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AUTOMATION OF OVERHEAD MAGNET CRANE SYSTEM IN THICK STEEL PLATE STORAGE YARD

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Abstract: This paper presents an automation scheme of an overhead magnet crane that is used as an essential part of storage yard automation. First, load cells are introduced to detect the number of lifted steel plates. Then a current control algorithm to lift the right number of steel plates is proposed and implemented by using the on-line tuning look-up table. Finally, the overall hardware and software description for automatic crane operation is presented. The results have been successfully implemented on POSCO's No.2 thick steel plate storage yard.

Keywords: On-line control, real time systems

1. INTRODUCTION

Automating the operation of the thick steel plate storage yard is one of the important examples in factory automation. There are many subsystems to consider for storage yard automation, but the magnet crane control is probably the most difficult to operate. Once the steel plates produced from the continuous caster move on the rollers and arrive at the storage yard, they are removed from the roller to be stacked for temporary storage, rearranged among stacks according to customer demands or moved from stacks to the customer truck for shipping. All of these operations are carried out by the overhead magnet crane as shown in Figure 1. It is similar in its structure to the three axes gantry-type robots. The crane body moves along the side rail and the crab moves along the body so as to position the trolley at the desired stack position. The trolley moves up and down to lift and drop the plates.

Before the magnet crane system is automated, the operation of the magnet crane was mainly controlled by a crane operator and an assistant at the yard. His main job is to inform the magnet crane operator of the correct location to lift the plates and of the number of the steel plates to lift using the wireless communication unit. Getting the ordered number of plates to lift from the assistant, the operator determines the amount of current based on his experience and exerts current to the magnets using the control lever. When the plates are lifted, the assistant counts the number of lifted plates with his eyes and signals the number to the operator with his hands. If the number of the lifted plates is greater than the ordered one, the operator tries to decrease the amount of current to drop some of the plates until the number of lifted plates matches the ordered one. If the number of lifted plates is smaller than the ordered one, the operator lays the plates back on the stack, increases the amount of current, and tries again to lift the right number of plates. Once the correct number of plates is lifted after the above trials, the assistant leads the operator to the designated location to discharge the plates. This guide-assisted crane operation suffers from some drawbacks. First, the working environment in the storage yard is not human-friendly. There is much dust, the plates dropping on the stacked plates make large noises, and if any hardware faults occur while carrying the plates, the assistants

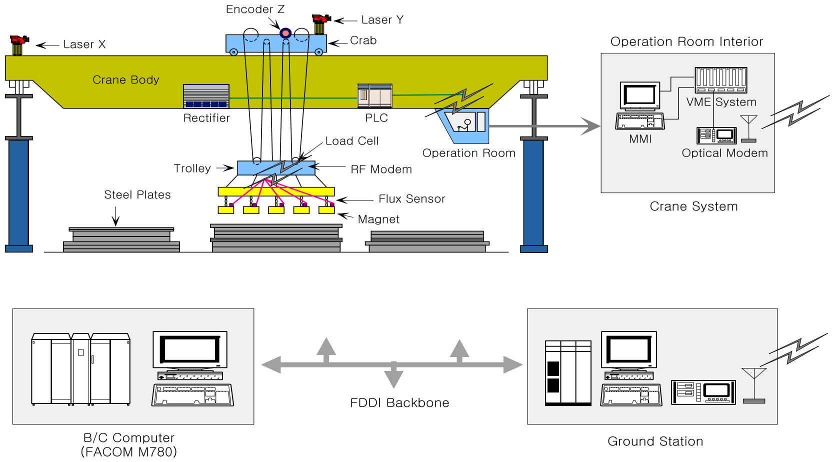

Fig. 1. The overhead magnet crane system

on the steel yard could be in serious danger. Second, this operation requires an assistant and an operator thus it is not cost-effective. To stay cost competitive in the international market, some measures are required to reduce the man power while increasing productivity. For this end, an automatic operation scheme of the crane and the magnets is developed to do the same tasks without any operator and any assistant.

Under the proposed crane system, the works proceed as follows. Job order file that contains the ordered number of plates, the steel plate information such as weight, width, and length, and destination is directly given to the crane computer by using an optical communication module. The computer system mounted on the operation room then analyzes the job order, and controls the crane to the ordered position by sending commands to the motor drive. Calculating the right amount of current based on the proposed algorithm, it drives current to the magnets by sending a current command to the rectifier. Then it lifts the steel plates and counts the number of plates attached to the magnets by comparing the weight measured by the load cells with the weight calculated from the process computer located at the ground station. According to the counted number of plates, the computer system automatically tries to decrease or increase the amount of current. If the ordered number of plates is lifted correctly, then it moves the crane to the designated position.

