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Review

Control strategies for crane systems: A comprehensive review

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ABSTRACT

Crane systems are tremendously utilised in numerous heavy load transportation industries, and therefore, the control of crane systems is a well-established research field. As the last review paper was published more than a decade ago, there is a lack of collected and organised information regarding the latest and the newest updates on control strategies for crane control systems. Hence, this paper presents a comprehensive review of crane control strategies discussing the latest research works during the years from 2000 to 2016. Various crane types and control issues are highlighted, followed by the main focus of this paper, an extensive review of the control schemes for diverse types of crane systems that have been carried out in the 21st century. A brief review on modelling of single-pendulum and double-pendulum crane systems is also given. In addition, anti-sway control systems for industrial cranes that are available on the market is described. This paper summarises most of the related work and also pays a special focus on research trends regarding the control of crane systems that have been previously published in the literature. It is envisaged that this review paper will be helpful to new researchers when identifying research directions for this particular area of interest.

Contents

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1. Introduction

Cranes are machines that are used for transporting heavy loads or hazardous materials from one place to another place. These actions commonly take place in industries such as factories, construction, marine industries and harbour loci. Numerous types of cranes are widely used in many industrial sectors, such as an overhead or bridge crane, a gantry crane, a boom crane and a rotary (tower) crane. They can be classified based upon the degrees of freedom that the support mechanism offers at the suspension point [1].

The issues in a crane system involve the ability of reducing the sway angle of the payload and moving it to a desired position with a fast crane motion [2]. In order to successfully transport the load to a desired point, the load swings need to be minimised [3]. The crane's motion is prone to an excessive load swing that could affect the positioning accuracy, the quality, the effectiveness and the safety. Consequently, a failure to control the sway angles would lead to a difficulty in the automation of the system by the worker, together with a possible damage to the quality of the load or the operating environment around the construction work. In addition, it would take a longer time being required for the task's completion and this may reduce the production volume. Statistics have shown that traditional docking equipment wastes more than 30% for fixing the load per the loading time [4].

Cranes can be controlled by using several approaches for their operations, which usually involve the process of gripping, lifting, transporting the load, then lowering and un-gripping the load. A damping capacity of the system plays a significant role towards the precision motion performance, where its capability can be further improved by applying passive or active damping techniques. External dampers such as dashpots and viscous dampers are examples of the passive alternative [5]. Besides, techniques to reduce crane sways by using a coriolis force produced by a radial spring and a damper [6] and a cable passive damper system [7] were also proposed. On the other hand, feedback or feed-forward control strategies are the active approaches that can be utilised. These strategies are the main focus of what is to be reviewed in this paper. It can be found that for more than one decade, there is no article in the literature that provides a comprehensive review of the control strategies for crane systems. The last review article was published in 2003 [1] and it presented research work between 1961 and 2001. The article reported on two approaches for the modelling of cranes and the various control techniques that were used for several cranes, especially for gantry and rotary cranes. Modelling to obtain an accurate dynamic model of a crane system is an important step towards the development of an efficient and satisfactory controller. In [1], modelling of various single-pendulum cranes were presented in details and has been an established research work. Nevertheless, modelling of double-pendulum cranes was not covered in [1]. A brief review paper was also presented in a conference in 2012 [8]. However, the article focused only on the work that was related to the applications of intelligent control for crane systems.

In this paper, initially, a brief review on modelling of single-pendulum and double-pendulum crane systems during the years from 2000 to 2016 is presented. As there is a lack of information regarding the latest and the newest updates, this paper then focuses on a comprehensive review of control strategies for numerous types of crane systems during the same period. This includes recent work and the latest work with up-to-date control schemes that were not reviewed in the previous review article [1]. The control strategies that are covered in this article are divided into open loop and closed-loop control techniques. In addition, anti-sway control systems for industrial cranes that are available on the market are also described. The goal is to organise and summarise most of the work, and to identify the research focus and the trends in the literature on the control of crane systems.

2. Crane types and control issues

Numerous types of cranes have been used in diverse industrial sectors. These include bridge cranes, gantry cranes, tower cranes (rotary) and boom cranes. In general, these cranes can be categorised into two groups, according to their structures and their motions: (1) Bridge cranes and gantry cranes, (2) Tower cranes and boom cranes. The structures of these cranes are illustrated in Fig. 1. A bridge crane, also known as an overhead crane, operates on an elevated runway system, along a production line, or the length of a factory. Commonly, it has three degrees of freedom (DOF) or hook motions in the *X*, *Y* and *Z* directions. The trolley can move to the right and to the left directions along the girder. On the other hand, the girder is

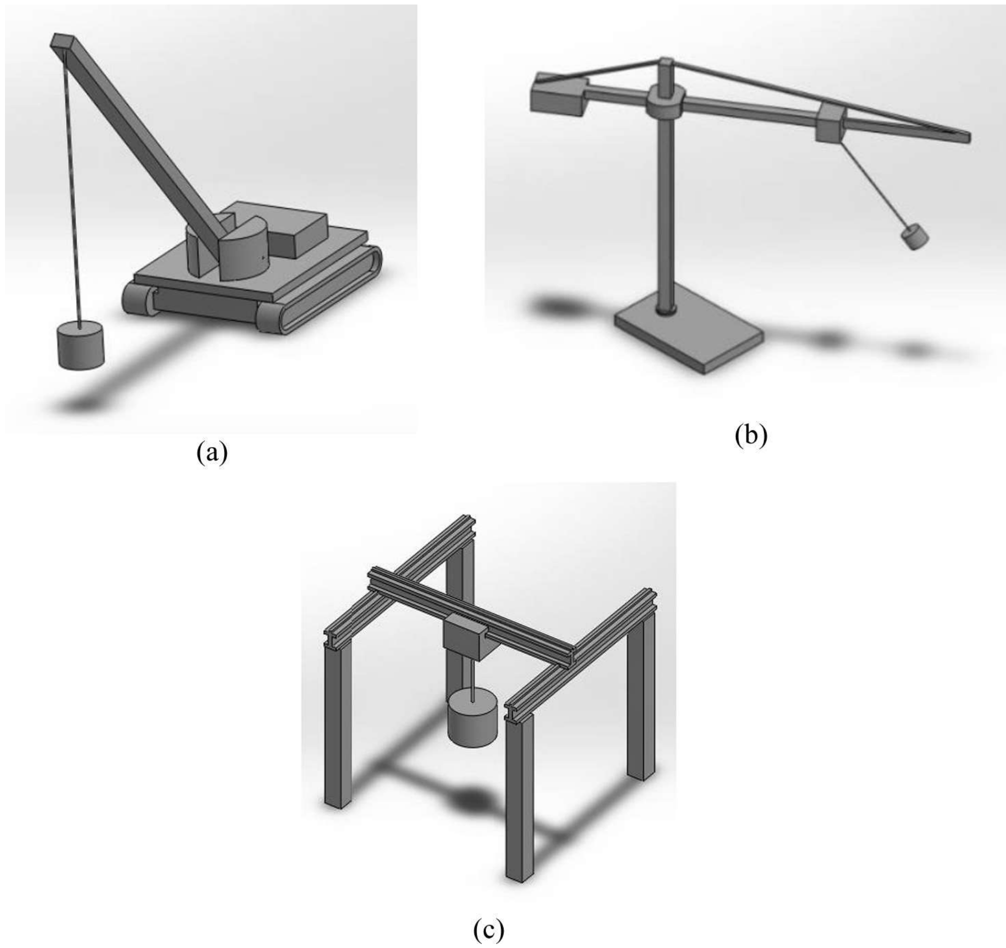

Fig. 1. Structures of (a) a boom crane, (b) a tower crane and (c) a bridge/gantry crane.

mounted on a bridge in an orthogonal position and this creates forward and backward motions. Besides, the hook can be hoisted up and down to place the load vertically. A gantry type of crane is quite similar to that of a bridge crane, except that it is mobile and it operates on a runway at floor level and it is supported by a pair of rigid steel legs. The gantry crane is commonly used in factories, shipyards and warehouses.

Meanwhile, tower (rotary) cranes have a radial motion that rotates the jib about a fixed vertical axis which is normally up to 180 or 360 degrees. The trolley moves the load along the jib in a translational direction. The hook can also be hoisted up and down. The tower crane is widely applied in the construction of tall buildings and the transportation of a huge load from one location to another location. Normally, a tower crane is located in a fixed place [3], repeating similar processes, especially on a construction site. On the other hand, a boom crane is commonly used on a ship or for constructions. It consists of a rotational motion at the base and it is attached with a boom which also moves by rotation. Similar to other cranes, a boom crane has a suspended cable in order to move the load upward and downward. Fig. 2 shows photos of the laboratory overhead and tower cranes located at the Faculty of Electrical Engineering, Universiti Teknologi Malaysia.

Cranes can be considered as being under-actuated systems where they have a lower number of actuators than degrees of freedom. This may be due to the necessity to decrease the cost, the complexity, the size and the weight of the cranes. However, this makes them difficult to control due to their complex dynamics and when they exhibit non-holonomic behaviour. The main goal in the control of a crane system is to achieve a precise trolley positioning and to eliminate the payload/cargo sway angles, such that the load can be transported in a minimum time to the destination with less or without sway. Therefore, a skilled operator is required in order to automate the crane and to compensate for the load sway motions, as the load behaves similar to a pendulum motion and it is likely to swing freely. The operator might need to slow down and properly compensate for the crane's manoeuvres, in order to dampen out the payload oscillations that may interrupt the crane's performance. If a severe sway occurs, the operation needs to be paused until it stops swinging. Moreover, the hoisting functionality of the crane is one of the challenges that is faced by crane operators, as it also hugely affects the swinging of the payload [9].

