Automatic Control of Unmanned Cranes at the Pasir Panjang Terminal

Thomas Gustafsson and Claes Heidenback

Luleå University of Technology, Sweden. thomas@sm.luth.se
ABB Industries / Crane Systems. claes.heidenback@se.abb.com

Abstract

The overhead bridge cranes (OHBC) at the Pasir Panjang terminal in the Port of Singapore are operated remotely. Each operator can handle up to six cranes. This is possible due to the highly automated system that controls the cranes. This paper describes the control system that is implemented in the terminal.

1 Introduction

The continued growth of the container business has meant that all ports need to be able to offer ship owners facilities for container traffic. Accurate handling, fast turnaround and speedy forwarding are what shipping lines expect no matter how large or small the port. The ABB Advant Crane Control System is a modular system that is designed to meet the demands of increased automation from port operators. A significant step towards the unmanned crane was taken already in 1987 when ABB introduced an accurate Load Position Sensor (LPS) together with the CPC sway, position and path control package for container cranes.

The largest installation of the ABB Crane Control System is at the port of Singapore where the first systems was implemented for STS cranes at the Brani terminal and in 1997 at the Pasir Panjang terminal on RMG and bridge cranes. One of the key modules is the automatic crane control system that makes it possible with unmanned pick up and landing of containers.

An unmanned crane is in the following a crane, which is able to operate without any person, located on the crane or directly controlling the crane from the ground. For safety reasons the unmanned crane may need human assistance from a remote location in case of operation in manned areas or interfacing with manned vehicles.

Regarding the control of the load oscillations (anti sway control) there are mainly three principles that can be found in the literature: time-optimal control, programmed acceleration in combination with or without feedback control and mere feedback control.

Time-optimal Control: The most common approach is to use a time optimal open loop strategy. Time optimal control of bridge cranes is found in Mårtensson [10], and of rotary cranes in Sakawa et al. [14]. Other references are Karihaloo & Parberry [8] and Manson [9]. Auernig & Troger [2] use a different approach since they control the length of the suspension wire to dampen the oscillations in the load. There is no known working commercial implementation of a time optimal controller applied to crane control.

Programmed Acceleration: A method that can be used on real cranes is to approximate the time optimal strategy with an acceleration profile of the trolley. Jones et al. [7], Morishita et al. [11] and van de Ven [18] use different methods to calculate the switching times for acceleration changes but they all utilize a feedback controller at the end to eliminate remaining oscillations in the load.

Ohnishi et al. [12] solves the problem differently and starts with a feedback controller to reach maximum speed of the trolley without oscillations. Then programmed acceleration is used to stop the load at the correct position. This method has the advantage that the open loop controller always starts with a well known state. Ohnishi's method is also tested on a real cranes.

There exists a working commercial system, that is based on programmed acceleration. It was developed by Sternad [17] and Bryfors [3] and is used mainly on coal cranes where the loading and unloading positions are well defined.

Feedback Control: The third method is to use a feedback controller. Simple models of trolley cranes are often used as a design example in control engineering textbooks, e.g. in Schmidtbauer [16] and Ackermann [1]. A more complete treatment is found in Hazlerigg [6], Ridout [13] and an adaptive approach is made by Zinober [20]. Salmiinen [15] uses a robust design method to design a pole placement controller that is tested on a full scale trolley crane.

In [4] and [5] a feedback control of a rotary crane is presented that also has been implemented in real cranes and was one of the first available commercial systems for automatic crane control.

Experiments have also been made with rule based control by Yasunobu et al. [19]. The rules are derived from skilled crane operators and the rule selection is made with fuzzy logic.

2 Some technical challenges

Accurate control of load position including skew motion

To stack up to eight containers high without any manual assistance or any mechanical stacking guides requires highly accurate position control of the load in 4 directions, trolley, gantry, hoist and skew. A closed loop control is a must when the required stacking accuracy is within a couple of centimeters. High resolution in loop feedback is important for example for the skew controller, where a small skew angle will give a rather large error on the container corners measured against the container below. The position control of the load in the trolley and the gantry direction is rather straight forward using a mathematical model of the pendulum process and a closed loop for correction, but as a skew pendulum process is depending on the load weight and even how the weight is distributed in the container it puts high demands on a robust controller with fast feedback from both the load angle and the actuator position and speed. Problems that will affect the total accuracy, for example the rigidity of the mechanical structure, have to be taken in consideration.

Measuring the position of stacked containers in four dimensions

Before the stacking can begin a reliable reference must guide the crane to the correct position. A high performance position control is useless if the position reference is inaccurate. To develop a dedicated 3-dimensional laser scanner for crane applications turned out to be the only solution to this problem, the Target Position Sensor (TPS) was born. The TPS units operate as the eyes of the crane and are able to find, while the crane approaches the target, the exact location of the target stack in all dimensions fast enough to provide a smooth travel path thereby avoiding any slow down of the operation.