Some papers and technical reports on the automation of the overhead magnet system have been reported from our laboratory as shown in (Sang Y. Park and Park, 1998; B.K. Kang and Lee, 1998; Lee and Park, 1994). In contrast with these papers and reports, this paper introduces the techniques using the load cells, the updated algorithm of current control, and presents the whole automated crane system. The overall automation system consists of several sub units: the counting unit of the number of plates attached to the magnets, the current control unit to determine the amount of the current to lift or drop the desired number of plates, the position tracking and the motor control unit of the crane and the ground station unit for management of storage yard map.

The remainder of this paper is organized as follows. The detection system of the number of steel plates is presented in section 2. The current control systems in section 3 and the hardware and software components of the crane system are proposed in section 4. Finally, the conclusion is given in section 5.

2. SYSTEM AND ALGORITHM FOR DETECTING THE NUMBER OF STEEL PLATES

A load cell is classified as a force transducer that converts force or weight into an electrical signal. A strain gauge is the heart of a load cell, which changes its resistance value when the stress is applied. Multiple strain gauges are connected to create the four legs of a Wheatstone-bridge configuration. When an input voltage is applied to the bridge, the output becomes a voltage proportional to the force on the cell. This output is amplified and processed by electrical circuitry and the resulting weight value is sent to the VME system by $RS422$ serial communication.

It is important to minimize the error between the real weight and the weight sensed by load cells. As the crane swings back and forth when it moves and since there are considerable sensor noises, the measured values always come with errors. To minimize these errors, the pin type eight load cells was installed into the pulley axes of the wire ropes, and the average weight is acquired after each value of the load cells is summed. As the results, the errors never exceeded 200 kg as shown in Figure 2. The number of plates can be determined by comparing the weight of the

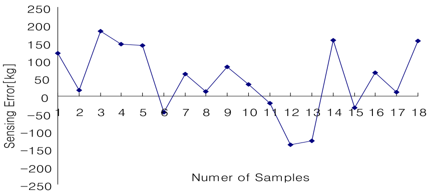

Fig. 2. Profile of sensing errors acquired at POSCO's No. 2 thick steel plate storage yard

plate information from the ground station with the weight measured from the load cells. Now, let the weight M measured by load cells be

$$M = \sum_{j=1}^{N} (m_j + \Delta m_j) \quad ,$$

where N is the total number of plates attached to the magnets, m_j denotes the weight of the jth steel plate which is given by the ground station and Δm_j is the measurement error of m_j. Then, to determine the correct number of steel plates attached to the magnet, the total measurement error must be small than half of the lightest steel plate. Consequently, the detection algorithm must satisfy

$$\left| \sum_{j=1}^{N} \Delta m_j \right| < \frac{1}{2} \min (m_1, m_2, \cdots, m_{N+1}) \quad , \ (1)$$