Cranes are known to have stability issues due to the oscillations of the payload and when it is accompanied by the cart/trolley motion. The relationships between the trolley and the payload oscillations are nonlinear and they are highly coupled. Moreover, external disturbances such as the wind and the presence of uncertainties may also disrupt the crane's performance. The uncertainties normally involve an unknown friction, a cart mass, a load mass and a cable's length. In fact, the

(a) Overhead Crane

(b) Tower Crane

Fig. 2. Laboratory cranes at the Faculty of Electrical Engineering, Universiti Teknologi Malaysia: (a) Overhead Crane, (b) Tower Crane.

trolley's motion and the inertia forces that are resulted from the motion could also induce the payload's oscillation [4,10]. As cranes are commonly lightly damped, any transient motion takes a long time to be dampened out [1]. Base excitations that are caused by an unstructured environment for the crane could also result in an undesirably induced payload motion. In addition, the compliance of the cable, the hook and the payload assembly, all contribute in the complex system's dynamics.

The payload sway angles or oscillations can be categorised into two components, namely longitudinal (in-plane angle) and lateral (out-plane angle). The longitudinal sway angle can be possibly suppressed by controlling the cart's motion, but control of the lateral sway direction may need a proper and effective control strategy [11]. Hence, it is desirable to design a control scheme that is capable of suppressing the load sways in both directions concurrently. Besides, in-plane and out-plane oscillations of the load may also occur when they are caused by external excitations at the suspension point due to the disturbances.

In addition, another important reason to have an effective crane control system is to ensure a safe crane operation. As reported in [12], that reviewed crane safety in a construction industry, cranes contribute to one-third of all construction and maintenance fatalities and injuries resulting in permanent disability. One of the major accidents was in Mecca, Saudi Arabia on 11th September 2015 [13]. The accident occurred in the Saudi Arabia's Grand Mosque, a few days before the Hajj season which 107 people died and more than 230 people were injured. A study by Rishmawi [14] on the crane accidents between January 2011 to October 2015 showed that the main reason for the accident was the case of the crane overturning or tipping over. Another reason reported was the case of victims struck by moving payloads. Both reasons of accidents can be related to payload sways, where payloads that swing out from a crane cause it to tip-over. Moreover, when payloads are lifted off the ground, they can swing sideways and strike people.

In the case of a large object, instead of utilising a typically used single-pendulum with a point mass payload, the use of a double-pendulum with a distributed mass payload is essential as studied in [15]. To test the effectiveness of the proposed controller, a 10-ton of industrial bridge crane was used with a slender-beam payload and a rectangle payload shape as illustrated in Fig. 3. A similar work with a distributed payload was also carried out in [16,17]. A small scale bridge crane was used with a large object that was hanged by the hook with four support cables attached to it as illustrated in Fig. 4. This hoisting mechanism creates additional angles relative to the suspension cables, as well as a twist angle, due to the payload twisting about the support cables and that need to be suppressed. Hence, the control strategy to be designed for this feature becomes more challenging and more complex, as it must include the payload swing and the twisting suppressions.

3. Modelling

In this paper, modelling is divided into a single-pendulum and a double-pendulum cranes. As the focus is on the control strategies, a brief review of modelling of the crane systems during the years from 2000 to 2016 is given. In the literature, modelling of various single-pendulum crane systems has been an established work and not much improvement was noted since the last review paper [1].

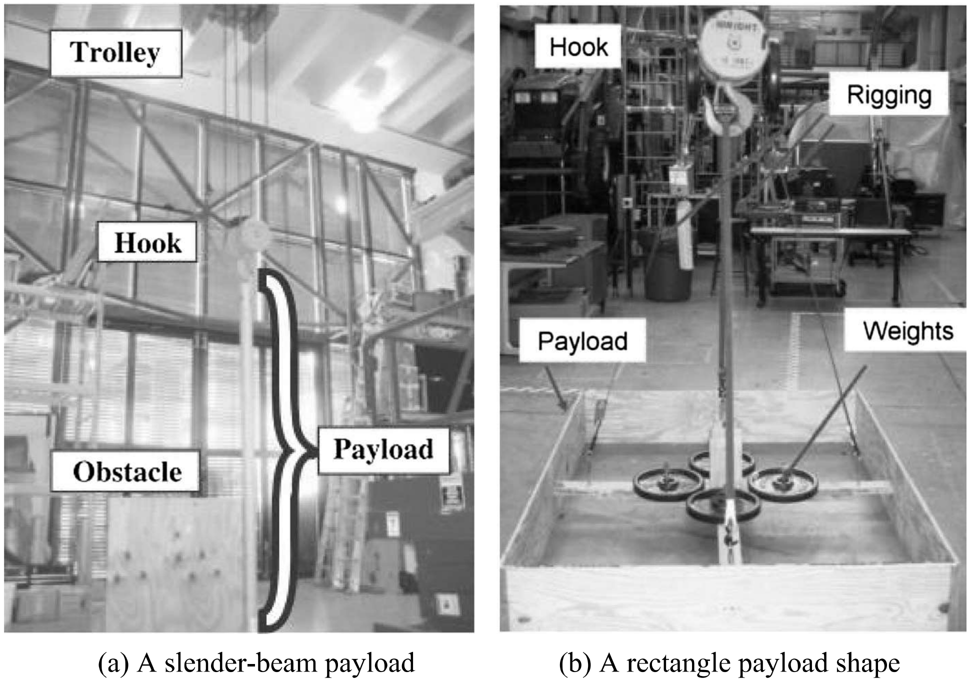

Fig. 3. A double-pendulum crane with distributed-mass payloads: (a) a slender-beam payload and (b) a rectangle payload shape [15].

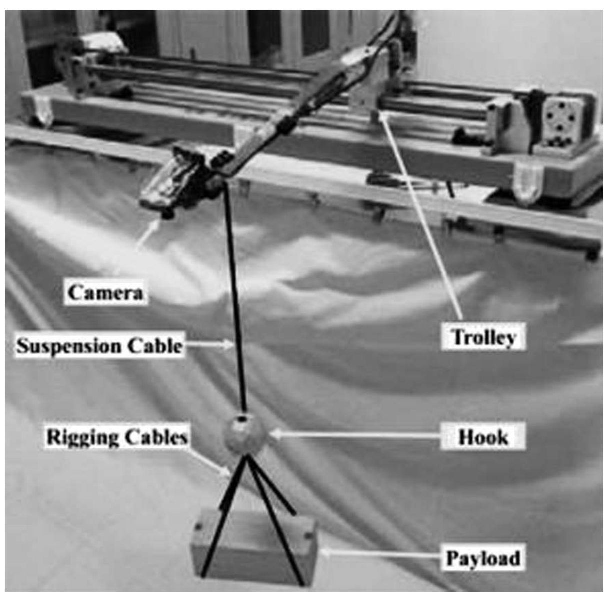

Fig. 4. A distributed-mass payload [17].

3.1. Single-pendulum crane systems

Several mathematical models of different cranes have been derived by researchers, and most of the approaches were based on the lumped mass methods. These includes modelling of a container crane [18,19], modelling of a gantry crane using the Lagrangian method [20–22], and modelling of an offshore hydraulic crane using a bond graph approach [23]. For an overhead crane, modelling was carried out by using the Lagrange approach [24–26], Takagi-Sugeno [27] and other approaches [28–30]. In [31], a method of modelling a three dimensional (3D) crane which allowed describing the energy flow was proposed. On the other hand, a rotary crane was also modelled using several approaches. These include a bond graph technique [32], finite element analysis [33], Lagrangian methods [34], and a computer based model analysis [35]. In [36], the finite element modelling was also used for modelling of a boom crane.

In order to obtain a more accurate dynamic model representing the crane systems, several researchers have considered and included several other parameters in their dynamic models. In [37], the elasticity and damping of the load-bearing steel structure as well as the friction in the main bearing, and the air resistance were considered for modelling of a gantry crane.

Good results were observed from this study. Several researchers [20,26,28–31] considered the variable length of cable in the model that simulate hoisting of the payload. In a later study, a complete model including a driver and a motor of the system was proposed by utilising both dynamic equations and curve fitting toolbox of MATLAB. The model was successfully tested on a 10-ton industrial crane [38].

3.2. Double-pendulum crane systems

For double-pendulum crane systems, it was found in the literature that the first publication for a gantry crane was in 1998, an overhead crane in 2004 [39], a bridge crane in 2006 [40], a tower crane in 2007 [41] and a boom crane in 2009 [42]. Since then, many articles were published involving modelling of the bridge and overhead cranes [15–17,43–53], the tower crane [9] and the boom crane [54]. In most of the work, the Lagrangian method was utilised for modelling of the cranes and used for a controller design. 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. However, the Kane's method was also used for modelling of a bridge crane [16,55].