Measuring vehicle position

Before a landing can take place on a vehicle the type of vehicle must be verified (for example distinguishing between several types of chassis and/or AGVs) and the exact location must be measured. These tasks put high demands on the flexibility of the sensor concept.

Control of landing

Once the target is found a landing control logic must see to that the container lands correctly before opening the twist locks. A damaged container, or uneven ground surface may cause one side or one corner of the container to land before the others and making it skew out of position. The actual landing position must be measured and a fault handling

Figure 1: The four building blocks of the electronic load control

logic must be able to deal with most exceptions before requesting assistance from remote control.

3 Electronic Load Control

The concept of electronic load control is defined as the process of controlling the motion and path (relative to the crane) of a load suspended from ropes. Because an accuracy of a couple of centimeters is essential in container handling, where even small adjustments are very time-consuming, it is crucial to have a fast and accurate feedback of the load position relative to the trolley. The basics of automation start with a high performance load control.

As seen in fig 1 the electronic load control consists of four parts.

Load Position Sensor (LPS)

The load position sensor is a key component in the ELC. The relative position between trolley and load in the trolley, gantry and skew directions is measured with an accuracy of 1 mm over a hoist rope length of 3 - 35 meters. The transducer is capable of providing this accuracy due to a fully digital image sensing system with a defined active target on the load.

As ELC is the basic package of automation several levels of control is provided to be used at different stages of the automation cycles.

Sway Control

Automatic sway control is available for trolley and gantry motions and is often referred to as anti-sway. Sway control is used when a manual intervention by remote control is required. Sway control converts a load speed reference signal given by the crane driver, or automatic crane control software, to a speed reference for the trolley/gantry drive of the crane. The controller uses the load position feedback from

the LPS system. The signal is filtered in such a way that the drive reference as quickly as possible brings the load from the actual state (speed, sway angle and sway speed) to the ordered speed and without any sway. For remote operation, sway control is necessary, as it is very difficult to get the feeling needed to manually compensate for the sway, when not sitting on the crane.

A software model of the process ensures continuous, smooth control. The technique adopted is very similar to that used by an experienced crane driver. The trolley (gantry) is accelerated so as to bring the load into motion. It then maintains an almost constant speed for an instant before being accelerated to the final speed so as to achieve the exact timing for it to "catch" the load when it has reached the right speed. The sway control has to be continuous so that it can respond to any changes in the reference and to any disturbances like wind and initial sway.

Position and Optimum Path Control

The position and optimum path control system adds a trolley/gantry and hoist positioning function to the basic sway control. The optimum path function calculates the most efficient combination of horizontal and vertical motions to minimize the cycle time.

Skew Control

The skew control uses the LPS to obtain the feedback of the actual load skew position. Either zero skew or a skew angle ordered by the crane driver/the landing control sequence serves as reference. The actuators can be screws/drums or movable rope sheaves powered by AC drives. Hydraulic cylinders can be used if the control is fast and accurate enough. The response must be very fast, since the skew motion has a short sway period.

4 Automatic Crane Control

Automatic Crane Control (ACC) handles all aspects of the relationship between the crane with suspended load and surrounding objects. ACC provides the eyes of the crane to identify obstacles and the position of targets like vehicles and stacks of containers by using the sensor TPS as described below. ACC provides

- Scanning of surrounding areas for detection of obstacles to improve the safety level, eliminate risks due to human errors and verify information in the terminal control systems.
- Guided or fully automatic landing on stacks and vehicles.
- Automatic sequencing of all crane movements based on production orders given by a terminal control system, enabling unmanned operation of the crane.

Figure 2: The building blocks of the automatic crane control

The functionality is delivered by the modules seen in fig 2.

Target Position Sensor (TPS)

The ABB Target Position Sensor is a high-resolution 3-dimensional laser range finder capable of scanning a large area when searching for objects.

The main reasons for standardizing on a dedicated 3-D scanner are to be able to minimize the number of sensors per crane and to make it possible to position these at the center of the trolley in order to avoid costly mechanical arrangements.

The laser scanner has several operational modes, whose characteristics can be changed in the software during operation. Its database contains a number of measuring targets like chassis and containers of different types defined by the user.

The main task for the TPS on an unmanned crane is to scan the target container/vehicle in trolley and gantry direction and evaluate the skew angle and target height for a complete set of target coordinates. A TPS can be ordered to perform one or more of the ACC functions as described below, simultaneously or in sequence, depending on the type of ordered automatic job.