The proposed algorithm to identify N is described by using the following pseudocode:

```
INPUT    $M$, $m_1, m_2, \cdots, m_{N_{max}+1}$
OUTPUT   $N$
Step 1   Set $M_s = 0$; $m_0 = 0$.
Step 2   for $i = 0, 1, \cdots, N_{max}$ do
             Set $M_s = M_s + m_i$; N = i;
             if $|M - M_s| < \frac{1}{2} \min_{1 \le j \le i+1} m_j$ then
                 OUTPUT($N$).
                 STOP.
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where N_{max} is the maximum number of plates which the magnet crane can lift. At the iteration $i = N - 1$, the if-condition is equivalent to $|m_N + \sum_{j=1}^{N} \Delta m_j| < \frac{1}{2} \min(m_1, m_2, \cdots, m_N) \le \frac{1}{2} m_N$, but this does not satisfy (1). At the next iteration $i = N$, the if-condition is satisfied and N can be obtained. Since the thick steel plates produced in POSCO(Pohang Iron & Steel Co.) mostly weigh over 400 kg, the above detection algorithm along with the load cells identifies very successfully the number of steel plates attached to the magnets.

3. CURRENT CONTROL OF THE MAGNETS

3.1 *Modeling of the Current Control System*

In the operation of the magnet crane, steel plates are lifted by using the magnetic force produced by the current exerted on the magnet coil. The relationship between the magnetic force and the current can be derived by using flux that stores the energy in the magnetic field. The minimum amount of current required to lift the steel plates is that which produces the magnetic force which is enough to overcome gravitational force.

According to Poynting's theorem (Scott, 1996), the stored magnetic energy E_m becomes

$$E_m = \frac{1}{2} \int_{vol} B \cdot H dv \quad . \qquad (2)$$

Substituting $B = \mu_0 H$ and $\phi_g = B S_g$ into (2) yields

$$E_m = \frac{\phi_g^2 l_g}{2 \mu_0 S_g} \quad , \qquad (3)$$

where μ_0 is the permeability of the air, ϕ_g is the flux that passes through the air gap, l_g is the air gap distance and S_g is the cross-sectional area of the flux path. If it is assumed that the changes in flux between the magnet and the plates result from a virtual differential displacement dl_g, then the change of stored magnetic energy becomes

$$dE_m = 2 \cdot \frac{dl_g}{2 \mu_0 S_g} \phi_g^2 \quad , \qquad (4)$$

where the coefficient 2 reflects the fact that the magnetic force is generated at both ends of the magnet shoe. By dividing dE_m by dl_g, the force to lift plates F_m is given as follows.

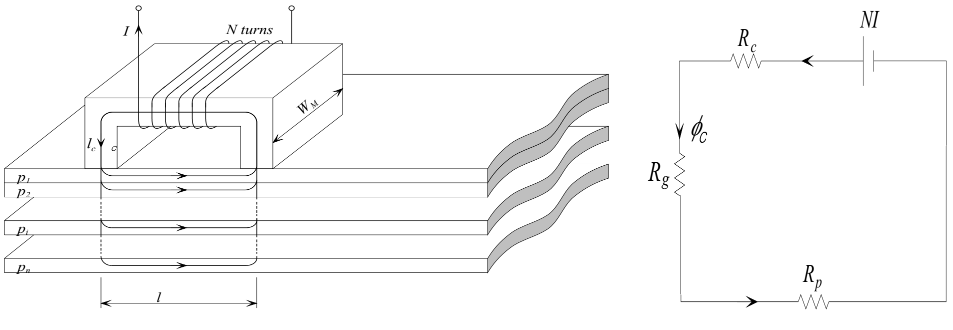
$$F_m = \frac{dE_m}{dl_g} = 2 \cdot \frac{1}{2 \mu_0 S_g} \phi_g^2 \ge g \rho t W_a L_a \ , \quad (5)$$

where g is the gravitational acceleration, ρ is the density of the steel plates, t is the thickness of plates, W_a is the average width of plates and L_a is the average length of plates. By using the equivalent magnetic circuit in Figure 3 (b) and the fact that ϕ_g equals to the flux of the magnet core ϕ_c, we obtain ϕ_c

$$\phi_c = \frac{N_c I}{R_c + R_g + R_p} \ , \qquad (6)$$

where N_c is the number of turns in the coil winding, I is the current that flows though the coil and R whose the subscripts c, p and g denote the core, the plates and the air gap, respectively is the corresponding reluctance. Substituting (6) into (5) yields

$$\begin{aligned} I &\ge \frac{1}{N_c} (R_c + R_g + R_p) \sqrt{\mu_0 S_g g \rho S_p L_a} \\ &= \frac{1}{N_c} \left(\frac{l_c}{\mu_c S_c} + \frac{l_g}{\mu_0 S_g} + \frac{l_p}{\mu_p S_p} \right) \sqrt{\mu_0 S_g g \rho S_p L_a} \ , \end{aligned}$$



(a) Flux path of the magnet and steel plates

(b) Equivalent magnetic circuit of (a)

Fig. 3. The simplified flux path of steel plates attached to a magnet and its equivalent circuit

(7)

where S with subscripts are the corresponding cross-sectional areas and l is the length of the flux path.

3.2 *Implementation of the Model*

N_c, l_c, S_c, μ_0, S_g, g, and ρ in (7) are the unknown constants and if it is assumed that B and H have a linear relationship, the variations of μ_c and μ_p are small; therefore the term $\frac{l_c}{\mu_c S_c}$ is unknown constant, $\frac{l_g}{\mu_0 S_g}$ is related to the number of plates, $\frac{l_p}{\mu_p S_p}$ is the function of total thickness and average width of plates, and $\sqrt{\mu_0 S_g g \rho S_p}$ is the function of total thickness and average width of plates. In the aspect of implementation, Formula (7) can experimentally be written as the following form:

$$I \geq F(n, t_a)|_{W_a=W_s, L_a=L_s} \alpha \left(\frac{W_a}{W_s}\right) \sqrt{\frac{L_a}{L_s}} \quad , (8)$$

where n is the number of plates, t_a, W_a and L_a are average thickness, width and length of the plates respectively, W_s denotes the standard width of the plates when the data are gathered, L_s is the standard length and α is the compensated term which has to be adjusted by trial and error. $F(n, t_a)$ is implemented in this paper by using a look-up table. The maximum thickness of plates that the crane can lift is 50 mm and the plates of 6, 8, 10, 12, 15, 20, 30, 40 and 50 mm thickness are common at the POSCO's thick steel plate storage yard. Consequently, the maximum number of plates that the magnet crane can lift can be easily calculated. For example, for plates with 6 mm thickness it is eight and for the plates of 8 mm, it is six. Currently, the actuators of the magnet cranes use voltage sources as power sources, and the computer system gives a voltage command to the rectifier PLC for actuating current. In order to remove the floating points, the digital values of the voltage have the range from 0 to 2200. The values in the look-up table as shown in Figure 4 are the amount of minimum voltage to lift n number of plates with average thickness t_a under $W_a = W_s,\ L_a = L_s$. The minimum voltage $V_{t_a}^n$ to lift n plates with t_a can be obtained by the linear interpolation with Figure 4.

$n \backslash t_a$	6	8	$\cdots$	$\cdots$	40	50
1	75	95	$\cdots$	$\cdots$	450	500
2	110	180	$\cdots$	$\cdots$	2200	2200
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
7	1400	2200	$\cdots$	$\cdots$	2200	2200
8	2200	2200	$\cdots$	$\cdots$	2200	2200

Fig. 4. The look-up table for linear interpolation

Because $V_{t_a}^n$ is the minimum voltage to lift n plates, the amount of the required voltage reference V_R is

$$V_R = \frac{V_{t_a}^n + V_{t_a}^{n+1}}{2} \alpha \left(\frac{W_a}{W_s}\right) \sqrt{\frac{L_a}{L_s}} \quad . \qquad (9)$$

$n \backslash t_a$	6	7	$\cdots$	$\cdots$	18	19
1	92	115	$\cdots$	$\cdots$	345	360
2	170	215	$\cdots$	$\cdots$	1330	1340
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
7	1800	1900	$\cdots$	$\cdots$	2200	2200
8	2200	2200	$\cdots$	$\cdots$	2200	2200

Fig. 5. The look-up table for on-line tuning

The results applied the above algorithm to the G2 crane showed that the initial success rate of lifting the exact number of plates at the first trial was 100 % for $t_a \geq 20$, but it was relatively poor for $t_a \leq 19$. Therefore other methods are needed for $t_a \leq 19$. After calculating V_R by (9) and Figure 4, the detail look-up table is made for $t_a \leq 19$ as shown in Figure 5. Unlike Figure 4, the values in Figure 5 are not the minimum voltage, but the reference voltage to the actuator. Whenever the crane is not able to lift the exact number of plates ordered from the ground station, the Figure 5 is tuned on-line. The updating rules for two cases are as follows.

a. When the number of lifted plates is more than that of ordered plates

$$\begin{aligned} V_{t_a}^{n_o} &\Longleftarrow V_{t_a}^{n_o} - |V_{t_a}^{n_o} - V_{t_a}^{n_o-1}|\frac{\Delta^+ n}{N_{t_a}} \quad , \\ V_{t_a}^{N} &\Longleftarrow V_{t_a}^{n_o} \end{aligned} \tag{10}$$

where V is the reference voltage, the superscripts of V denote the number of plates ordered from the ground station, and the subscripts of V denote the average thickness, $\Delta^+ n$ is the difference between the detected number and the ordered number, and N_{t_a} is the number of the sections between $V_{t_a}^{n_o-1}$ and $V_{t_a}^{n_o}$ or between $V_{t_a}^{n_o}$ and $V_{t_a}^{n_o+1}$. As it is more difficult to lift the exact number of plates for thinner plates, the sections are divided more finely for thinner plates. Consequently, the thinner the plates are, the greater N_{t_a} is. The updating rule (10) means that if the crane lifts the more number of plates than that of ordered plates with the reference voltage $V_{t_a}^{n_o}$, then decrease $V_{t_a}^{n_o}$ in the direction of $V_{t_a}^{n_o-1}$ in Figure 5 considering the average thickness and the difference between detected number and ordered number. And update $V_{t_a}^{N}$ as $V_{t_a}^{n_o}$.