In this paper, a brief formulation for modelling of an overhead crane using the Lagrangian method is given. A schematic diagram of a double-pendulum overhead crane system is illustrated in Fig. 5. The crane consists of three independent generalised coordinates namely the trolley position, x, hook angle, θ_1 and payload angle, θ_2. m, m_1, m_2, l_1 and l_2 represent the trolley mass, hook mass, payload mass, cable length between the trolley and the hook, and cable length between the hook and the payload respectively. F is an external force applied to the crane. The Lagrange equation with respect to the coordinate, q_i is

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = T_i \tag{1}$$

where L, q_i (i = 1, 2, 3) and T_i represent the Lagrangian function, generalised coordinates (q_1, q_2 and q_3 represents x, θ_1 and θ_2 respectively) and a non-conservative force respectively. By finding the kinetic and potential energies of the system, the Lagrangian function can be written as:

$$\begin{aligned} L = {} & \frac{1}{2}m\dot{x}^2 + \frac{1}{2}m_1[\dot{x}^2 + 2\dot{x}l_1\dot{\theta}_1\cos\theta_1 + l_1^2\dot{\theta}_1^2] + \\ & \frac{1}{2}m_2[\dot{x}^2 + 2\dot{x}l_1\dot{\theta}_1\cos\theta_1 + 2\dot{x}l_2\dot{\theta}_2\cos\theta_2 + l_1^2\dot{\theta}_1^2 + l_2^2\dot{\theta}_2^2 + 2l_1l_2\dot{\theta}_1\dot{\theta}_2\cos(\theta_1-\theta_2)] \\ & - m_1g[l_1(1-\cos\theta_1)] - m_2g[l_1(1-\cos\theta_1) + l_2(1-\cos\theta_2)] \end{aligned} \tag{2}$$

where g is the gravitational acceleration. By differentiating Eq. (2) and obtaining terms as in Eq. (1), the dynamic model of the double-pendulum overhead crane system can be obtained as:

$$(m+m_1+m_2)\ddot{x} + (m_1+m_2)l_1\ddot{\theta}_1\cos\theta_1 + m_2l_2\ddot{\theta}_2\cos\theta_2 - (m_1+m_2)l_1\dot{\theta}_1^2\sin\theta_1 - m_2l_2\dot{\theta}_2^2\sin\theta_2 = F \tag{3}$$

$$(m_1+m_2)l_1\ddot{x}\cos\theta_1 + (m_1+m_2)l_1^2\ddot{\theta}_1 + m_2l_1l_2\ddot{\theta}_2\cos(\theta_1-\theta_2) + m_2l_1l_2\dot{\theta}_2^2\sin(\theta_1-\theta_2) + (m_1+m_2)gl_1\sin\theta_1 = 0 \tag{4}$$

$$m_2l_2\ddot{x}\cos\theta_2 + m_2l_1l_2\ddot{\theta}_1\cos(\theta_1-\theta_2) + m_2l_2^2\ddot{\theta}_2 - m_2l_1l_2\dot{\theta}_1^2\sin(\theta_1-\theta_2) + m_2gl_2\sin\theta_2 = 0 \tag{5}$$

The details derivation of the formulations can be obtained in [56].

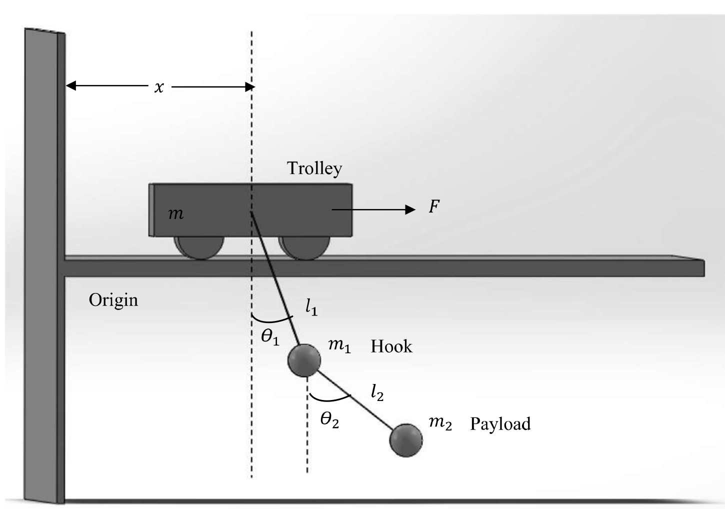

Fig. 5. A schematic diagram of a double-pendulum overhead crane.

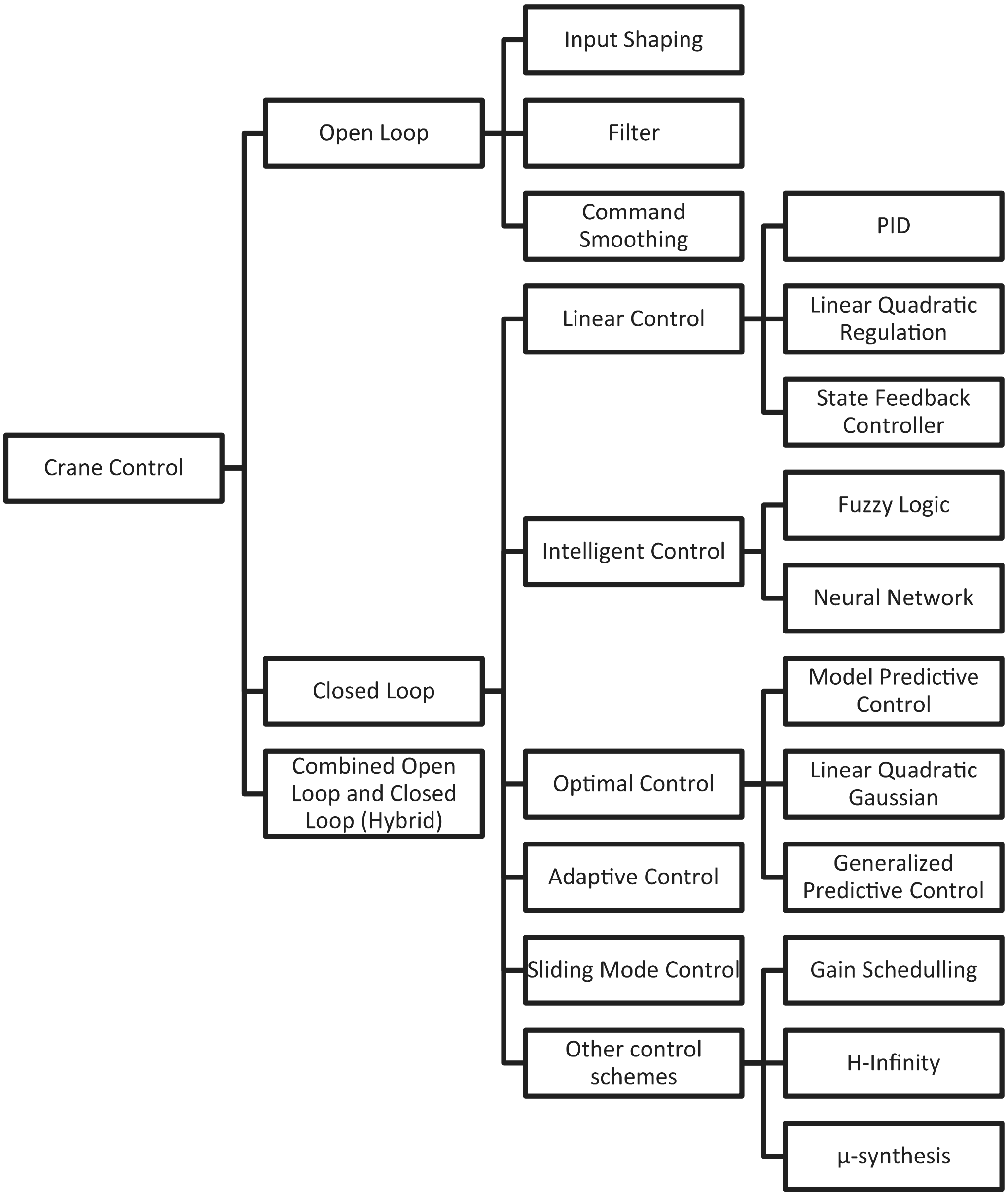

Fig. 6. Control schemes for a crane system.

4. Control schemes

In order to overcome the addressed control issues, many researchers have proposed solutions by developing several control schemes for a crane system. The developed control schemes can mainly be categorised into the open loop and the closed-loop techniques. Besides, a controller based on a combined open loop and closed-loop technique has also been proposed. In this section, the controllers are reviewed and discussed based upon these categories and they are divided into various control techniques, as shown in Fig. 6. In addition, a subsection on review of control techniques to help human operators and to prevent cranes from tipping over is also included. Note that the controller designs and their equation derivations are not within this paper's scope. Interested readers can refer to the relevant articles based on the citations provided for any further information.

4.1. Open loop control schemes

Open loop control schemes have been widely utilised by numerous researchers, mainly for control of the payload's sway. Open loop schemes are easy to implement, because there is no requirement for additional sensors in order to measure the sway angles, and this certainly saves in terms of the cost [57]. However, the main drawback of this type of technique is that it

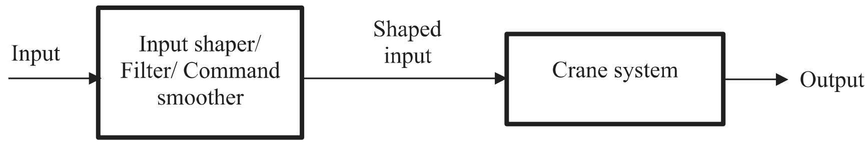

Fig. 7. A block diagram of open loop control strategies for a crane system.

is sensitive towards external disturbances [58]. An example of an external disturbance that always affects a crane's performance is the wind or an ocean wave for a crane that is used on ships. For the open loop control technique, the control input does not commonly account for the changes of the system. In this paper, the three main open loop techniques, namely input shaping, filtering and command smoothing, are reviewed. Fig. 7 shows a block diagram for the implementation of the open loop control strategies for crane systems.