The following ACC functions are available:

4.1 Profile Scanning System (PSS)

PSS is used to gain information about the environment to the path control in order to avoid obstacles. One or normally two (if scanning in both travel direction is required) Target Position Sensors (TPS) mounted on the trolley are used for scanning ahead of the motion. The following functions can be performed:

- Stack profile scanning, scanning the height of the containers in a bay on a ship or a row in the stacking yard.

- Comparison of a stored stack profile received from the terminal control system with the measured stack profile.
- Collision protection during automatic operation. Scanning ahead of a motion to detect any unknown obstacles.

Landing Control Sequence (LCS)

The LCS software module handles the motion below the safe height over any object. Two Target Position Sensors, mounted on each side of the trolley are employed. The function uses the TPS transducers for the measurement of the vehicle (AGV) or stack positions. The target position measurement is used to give the Electronic Load Control (ELC) an accurate reference position.

Chassis Alignment System (CAS)

This function requires at least one TPS transducer normally mounted on the crane leg. The measured vehicle position is used to correct an ELC lane reference in the trolley direction and to control indication signals to the truck driver for positioning the vehicle in the gantry direction. When the vehicle is in the right position the crane hands over to a remote operator for manual landing. The function is used when a manned vehicle is to be guided to park within a certain area relative to the crane.

Automated Control Sequence (ACS)

The Automated Control Sequence schedules the operation of an unmanned container crane. It is designed to handle job orders from a terminal control system containing various combinations of hoist, trolley and gantry and skew motions. The ACS breaks down the whole job order into suborders for:

- Profile Scanning System (PSS)
- Positioning the load (ELC)
- Landing Control Sequence (LCS)
- Remote Crane Control (RCC), if operation in manned areas is required.

5 Anti-Sway Control

To illustrate some of the inherent problems with anti sway control we study a simplified model of a crane,

$$\ddot{x} = -\ddot{x}_t - \omega^2 x - 2\xi\omega\dot{x} \quad (1)$$

$$\ddot{x}_t = \frac{v_{max}u_t - \dot{x}_t}{T_t} \quad (2)$$

Where x_t is the trolley position and x is the position of the load relative to the trolley. The input u_t is normalized such that only values $|u_t| \leq 1$ are admissible. The maximum

Figure 3: Simulation of a simple linear anti sway controller

Figure 4: Control signal and trolley speed for a simple linear anti sway controller

speed is captured in the constant v_{max} . The time constant T_t is determined by the servo controller for the electrical drives. The relative damping ξ is almost constant while the parameter ω varies with both the load mass and the length of the wires.

The main problem with a simple feedback controller is the saturation of the control signal that limits the performance. An example shows some of the problems. Let $x_m = x_t + x$ be the position of the load and design a position controller for x_m that places all the poles of the closed system at $\omega_p = -\rho\omega$. In figure 3 we can see that, with $\rho = 1$, the load oscillates heavily and that the final positioning is very slow. By choosing a larger value of ρ trying to speed up the positioning only gives larger oscillations and slower positioning. The reason is that the control signal is saturated and the system is in open loop for most of the time. This is evident from fig 4.

Our method to deal with saturation is to use a multiple controllers in cascade where the innermost controller is used to deal with nonlinearities which makes the design of the outer controllers much easier. In fig 5 we can see that the cascade controller manage to accelerate the load to full speed without oscillations and that the final positioning is well controlled.

Figure 5: Control of load in trolley direction with a cascade controller

Figure 6: Remote set point from joystick, trolley and load speed for RMG crane 202 at Pasir Panjang terminal. The set point for the load speed is changed to 2.5 m/s at $t = 2.8$ and reset to zero at $t = 18.2$. The variation in the trolley speed is due to the measurement system and does not reflect true variations in the trolley speed.

Implementation

The cascade controller is implemented with a reduced Kalman filter. The system has four states. We can with high accuracy measure both the speed and position of the trolley. The observer only includes the two states for the load pendulum. The input to the observer is the trolley speed and the trolley position and the measurement of the load position from the LPS.

To compensate for time delays in the measurement system a prediction of the four states are made and used in the cascade controller.

The tuning of the cascade controller is important to achieve high performance. Most important is to get high performance in the final positioning, this is basically achieved by using gain scheduling. In figure 6 we see a typical run when the crane is remotely operated. The set point for the load speed is changed to full speed and when full speed is achieved the set point is reset to zero.

Figure 7: Skew control for an OHBC crane at Pasir Panjang terminal with an empty 20 ft spreader and with 21 meters line length. An oscillation is started with manual control. The skew controller is turned on at $t \approx 42$. The set point is changed to 0.05 at $t \approx 66$ and changed back to zero at $t \approx 93$.

6 Skew control

With asymmetrical loaded containers, wind disturbances or running the gantry and trolley simultaneous it is unavoidable with torsional oscillations of the load. Since the wire arrangements for the OHBC cranes has very little damping it is necessary to control the torsional oscillations.

