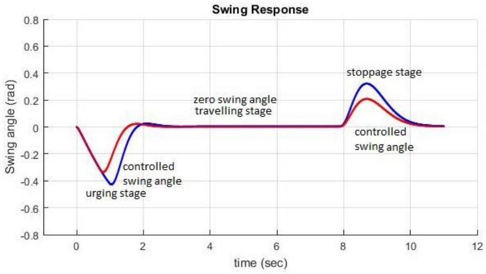

Figure 7. Schematic of swing angle with 10-meter cable length.

In figures 6 and 7, the results show the swing angles of the system which are Θ and α with 5 m and 10 m cable length respectively. Neither angle exceeded 0.2 rad, which is equal to approximately 11° from the beginning stage until the movement reached the final position. In addition, previous techniques used to control the crane, such as PID were developed with the aid of other techniques like neural networks or with the use of two PID controllers. Also, a fuzzy logic controller was considered to be a complex technique due to the computational costs such as fuzzification, fuzzy operator and defuzzification. Furthermore, fuzzy sets and the fuzzy rules are difficult to determine. Model predictive control has also been used to control cranes. It has its advantage of dealing with constraints but more computation is required and it shows poor performance with external disturbance. Furthermore, comparing with most published papers in term of performance, it showed the crane’s behavior during the travelling only, however, the stoppage in the final position has not been mentioned, as we have seen that, the stoppage will generates an oscillation of the load. From the simulation results, we can see that, the control scheme of the proposed technique gave a better results in term of tracking position and swing suppression., when it compared with previous research such as in [31] where the swing angle of the load was more than 25° and fell to 10° using the extended linearization approach however, the load kept swinging during the travel. To conclude, this paper shows the simplicity of the proposed strategy compared with the complexity of the published alternative. Thus, the results show the robustness of the proposed strategy with no load swing and no sensitivity with long cable length or with external disturbance.

5. Conclusions

A pragmatic control technique is presented in this paper. A simple mathematical model was derived for the gantry crane system using a state-space representation. Practical controllers to control the position and swing of the gantry crane, were developed. The designed controllers showed that an efficient suppression of the swing angle of the load while travelling to almost zero swing. In addition, the technique is demonstrated with the aid of a JavaScript state-space model and MATLAB. The simulated results show an accurate position for the trolley along the jib to the demanded position with no swing of the load resulting. The used strategy shows a robust and efficient result in term of simplicity and a reduction in load swing compared with previously published work.

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