4.1.1. Input shaping

Input shaping is one of the open loop techniques that can be applied in real time. This technique has been utilised pervasively by many researchers for an effective feed-forward control of minimising the motions that are induced by the vibrations or the oscillations of flexible structures such as cranes. A detailed review on control of flexible structures by using command shaping was presented in [59]. An anti-swing crane control by using input shaping has been widely implemented in the literature [60–68]. By using this technique, the system's vibration is reduced by convolving the command input signal with a sequence of impulses that have been designed based upon natural frequencies and damping ratios of the system. For gantry cranes, the implementation of input shaping for the control of a sway have been proposed in [20,38,69–71]. On the other hand, the implementations for an overhead crane include a zero vibration (ZV) and a zero vibration derivative (ZVD) input shaping [72], a zero vibration derivative-derivative-derivative (ZVDDD) input shaping for bridge cranes [53], container cranes [52,73–75], boom and pneumatic cranes [76,77], and for rotary cranes [78–80].

The input shaping technique is mostly based on a linear analysis or a linear system [9,78,81]. Unlike a bridge crane that behaves linearly, a tower crane inherently has nonlinearity behaviour, due to the tower's rotational movement. When considering a purely radial motion, the tower crane has linear dynamics. However, in practical, the tower crane involves both radial and tower rotational movements, where the payload oscillations that are induced are in both radial and tangential motions. The nonlinear behaviour of the motions comprises of moderate to high speed rotational components [78]. Hence, it is crucial for enhancing the input shaping method so that it may accommodate for the nonlinearities that are linked with the rotational motion of a tower crane system.

Input shaping has been shown to work effectively for nonlinearities with a relatively small influence on the total system's dynamics [9]. The effects of nonlinearities are more substantial for a tower crane that deals with a rotational movement. In order to tackle this issue, Vaughan et al. [9] have successfully presented a novel command shaping algorithm in order to accommodate for the nonlinearities which are more robust to the varying dynamic effects that are caused by the nonlinear slewing motion of a tower crane. The authors introduced a multimode specified insensitivity input shaper by utilising a technique that suppressed the two frequencies that were robust to the variations in the two modes. Note that the robustness can be achieved by suppressing the vibration at some point near the modelling frequencies. Hence, through this method, the designer may specify the frequency range over which the vibration is suppressed. The proposed control algorithm was also tested for its robustness by varying the cable length. The other method that has been addressed for countering the vibration that is caused by the radial and the tangential motions of a tower crane was by implementing a radial motion of the assisted command shapers [78]. Besides, this method can also be implemented on other types of cranes due to their nonlinear behaviour, such as boom cranes that contain rotational joints.

The open loop technique that is offered by input shaping is sensitive to external disturbances as well as to parameter variations [58]. Besides, it is also sensitive towards the frequency of the oscillations. Moreover, by using input shaping, the initial sway angle has to be zero, or else it may cause an in-load oscillation intensification [57]. Despite these drawbacks, input shaping is considered as being low cost, as it does not require additional sensors for a load sway measurement and it is also easy to implement [57]. Some efforts of combining several feedback control schemes with an input shaper have been proposed [82–85]. This combination allows for the controller to act in three different ways: (1) A feedback scheme that will effectively control the cart's position; (2) A feedback scheme that may also detect and reject disturbances; and (3) An input shaping that is utilised to suppress the payload oscillations. Fig. 8 illustrates a block diagram of a hybrid control strategy for the crane system. Masoud et al. [50] designed a hybrid command-shaper by generating acceleration commands to suppress travel and residual oscillations of a double-pendulum overhead crane. Verifications on a laboratory overhead crane showed a significant reduction in the residual oscillations. Recently, a combined input shaping and feedback control for a double-pendulum system which can be applied to a crane system was proposed [86]. Huang et al. [82] presented a combined command shaping and feedback control to eliminate the payload oscillation and to reduce the effect of wind gusts of a mobile boom crane. The simulation and experiment results showed that the proposed controllers were robust and may reduce the various combinations of driving motions and wind disturbances.

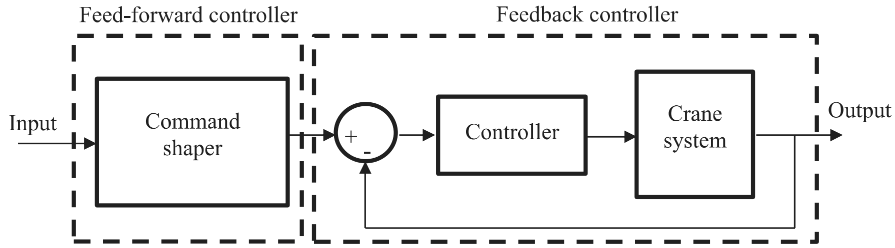

Fig. 8. A block diagram of a hybrid control strategy for a crane system.

Several other shapers which are not based on an impulse sequence have also been presented. These include an input shaping technique by using the system's output speed [87], a continuous function input shaping [88], a frequency-modulation input shaping [72] and an input shaping with a distributed delay [89]. A comparison between digital filtering and input shaping has been presented in [66]. Recently, an input shaping that can handle hoisting in a 3D crane system has also been designed by using a system output [90].

4.1.2. Adaptive input shaping

In general, most of the conventional input shapers as discussed in the previous section were designed based upon fixed system parameters. Therefore, in the case of time variant systems, or systems with parameter uncertainties, such as a crane operation with payload hoisting, in which the system's natural frequencies and damping ratios change, an input shaper that can adapt to the changes is required. In the literature, this is known as adaptive input shaping. The techniques are mainly based upon an adaptation of the natural frequencies and the damping ratios, in order to update the magnitudes and the locations of the impulses of the input shapers.

In an effort to address the effects of payload hoisting and the parameter uncertainties in crane systems, adaptive input shapers have been developed. Cutforth and Pao [91] proposed an adaptive input shaping based upon flexible mode frequency changes in order to cope with the parameter uncertainties. Furthermore, an investigation on adaptive discrete-time controls in which the amplitude and the locations of the impulses are updated in order to cater for the system's uncertainties have been studied [92]. A time domain adaptive command shaping was proposed in [93] by using a direct method, in which the coefficients of the desired command shaper can be estimated directly without a need to acquire system parameters information. In another work, the author proposed an adaptive time delay command shaping for both single and multi-mode systems [94].

To control the hoisting effect, Singhose et al. [20] have investigated an input shaping design by using an average travel length approach for gantry cranes. Other works have included an adaptive input shaping for 3D overhead cranes [95], an adaptive input shaping for an overhead crane with hoisting [96], an adaptive algorithm input shaping for variable mass and cable lengths [97], and a modified adaptive input shaping [98].

4.1.3. Filters

Several filters including the Infinite Impulse Response (IIR) filter and the Finite Impulse Response (FIR) filter have been investigated for the control of a crane's payload sway. It has been shown that the IIR filters have no precise phase and they are usually difficult to control, while the FIR filters always have a linear phase and are easy to control. Some of the investigations involving the IIR filters have been implemented for the control of an overhead crane [99], a gantry crane [100] and a rotary crane [101]. On the other hand, the FIR filter has been designed for a rotary crane [102], a gantry crane [103] and a boom crane [104]. Other studies have included a multi-input multi-output (MIMO) FIR feed-forward for a tracking control [105] and an input shaping using an FIR filter [106].

4.1.4. Command smoothing

Command smoothing is a control strategy that can greatly suppress the vibrations through smoothing the original command [53]. The smoother is designed by estimating the system's natural frequency and the damping ratio. There are several smooth command profiles that have been used in order to reduce the vibrations and the oscillations, such as the S-curve, the trigonometric transition function, the Gaussian, the spline function and the cam polynomial. Based on Xie et al. [53], the proposed command smoothing method was insensitive towards the modelling error in the high frequency range when compared to the ZVDDD that was insensitive towards the low frequency range. It was tested and verified on single and double-pendulum crane systems. The designed smoother has also been shown to work successfully on a multi-mode system for vibrational suppression. However, the smoother can only be operated in order to reduce the oscillations by a desired response commanded by a human operator. Besides, it was also unable to reject the external disturbances.

In [16,17], command smoothing was used for oscillation suppressions of a bridge crane that utilised a double-pendulum and attached with a distributed mass payload. This feature has an additional twist angle that needs to be controlled which is twisted about the cables that are attached to the hook. The designed robust smoother was a combination of a low-pass and multi-notch filter that was capable of eliminating the first and the second mode frequencies of the payload swing, respectively. It was found that by reducing the payload swing angles, a significant reduction in the twist angle was achieved. Recently, the command smoothing technique was combined with a wind-rejection command to suppress operator-induced oscillations and to reject the wind disturbance of a bridge crane with a distributed-mass payload [55]. The effectiveness of the combined control structure was validated on a laboratory bridge crane.

A comprehensive comparison of the input-shaped step function and command smoothing by using the S-curve has been carried out for reducing the payload sway angles of a portable tower crane system [107]. The result has shown that the input-shaped step function method was more effective when suppressing the oscillations and the vibrations, rather than the command smoothing. Moreover, the input-shaped step profiles were shown to be robust to the modelling errors and they were capable in moving a system faster than the S-curve command. In another work, Alghanim et al. [108] proposed a technique to generate an optimal discrete-time shaped acceleration profile for simultaneous travel and hoist manoeuvres of an overhead crane. Successful performance of the technique was validated using a scaled model of an overhead crane.