To land the load on misaligned targets we also have to control the angle of the load relative the target. For that purpose two of the wire suspensions on the trolley are movable by electrical motors and by moving them in opposite directions we can rotate the load.

The dynamics for the skew pendulum is not easily calculated but by using a simplified geometry we can get a dynamical model for how the skew angle α is depending on the actuator position x_s

$$\ddot{\alpha} = -f(\alpha, m) \sin \alpha - K(\alpha, m)x_s \quad (3)$$

Where m is the mass of the load. Since the functions f and K are not known exactly we have designed a controller that is robust to parameter variations. The controller is also designed to handle the saturation in the actuator that has limitations in both position and speed.

Results from an experiment is shown in fig 7. No plots of the actuator signal is available, but it is saturated during the set point changes.

7 Conclusion

It has been demonstrated in practice that it is possible with an unmanned operation of container cranes. This is made possible by using sensors with high accuracy and controllers

with robust performance. For safety reasons a crane must, however, be operated or supervised by an operator if the crane is moving over manned areas. The advantages of remote or unmanned crane operation are among others, increased availability, improved physical working environment for operators and improved utilization of human resources as no traveling to/from and climbing on/off cranes is needed in shift changes, breaks etc. An unmanned crane could use higher acceleration for the trolley and gantry as the comfort for the operator is no longer an issue. In this case the structural resonances of the crane must be taken into consideration as the higher acceleration will introduce structural oscillations that will degrade the performance.

References

- [1] J. Ackermann. *Sampled Data Control Systems: analysis and synthesis. A unified approach*. Prentice-Hall, Inc., Englewood Cliffs, 1985.
- [2] J. W. Auernig and H. Troger. Time optimal control of overhead cranes with hoisting of the load. *Automatica*, 23:437–447, 1987.
- [3] U. Bryfors. private correspondence. ABB Drives AB, 1993.
- [4] T. Gustafsson. *Modelling and Control of Rotary Crane Systems*. Doctor of technology thesis, University of Luleå, June 1993.
- [5] T. Gustafsson. On the design and implementation of a rotary crane controller. *Eur. J. Contr.*, 2:166–175, 1996.
- [6] A. D. G. Hazlerigg. Automatic control of crane operations. In *Proc. of 5th Int. IFAC Congress*, 1972. paper 11.3.
- [7] J. F. Jones and B. J. Petterson. Oscillation damped movement of suspended objects. In *Proc. of IEEE Int. Conf. on Robotics and Automation*, Philadelphia, 1988.
- [8] B. L. Karihaloo and R. D. Parberry. Optimal control of a dynamical system representing a gantry crane. *ASME Journal of Optimization Theory and Applications*, 36:409–417, 1982.
- [9] G. A. Manson. Time-optimal control of an overhead crane. *Optimal Control Applications & Methods*, 3:115–120, 1982.
- [10] K. Mårtensson. New approaches to the numerical solution of optimal control problems. Technical Report No. 7206, Lund Institute of Technology, Division of Automatic Control, 1972.
- [11] I. Morishita and K. Deguchi. Microcomputer control of overhead travelling. In *Proc. of ACTA IMEKO*, pages 403–410, 1979.
- [12] E. Ohnishi, I. Tsuboi, T. Egusa, and M. Uesugi. Automatic control of an overhead crane. In *Proc. of IFAC Control Science and Technology*, pages 1885–1890, Kyoto, Japan, 1981.
- [13] A. J. Ridout. New feedback control system for overhead cranes. In *Proc. of Electric Energy Conference*, pages 135–140, Adelaide, 1987.
- [14] Y. Sakawa, Y. Shindo, and Y. Hashimoto. Optimal control of a rotary crane. *ASME Journal of Optimization Theory and Applications*, 35:535–557, 1981.
- [15] R. Salminen. *Robust Pole Placement Control of a Trolley Crane System*. Doctor of technology thesis, Helsinki University of Technology, May 1992.
- [16] B. Schmidtbauer. *Analog och Digital Reglerteknik*. Studentlitteratur, Lund, 1988. (In Swedish).
- [17] M. Sternal. *Programmerad lastväg med pendlingsdämpning för gripskopecranar*. Master thesis, Uppsala University, Aug 1981. Classified.
- [18] H. H. van de Ven. Time-optimal control of a crane. Technical report, Department of Electrical Engineering, Eindhoven University of Technology, April 1983.
- [19] S. Yasunobu and T. Hasegawa. Evaluation of an automatic container crane operation system based on predictive fuzzy control. *Control-Theory and And Advanced Technology*, 2:419–432, 1986.
- [20] A. S. I. Zinober. Self-adaptive control of the time-varying nonlinear crane problems with disturbances and state constraints. *Control and Computers*, 14(3):103–109, 1986.