4.2. Closed-loop control schemes

The other control scheme that has been commonly designed for a crane control system has been a feedback-loop control scheme. It was a great control scheme that enabled the crane system to adjust its performance based upon the desired output response. Feedback schemes utilise the measurement and the estimation of the system states to reduce the oscillations and to obtain an accurate positioning for the system. Hence, the feedback loop or the closed-loop control schemes seem to be less sensitive to disturbances and parameter variations [109]. Fig. 9 illustrates a block diagram for the implementation of the closed-loop control strategies for crane systems. However, the feedback control systems require sensors for determining the cart's position, as well as the load's sway angle [5]. Adding the necessary sensors into the crane system couple with the difficulties in installing them requires an additional cost. Moreover, for the feedback control system, the stability issues and noise problems arise which may be very risky for such big, powerful and expensive machines. One of the drawbacks of the closed-loop system is that they are slow, due to the input delay in the feedback loop. For instance, a determination of the payload sway angle is required prior to the action of the control scheme in order to dampen out the oscillations [84]. However, a better design might result in a fast performance. Another real drawback for the applications of feedback controllers on industrial cranes is the requirement to measure the payload sway and velocity accurately. Besides, the installation of a sensor on the crane for the purpose of a feedback strategy, in conjunction with human operators, could disrupt the process, because the human operator tends to be annoyed by the motions that are induced by the computer control [9]. Two feedback controllers can also be combined in order to cater for the sway and for the tracking control, concurrently. By using this control strategy, the designer is able to handle different trajectories depending upon the working environment [109]. In this paper, the closed-loop control strategies have been divided into a linear control, an optimal control, an adaptive control, an intelligent control, sliding mode control and other control schemes as shown in Fig. 6.

4.2.1. Linear control

4.2.1.1. Proportional integral derivative. One of the linear control techniques that are pervasively applied for crane systems is the Proportional Integral Derivative (PID) control. To cater for a different cable length, the PID controller gains can be tuned based on the length. In the literature, several methods have been investigated which include the root locus technique [110] and numerous computational intelligence techniques, such as the particle swarm optimisation (PSO) [111,112]. In fact, proportional derivative (PD) type controllers have also been used in order to control the sway angles, due to their ability in tackling the oscillation problems [67,112–114].

In the literature, it has been found that most of the PID controllers were developed with the aid of other techniques, or by using two PID type controllers for control of the position and the load's sway. The position control of a gantry crane system with a sway elimination has been successfully proposed in [57] by using the Neural Network Self-Tuning (NNST) procedure as an estimator in order to tune the PD controller gains. The proposed training algorithm for the NNST was inspired by the sway elimination of an input shaper. In [2], a new neural PID controller was proposed. This was due to the difficulties when tuning the PID gains so as to yield a good system response for controlling the gantry position and the sway angles of a gantry crane. The proposed control strategy did not require large derivative and integral gains, with a guarantee of asymptotic stability system, when compared to other classical PIDs and neural PIDs. For gantry crane systems, several other works that involved with the PID controller were a fuzzy-based PID [4], a neural network-based PID [2,115,116], a PSO-based PID

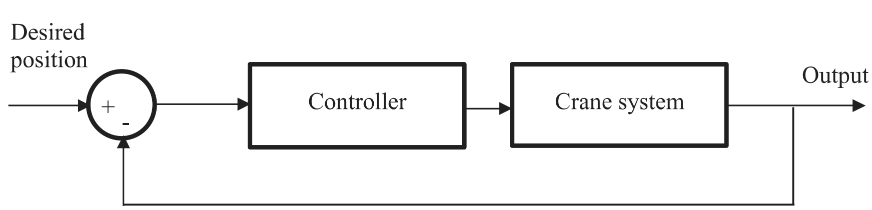

Fig. 9. A block diagram of a closed loop control system for a crane system.

[111,117], an intelligent combination of a PID controller with input shaping and a multi-objective optimisation approach [83], and a genetic algorithm (GA)-based PID [118].

PID controllers have also been designed for a rotary crane system. A significant reduction in the system's swaying, with an elimination of the disturbance effects, has been achieved with the PD-type fuzzy logic when compared to the LQR controller [5]. The authors also compared the performance of a PD-type fuzzy logic with a PD controller for an active sway angle control [113]. The simulation results showed that the sway angles were significantly reduced by using the PD controller when compared to the PD-type fuzzy logic. However, in terms of the speed of the response, the PD-type fuzzy logic performed better. In another publication, the authors designed a hybrid collocated PD with a non-collocated PID (PDPID) and compared it with a collocated PD for controlling the sway angles and the input tracking capability at the resonance mode of the pendulum sway [110]. It was demonstrated that the PDPID showed better results with a reduction of the sway, but it was slower in the tracking response, with a higher overshoot than the collocated PD controller.

Kawada et al. [119,120] concluded that the PD controller was useful for controlling a lifted load for a mobile crane. However, it was difficult to find a set of suitable control parameters in the case of time varying and/or nonlinear systems. Thus, GA was implemented to obtain the optimal parameters for the controller gains [114,121].

4.2.1.2. Linear quadratic regulator. A Linear Quadratic Regulator (LQR) has been used for the control of crane systems. Yang and Xiong [122] applied an LQR method for the anti-sway control of an overhead crane. A parametric formula technique was used in order to solve the LQ inverse problems when finding an appropriate weighting matrix, Q. The LQR method has also been utilised for the anti-sway control of a mobile harbour crane [123]. The crane had an additional feature installed that was named a micro trolley which added two DOFs in order to suppress the swing of the container due to the wave induced motions. The main objective of the proposed control was to reduce the trolley's position error that was based on a cost function with three weighting factors, namely a control input, a trolley position error and a relative motion between the trolley and the container positions. As proposed by Adeli et al. [124], a parallel distributed fuzzy LQR controller that was combined with a GA was designed for the anti-sway control of a double-pendulum type overhead crane. A fuzzy controller was used in order to minimise the upper bounds of the quadratic performance function, whereby a GA was utilised in order to only select the important rules among all of the rules generated. The simulation results showed a satisfactory and faster response.

Another linear controller that has been used was a state feedback controller as implemented in [125–127] for a boom crane system in order to control the load sway angles in vertical and horizontal boom motions, as well as in the vertical and horizontal boom angles. In [128], a state feedback controller was utilised in order to achieve a robustness with respect to a rope length's variation and a linear matrix inequality (LMI) approach was formulated. However, the design of a linear controlled system requires for a linearised crane system which may be insufficient in terms of the precision of the model's representative. The nonlinear factors, such as the wind, the cable length's variation, the load mass and the trolley friction of the crane system were not included. All these factors may influence and minimise the reliability and the performance of the linearised model.

4.2.2. Optimal control

Optimal control is known as a strategy in which a control signal optimises a certain cost index. The control strategy was first introduced as an open loop scheme in order to design an optimal sequence control. There are two optimal control strategies that are regularly applied in industries, namely a Linear Quadratic Gaussian (LQG) control and a Model Predictive Control (MPC). This is due to their assurance in closed-loop stability.

4.2.2.1. Model predictive control. A Model Predictive Control (MPC) has become one of the most popular multivariable control algorithms owing to its advantages in dealing with constraints, its capability of utilising simple models, its closed-loop stability assurance and its robustness against parametric uncertainties [129]. An enormous amount of research has been carried out and has been reported by using an MPC for controlling gantry cranes and overhead cranes [129–133]. The MPC-based schemes for a constrained under-actuated state (the swing angle) were also presented in recent papers [134,135]. The optimum methods for an MPC controller have depended upon the desired criterion function that was selected by the designer. Much of the research for MPC controller designs has mainly focused on the position control and a sway angle reduction. For instance, Jolevski and Bego [130] have considered two criteria functions that have indicated the tasks of positioning the cargo to a target position in a minimum transfer time and with a prevention of the cargo sway that was caused by the cargo's acceleration together with external disturbances. In order to obtain a solution for the criteria functions or the objective functions of the MPC, multi-criteria optimisation was utilised where the contribution of the individual functions was defined by its weight in order to achieve an optimum control signal.

In terms of the MPC's robustness, the concept of moving the horizon based on the next sampling step was applied in which the optimum future control signal was defined by the predictive horizons. As proposed by [129], instead of expecting the cargo to arrive quickly towards its end position and reducing the sway angles of the overhead crane, an energy efficiency can also be included in the objective function such that the crane consumes a low energy. A feedback strategy with a new objective function that was based on energy efficiency and safety were formulated to find the optimal solution. An industrial application of MPC was demonstrated in [136] by using the LIEBHERR harbour mobile crane (boom crane) and it was shown that the controller has a remarkable capability for anti-sway and tracking control with a synchronous luffing and slewing movements. The work was further enhanced with an additional feedback loop to increase the robustness of the control system [137].

MPCs have also been implemented for the control of tower cranes [138,139]. In [138], an MPC was used in order to generate an optimal position reference signal. This was combined with a cascade control in order to track the reference position, and thus, it reduced the payload oscillations and rejected the disturbances while taking in the effect of rope length variations. In [139], an MPC was designed and implemented on a laboratory tower crane. In addition, Kimiaghalam et al. [140] implemented the MPC to improve robustness and to control the induced payload swing of a shipboard crane. The algorithm was combined with a feedforward control to minimise the displacement of the load in a horizontal direction.

4.2.2.2. Linear quadratic gaussian and Generalized predictive control. A Linear Quadratic Gaussian (LQG) optimal control has been proposed in order to reduce the payload swings of an overhead crane [141]. In this proposed control strategy, a quadratic derivative of a state variable term was added into the common standard performance indexes of the LQG for both the control and the estimation. This additional term gave an extra weighting function to be designed in order to minimise the given performance indexes. The results showed that the assigned additional weight could be used in order to reduce the swing angles. Two types of controllers, LQG and the Generalized Predictive Control (GPC) were successfully applied and compared in [142,143] for controlling the load pendulation of an offshore crane.

In [144], the GPC based control strategy was also developed and implemented on an overhead system by taking into account the swing constraint of the crane to ensure the payload swing within the allowable range. The proposed controller aimed to enhance the robustness against the variation of operating conditions subject to rope length and mass payload, as well as for reducing the residual vibration and limiting the transient oscillation. An online estimation by using a recursive least square method was used to estimate the dynamic model parameters. As measurement of payload deflection is hard and costly, a sensorless approach was proposed by using the GPC algorithm with a fuzzy interpolator. The developed techniques were implemented on a laboratory scaled overhead crane. Furthermore, the GPC and PSO algorithms were proposed in [135] to solve a constraint optimisation problem at each step time which minimise the cost function based on lower and upper bounds of control signal and payload deviation.

4.2.3. Adaptive control

An adaptability towards the parameter uncertainties and the external disturbances of the system has been widely investigated by using an adaptive control method as proposed by numerous researchers in [145–152] for overhead crane systems, and in [153] for a tower crane system. An adaptive control has the capability of estimating these parameter uncertainties in the sense of a Lyapunov-based control design. Hence, this advantage could motivate the design of those control schemes that are based on a nonlinear model which represents nonlinear systems precisely [145]. An adaptive control for an under-actuated overhead crane in the presence of parametric uncertainties was designed in [148]. The adaptation against the presence of uncertainties by using an adaptive control method has shown that it was capable of achieving a precise cart position and eliminating the residual swing. The method has offered an effective control strategy due to its instantaneous feedback scheme for the robustness of a control system.

An accurate position of the trolley and a reduction of the sway angles are the main targets in a crane control system, but the effect of a hoisting motion is also crucial to be included and to be incorporated into the control strategies. By considering the hoisting motions or the rope length variations within a trolley position would lead to an increased working efficiency. Thus, it is one of the important requirements in a crane control system. A nonlinear adaptive control of an overhead crane while taking in the effects of load hoisting was proposed in [145,150]. In the articles, an adaptive control that employed an adaptation of unknown plant parameters including friction forces and an unknown payload weight was constructed. An adaptive tracking controller for a double-pendulum overhead crane was also proposed by [51]. The asymptotic stability of the system was assured by Lyapunov techniques and simulation results showed that the proposed adaptive controller was robust to system parametric uncertainties and external disturbances.

Besides, Model Reference Control (MRC) has also been addressed in the literature due to its robustness to the system uncertainties and nonlinearities. Numerous MRC applications have been focused on the state tracking control but fewer on the issues of the control effort. Recently, both criteria were considered in [154], in which an input shaping was combined with the MRC (IS-MRC) to enhance the robustness in suppressing the hook and payload oscillations for a double-pendulum crane. The input shaped enhanced the MRC robustness by reducing the complex behaviour of the states of the reference model and the plant. The controller was implemented on a bridge crane and showed an effective reduction of the hook and payload oscillations. The IS-MRC has also been implemented on a lab-scaled tower crane system [155]. The robustness of the IS-MRC was further improved in [156] while maintaining satisfactory tracking and control effort.

Moreover, numerous works that have combined the adaptive control scheme with other control schemes have also been reported. These have been proposed in order to enhance the robustness of a control strategy, as well as the requirement for producing a high quality controller, in order to control the under-actuated cranes with less of a payload swing. For instance, a combined Model Reference Adaptive Control (MRAC) and a Sliding Mode Controller (SMC) were designed for an overhead crane in [157] to achieve robustness and to ensure uniform system responses against the variation of system parameters. The proposed controller did not require a priori information of the uncertain parameters, such as the payload and the friction, due to the adaptation of the controller to estimate those values automatically. Some other combinations of an adaptive control with other control schemes have been an adaptive fuzzy sliding mode controller [158], an adaptive back-stepping control [159], a fuzzy adaptive PID controller [4], a motion planning-based adaptive control [147], and a direct adaptive fuzzy sliding mode proportional integral tracking control [160].

4.2.4. Intelligence control

Numerous intelligent controllers have been utilised for crane systems. These controllers have been mainly based on Neural Network (NN) and fuzzy logic controllers.

4.2.4.1. Neural network. One of the remarkable intelligent controllers that have been applied in crane control systems is the Neural Network (NN). The use of an NN has been significant as an intelligent approach in order to counter the problem of mathematical models. An NN has a good nonlinear processing ability and a robustness with an inherently parallel architecture [3]. Moreover, an NN is robust to a cable length variation and the uncertainty, by implementing a feedback scheme [57].

Numerous researchers have implemented an NN for an overhead crane system. The work by Lee [161] has proposed a combination of an NN and an SMC, in order to achieve a precise trolley position and to eliminate the payload sway angles. An SMC has been used as a self-tuning algorithm for the purpose of tuning the proposed NN parameters. The other applications of an NN have been a self-tuning NN [162], a Radial Basis Function Network (RFBN) with a PSO as a learning algorithm for the trolley positioning and the sway eliminations [163], and the Recurrent Neural Network (RNN) with a gradient descent method for the online tuning of the RNN parameters [164].

For the case of a rotary crane, various feedback control schemes for reducing the payload swing have been implemented. However, such control methods are only capable of lessening the payload swing in a circumferential direction, not in a radial direction. One of the approaches that has been used to solve this problem has been by utilising a linear feedback law and a switching between the two modes of radial and circumferential directions. As a consequence, this method has required knowledge of difficult control theories and also has been unable to control the swing angles for the crane's rotation higher than 90 degrees. To address this problem, Nakazono et al. [165] proposed a NN controller with an evolutionary computational training that was able to control the load swing in both the circumferential and the radial directions, concurrently. Moreover, the proposed algorithm was effective and simpler to realise than a conventional controller.

A hybrid evolutionary algorithm was proposed in [3] in order to control an under-actuated three-dimensional tower crane system by using an RNN. The hybrid approach of an evolutionary algorithm was designed by embedding the genetic operators of the GA (crossover and mutation) into the PSO in order to create an offspring with a consideration of the parent's selection that was based on fitness results. The hybrid algorithms were utilised in order to construct an RNN-based controller. It demonstrated a good performance as it was able to drive the system to a desired point. A recurrent NN was also designed for a rotary crane system [166] and it showed that the recurrent NN was superior when compared to a feed-forward NN. Furthermore, the artificial NN was proposed by Drag [167] to control the position of the payload of a shipboard crane and good results were achieved.

4.2.4.2. Fuzzy logic controller. A Fuzzy Logic Controller (FLC) has also been utilised pervasively in many crane control systems. An FLC has a strong adaptability and it was not required to obtain an accurate model of the controlled object due to its intelligent method [4]. As the systems became more complex, such as the crane systems with nonlinearities, it was hard to obtain the mathematical model. Hence, an FLC has a benefit, as it replaces the role of a mathematical model with a fuzzy model, based on the rules constructed in an if-then format. Moreover, it was also good in dealing with unstable and complex machines, with nonlinear systems, and with optimal point control problems [168].

An FLC has been widely utilised in order to control the trolley's position and the load swing angles for gantry and overhead cranes [109,144,168–174]. In [175], a fuzzy logic-based robust feedback anti-sway control which can be applicable either with or without a sensor of a sway angle was proposed and verified on a laboratory overhead crane. In [176], an NN was utilised with an FLC in order to perform as a neuro-fuzzy controller for a 3D crane system. The main approach of the proposed control strategy was the use of a sliding mode theory as a learning algorithm in order to tune the neuro-fuzzy parameters. In other work, Li et al. [177] have proposed the combination of an NN and a fuzzy on a special crane system. The learning algorithm that was adopted for the neural fuzzy controller was based on an ant colony optimisation and showed a fast convergence performance when compared with the back propagation algorithm.

Besides, an FLC can also be used to tune the PID gains and the strategy was known as a self-tuning fuzzy PID controller [4]. The output signals from an FLC have been used to fine-tune the PID parameters. This strategy may lead to a precision control in terms of a performance response that is better than the conventional PID controller. In addition, an input shaping based FLC has been proposed by [178] for a double-pendulum type overhead crane. Input shaping as a feed-forward controller was designed in order to optimise the control command that was generated by a fuzzy control. The article addressed the method in order to avoid the exponential rule explosion of an FLC by applying single input rule modules. The proposed method has shown feasibility, validity and robustness, as an anti-sway control for an overhead crane.

The implementation of an FLC in rotary/tower crane systems was proposed in [34], in order to control the position and the tip displacements of the flexible link that resembled the structure of a tower crane system. The sway angles of the pendulum that were attached to the link were also controlled. A hierarchical artificial NN-based adaptive FLC has been employed where it had two subsystem controllers for the position control and the vibrational absorption control. Some other applications of an FLC for tower cranes have been an anti-sway control with delayed uncertainties by using a robust adaptive fuzzy control [179], an anti-swing controller by using a fuzzy clustering technique [180], an FLC by adopting two independent subcontrollers that were responsible for controlling the radial and the rotational movements of a crane [181,182], and an anti-swing control by using an FLC in which the rules have been obtained by mapping the performance of a time-delayed feedback controller [109].

4.2.5. Sliding mode control

Due to its known robustness, the Sliding Mode Control (SMC) has attracted researchers in many diverse fields, including those in crane control. The approach control method of an SMC is suitable to be utilised for crane systems as it is effective under uncertainty conditions. Despite this remarkable benefit, it is also known to be robust and very accurate [183]. Numerous publications on SMC have been reported for the control of overhead crane systems [184–186]. There are plenty of SMC designs, including a terminal SMC [187], a second order SMC for a container crane [188], a second-order SMC for a 3D overhead crane with uncertain parameters [189], a hierarchical SMC [56], an integral SMC [190], and a discrete time integral SMC [191].

It has been shown that the SMC offers a promising control scheme for rejecting the uncertainties and the nonlinearities of the system. In [192], an offshore crane was controlled by using a second order SMC. The advantage of designing a higher order SMC when compared to a first order SMC is that it is capable of removing the relative degree restrictions. It also manages to eliminate the chattering with a proper design. This is due to a high frequency control switching [183,192]. In [193,194], an SMC was also used to control an offshore crane. Moreover, Vázquez et al. [195] implemented a second order SMC to control the asymmetric cylinder position of hydraulic system for a mobile hydraulic crane.

An SMC has also been combined with other control schemes in order to achieve a higher precision and robustness. The hybrid designs for crane systems have been an adaptive SMC [186,196], a fuzzy SMC [197–200], a combined input shaping and SMC [201] and a neural-based fuzzy SMC model [202,203]. Most of these approaches have aimed at suppressing the presence of uncertainties in crane systems including the cart mass, the payload mass, the flexibility of the cable, and wind disturbances.

4.2.6. Other control schemes

This section discusses several other controllers including gain scheduling, H-infinity and μ-synthesis that have been utilised for the crane control. Omar and Nayfeh [204] proposed a gain scheduling adaptive feedback control for controlling a tower crane in translational and rotational motions with taking effects on a wide range of cable lengths and loads. Hence, to adapt the variations of those parameters and to achieve a good system performance, the gains of the feedback controller were adjusted based on the criterion in which the settling time of the system should be equal to the period of load oscillation. The work was further enhanced in [69] which included a friction in the controller design in order to improve the system performance. A friction compensation technique was used to estimate the friction and an opposite control action was later utilised to eliminate it. Experimental study showed that the load sway was damped significantly as compared to the system without the friction compensation. As the process to determine appropriate gains always a time consuming and requires a skilful designer, a gain scheduling design through a fuzzy clustering technique was proposed by Sadati [180]. In the approach, the scheduler was designed based on the clustering results. It was shown that the application of fuzzy logic to gain scheduling was feasible, not expensive and easy to implement.

Furthermore, an H-infinity robust control has also been applied for the control of cranes. These include an H-infinity control for a rotary crane [205], a multi-objective H-infinity control for an overhead crane [206], an H-infinity control by using a graphical LMI region for a gantry crane [207], and an H-infinity for the point control of an offshore boom crane [208]. In [209], a variable structure control in conjunction with a μ-synthesis control scheme has been studied for the oscillation control of an overhead crane system. Other work includes a wave-based robust control for the vibration control of a gantry crane system [210], a robust control of a gantry crane system with payload hoisting [211], and a robust control with viscoelastic properties and hoisting for ship-mounted crane containers [212]. Recently, an error tracking control method for an overhead crane which did not require a zero initial payload swing angle was proposed [213]. Simulation and experimental results showed that the controller was robust over different cable lengths, desired positions, initial payload swing angles and external disturbances.

As studied in [11], offshore container cranes and shipboard cranes were exposed to a diversity of disturbances, namely wave and wind induced movements, which comprised of heave, roll and pitch motions of the mobile harbour. Consequently, the vibratory or surge effects of the ship that are induced by ocean waves may result in a collision between the cargo and the deck. Besides, offshore cranes involve parameter variations, such as changes of the load during the processes of stevedoring. Therefore, several other controllers have also been proposed for control of these types of cranes. Akiyama et al. [214] showed that by using a proper mathematical model, their restoring force of ship gave a large influence on the load sway. However, the control design was implemented on an actual shipboard crane by using a trial and error method. Suthakorn and Parker [215] explored the inverse kinematics based approach and an SMC strategy for reducing sea state induced payload swing for shipboard robotic cranes. This control strategy was used to facilitate faster "ship-to-ship" payload transfer in rough sea conditions. In [216], Straight Transfer Transformation (STT) was proposed to reduce the load sway by using simulation analysis. In another work, a novel control mechanism based on energy dissipation was developed for sway control of shipboard cranes [217]. The effectiveness of the proposed methods for damping out pendulation was verified through simulation studies. Jeng et al. [218] examined the outrigger force for a mobile crane based on a linear programming optimisation to ensure safe crane operations. In [219], a model-based optimal control for payload position of a mobile harbour crane was proposed, and the controller was efficient in a high frequency region.

4.3. Control of other issues

This section reviews various approaches used to control several other issues in crane systems which include feedback control with human operators, control techniques to prevent cranes from tip-over and techniques to control bouncing payloads during hoisting. These issues should also be considered to achieve a safe and excellent system performance.

4.3.1. Feedback control with human operators

Almost all cranes are controlled by human operators and therefore, the crane control system needs to be compatible with the operators [67]. In addition, the human operator is a feedback controller and their performances can vary widely from task-to-task and from operator-to-operator. Fig. 10 shows a block diagram of a crane control system with a human operator. In this case, the crane control problems are solved by the experience and intuition of expert and highly skilful operators. However, this is a challenging work, since the operator must execute the tasks while considering both work efficiency and safety [220]. Therefore, an auxiliary control schemes may be added to human-operated cranes to help the operators and improve the system performance [221]. Several investigations into this issue have been conducted by researchers at the Georgia Institute of Technology, USA. Their work mainly involved on the development of input shapers to help human operators operating the crane and verifications were performed by using a 10-ton bridge crane.

The input shaping techniques were developed in [67,221,222] to help the operators operating the bridge cranes. Experiments showed that operators performed manipulation tasks faster, safer and more effective with the input shaping [221]. Furthermore, a zero overtravel input shaper was designed to reduce an overshoot in a human-operated crane [222]. In [67], the input shaping controller was shown to perform better than the PD-control, with a lower average completion time and less energy consumption. The performance of the input shaping to help operators driving double-pendulum bridge cranes was also studied in [45,47,48,223]. Experimental results demonstrated the advantages of input shaping where the operators can drive the crane much faster and safer. In a practical application, cranes are also used to swing wrecking balls that demolish unwanted building and other structures, and the goal is to increase the pendulum swing. To achieve this goal, a method that aids an operator in maximising the swing of a crane payload was also designed and verified through numerous simulations and experiments [224].

In industries, a push-button pendent controller is widely used to operate a crane system. In [225], several user interfaces for a touchscreen crane controller were evaluated. Experiments conducted with an operator showed that the touchscreen controller can be effectively used to control a crane when compared to a standard controller. As a payload significantly lags behind their control inputs given by a human operator, a control method that aids the operator by graphically displaying a prediction of where the crane will stop was proposed in [226]. The combined predictive user interface elements and input shaping control demonstrated an improvement of the crane's performance in terms of task completion time and positional accuracy. In another work, a new interface that allowed human operators to drive a crane by moving a hand-held device (wand or glove) was developed in [227]. Experiments with two operator studies on the 10-ton industrial bridge crane demonstrated that the proposed hand-motion crane control was faster and safer than using a standard push-button pendent control.

In [228], a semi-automatic control system was proposed to check and revise the reference trajectory given by a human operator for an obstacle avoidance of an overhead crane. Even if the operator conducted errors in the joystick manipulation, the developed system can avoid the obstacle automatically. A haptic control system which can easily and safely transfer a load without colliding with obstacles for a rotary crane was also proposed [220]. In another work, a crane system which reduced the operator's burden by power assist and facilitated the intuitive operation of a heavy load was developed [229].

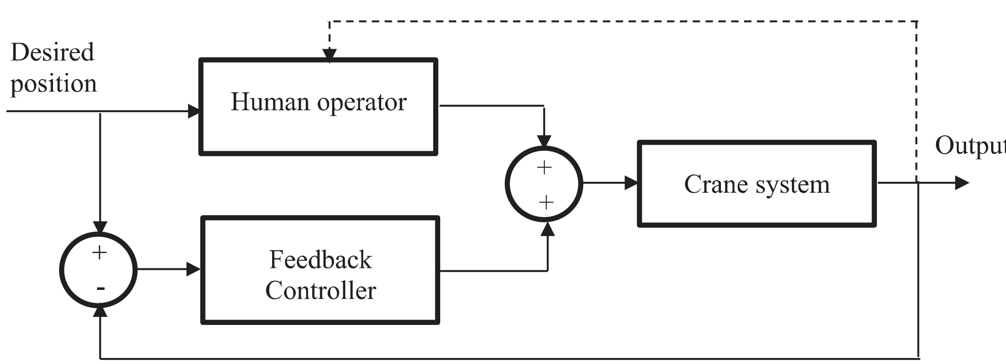

Fig. 10. A block diagram of a crane control system with a human operator.

4.3.2. Control of tipping the crane over

The case of crane's tip-over is among the main reasons for crane accidents [14]. Several efforts have been proposed to prevent cranes from tipping over. Abo-Shanab and Sepheri [230] revealed several case studies on tip-over response and gave several factors that affect the tip-over stability. These include load lifting/swivel and ground failure condition. In [231], the authors developed a model for studying the tip-over stability of a typical heavy-duty hydraulic log-loader machine. The simulation results showed that the flexibility of the base and ground contact minimises the machine stability, while the flexibility at the manipulator joints due to the hydraulic compliance improves the machine stability. Rauch et al. [232] conducted a stability analysis to find a solution of the payload weight and crane configuration that affect to the tip-over. A simple semi-dynamic analysis was studied and provided good approximations for the tip over stability and in order to handle payload swing. This method was also tested on a mobile boom crane with double-pendulum payloads [233].

In [234], the position of the movable counterweight was studied by using a stability safety factor method. By using the method, the minimum and maximum suitable positions that may keep the crane in a balance and safe conditions were calculated. Rishmawi [14] studied on the alternative tip-over stability methods for a movable counterweights and tandem lifting (two identical cranes lifting a shared payload). A method to determine the limits of the counterweight position that prevent forward and backward tip-over was proposed. Static and pseudo-dynamic stability was used to calculate the reliable prediction of the movable counterweight and some guidelines to make tandem lifting safer and less susceptible to tip-over accidents were provided.

4.3.3. Control of bouncing payloads during hoisting

To provide a safe crane operation, a case where a payload bounce during hoisting should also be considered. When a payload is heavy and the suspension cables are long, cable flexibility results in bouncing oscillation in the hoisting direction. Although many controllers have been designed to reduce the pendulum swing, less consideration has been given to this kind of problem [235]. Bouncing motions of the payload cause safety hazard and difficulty in accurate positioning during unloading operations. In the literature, this issue was investigated in [235,236]. A single-mode and a two mode input shaping were designed to control the bouncing motions of a payload during hoisting. Simulations were conducted based on a silo crane developed for handling the radiological waste containers at the Korean Radiological Repository, and experiments were performed on a portable tower crane at the Georgia Institute of Technology. The simulation and experimental results revealed that the designed input shaping was very effective at eliminating the payload bouncing motion.

5. Anti-sway control systems for industrial cranes

As crane control is important to increase productivity and safety, numerous companies have developed anti-sway control systems that may control the industrial cranes efficiently and eliminate the swaying load. Most of the products aim to speed up the handling time with an automatic operation of the crane system, and to decrease the crane's operator work burden so that the operator can fully focus on positioning, grabbing up and placing down the load. Table 1 provides a list of several companies and brief descriptions of their anti-sway control systems available on the market.

6. Key difficulties and future research directions

This section discusses the key difficulties and some future research directions that may be beneficial for researchers to embark into this research area.

As safety is an important criteria in the crane operation and crane tip-over is still the main reason for accidents, research on crane control to prevent cranes from tipping over can be further investigated. Besides the improvement in the mechanical structure of cranes, accurate measurement and control may greatly help to prevent from forward and backward tip-overs. In addition, efficient control algorithms for a precise positioning and low payload sway that take into account a moveable counterweight of a crane can also be explored.

It has been observed that recent research works are still lacking on the considerations for model uncertainties and parameter variations, together with the effects of external disturbances such as wind and sea wave in their control strategies. These issues are common in industries and they have significant effects on the crane's performance. Therefore, these factors should be taken into account when designing controllers for the implementation on actual cranes. A controller which is robust and insensitive to the parameter uncertainties and external disturbances is needed and, in this case, the SMC method seems to be the most effective method to tackle the problems. The performance of the SMC can be further improved by incorporating with an adaptation mechanism for the future research implementation.

The open loop control techniques including input shaping and command smoothing have been shown to be effective and practical for payload sway reductions of cranes with single- and double-pendulum dynamics. With the model uncertainties, parameter variations and external disturbances, adaptive and robust type of input shapers and command smoothers that can adapt and handle to the changes in the dynamics of the cranes need to be designed. In this case, fast and accurate online identifications and estimators of the crane's natural frequencies and damping ratios can be investigated. Thus, the shapers and smoothers can be updated to achieve a uniform performance under all conditions. Moreover, for double-pendulum cranes, robust multi-mode input shapers and command smoothers can be further explored.

Table 1
Anti-sway control systems available on the market.

Company	Product	Description
SIEMENS	SIMOCRANE Sway Control System [237]	The sway control system is based on calculations of a mathematical oscillation model. When a camera is used, the parameters hoisting height, swing angle and rotation angle are determined by means of optical contact-free measurement, and are incorporated in the calculation model. If the measuring signal of the camera fails, only the states of the model are used The axis is controlled in such a way that the load sway is eliminated not only when the maximum speed is reached, but also at the target position
MAGNETEK	Electromotive Systems' anti-Swing Control (ASC) [238]	The Electromotive Systems ASC consists of a stand-alone microprocessor-based controller operating sophisticated swing control software The controller uses a key pad with a digital display for entering information about the dynamics of the mechanical system. Load height information is obtained via an encoder (or other device) which is sent to the input terminals of the ASC controller. The software then sends an optimised speed reference signal to the appropriate adjustable drive (bridge or trolley motion) to prevent swing
CAMotion Inc. and PaR Systems	**EXPERT**OPERATOR Crane Controls [239,240]	**EXPERT**OPERATOR is a hardware module that intercepts pendant commands from the operator and converts them into expert commands. Then the modified commands are issued into crane to eliminate the cable sway The system does not require encoders, zone sensors, or other length measurement devices
KONECRANES	DynAPilot Sway Control System [241,242]	The Sway Control System is based on a travelling inverter control unit to help provide precision for load handling and to increase efficiency The control system calculates the optimal acceleration path using load height information and operator commands to detect and curtail load sway before it happens. The system also lowers the probability of grab collisions with walls and nearby equipment, protecting the load and reducing downtime and costs for repairs and clean-ups
ABB	ACS880 Drives with anti-Sway Control [243]	The control program creates a mathematical model of the crane's pendulum. It estimates the pendulum's time constant by continually measuring the hoist position and load properties, and factors in the swing velocity and angle When the operator changes the speed of the crane's travel, the drive quickly recalculates the required speed reference to compensate for the crane's speed change, preventing the load from swaying
SmartCrane LLC	AntiswayComplete [244]	The SmartCrane anti-sway control translates operator commands into carefully timed acceleration patterns that are transmitted in real time to a crane's PLC. These patterns vary only slightly from the operator's stick control or from a simple speed ramp, but the difference is enough to cancel out any sway resulting from the motion of the trolley

It was also found in the literature that the number of publications related to tower and rotary cranes was quite low when compared to those publications that related to gantry and overhead cranes. This may be due to the difficulties of controlling such complex under-actuated mechanical systems with a coupling that is between translational and rotational motions. Furthermore, a combined payload sway in the radial and tangential directions need to be controlled. It is envisaged that there are many research opportunities when designing effective controllers for tower and rotary types of crane. On the other hand, the implementations of controllers on real industrial cranes are desirable instead of using laboratory cranes, as the results will be more practical. For example, Neupert et al. [137] tested the developed MPC controller on a real mobile harbour crane.

Besides, an enormous amount of work has concentrated on crane control that was based on a single-pendulum with a point mass payload, when compared to a double-pendulum payload. In practical applications, crane systems with double-pendulum dynamics are essential to be considered especially when a large payload is used. A large payload can be modelled as a distributed mass payload and suspended from a hook. This case considered different hoisting mechanisms, and resulted in different system dynamics. Apart from transporting different payload/cargo masses, crane systems are also used to transport payloads with various shapes, which resulted in complicated system dynamics. This would be interesting to be studied in the future. With all the difficulties, the challenge in control of cranes with double-pendulum dynamics dramatically increased as compared to the case with single-pendulum cranes. An approximation to the original nonlinear dynamic equations might be needed for design of an effective controller. Moreover, another practical issue in control of a double-pendulum crane is the difficulty in obtaining an accurate payload angle and its location, as installation of a suitable sensor is difficult. The relationship between the hook and payload motions can be studied, and a controller based on the hook motion only or a sensorless method may also be explored in the future.

Many research works have investigated hybrid control techniques which have combined an individual control method with other control schemes. These approaches have been proposed in order to achieve a precise cart positioning and with a low payload oscillation, concurrently. One of the effective techniques is by using a combined feedback controller and a feedforward controller based on an input/command shaping technique. In this research area, further investigations can be conducted on the use of input shaper and command smoother inside the feedback loop for crane control. With this configuration, the system robustness may be improved but the overall closed-loop stability will be affected and need to be analysed. In addition, a new command smoother for a particular system can also be designed. The various types of control schemes that have been reviewed in this paper might not have covered all of the existing hybrid control methods that are available in the literature. Interested readers can refer to the references that have been cited in this paper. That may lead them to the other articles concerning hybrid control algorithms.

7. Conclusion

This paper has organised and summarised most of the research work during the years from 2000 to 2016 that was related to control schemes for crane systems. As cranes are used extensively in industries and with several challenging control issues, many researchers have proposed and have implemented various control algorithms, especially in achieving a precise cart/trolley positioning and reducing the payload sway angles of a crane. This review paper is expected to motivate and generate ideas for new researchers which could enhance and improve the existing schemes towards more effective control strategies for various crane systems.

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