b. When the number of lifted plates is less than that of ordered plates

$$\begin{aligned} V_{t_a}^{n_o} &\Longleftarrow V_{t_a}^{n_o} + |V_{t_a}^{n_o+1} - V_{t_a}^{n_o}|\frac{\Delta^- n}{N_{t_a}} \quad , \\ V_{t_a}^{N} &\Longleftarrow V_{t_a}^{n_o} \end{aligned} \tag{11}$$

where $\Delta^- n$ is the difference between ordered number and detected number.

After applying the current control method mentioned the above for a week from Oct. 19 2000 to Oct. 25 2000, the results of the works are gathered for nine days and made an analysis of the initial success rate which is defined as the percentage rate of the number of total works to the number of initially succeeded works. The initial success rate is approximately 95 % as shown in Figure 6. Compared with the fact that an experienced operator's success rate is approximately 70 %, the results are so satisfactory.

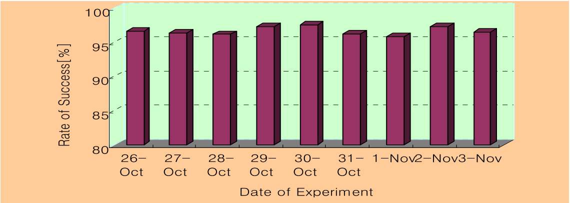


Fig. 6. Initial success rate

4. HARDWARE AND SOFTWARE CONFIGURATION OF THE CRANE SYSTEM

The POSCO's thick steel plate storage yard is an area of 83200 m^2 which has a storage capacity of 146000 tons. There are 1086 piling locations about 4.5 m wide by 6 m long per location and there are 23 overhead magnet cranes which can cover about 30 m wide by 150 m long. Under automated crane system, the crane computer system installed in the operation room as shown in Figure 1 works in place of an operator and an assistant.

The main computer system based on VMEbus is composed of a CPU board, two serial communication boards and a DIO(digital input/output) board. The VRTX*sa* running on the CPU is a real-time and multitasking operating system kernel for embedded microprocessor applications. The computer system interfaces with the ground station, sensors and two PLCs, controls the position of the crane along with laser D_x, D_y and the height of the hoist along with encoder D_z, drives the magnet current and detects the number of plates along with load cells.

a. Main computer unit
   - *CPU board*: a VM40 CPU board has an MC68040(25MHz) processor, a 4MB DRAM, a 2MB SRAM, and a 4MB FLASH ROM. The VM40 board with VRTX*sa* runs the application programs.
   - *Serial communication board*: two VMOD-2 boards with eight serial ports interface with the sensors. These serial communication ports receive the crane position from the laser sensor D_x and D_y, communicate with the ground station, communicate with one PLC for the crane motor control and the other PLC for magnet current control, receive the height of two grabs with two encoders, interface with the LCD, and get the key inputs. The method of serial communication is the full-duplex form at 19200 *bps* without parity check by $RS422$.
   - *DIO board*: the DIO board is used for controlling the emergency buzzer, and the LED that shows the faults at devices.

b. Ground station unit
The ground station manages the whole work schedules of the cranes, gives the information of the yard map and the stacked plates to the main computer system, and receives the crane position, faults at devices of the crane, and results of the work from the main computer system. The communication between ground station and crane computer system is achieved by using the optical modem. $RS422$ communication port connects the VME system to the optical modem.

c. Position tracking and motor control unit

- *Laser D_x, D_y*: measure a horizontal position and a vertical position respectively on the yard map.
- *Encoder D_z*: measures a height of the lifting magnets.
- *PLC for motor control*: a movement command to the PLC which transmits the command to the motor drive makes the crane move. With measuring D_x, D_y and D_z continuously, the main computer system handles position of the crane. After calculating the distance between current position and target position, the main computer gives a start command, an acceleration command at the 10 % point of the calculated distance, a slow command at the 90 % point and finally a stop command. In case of emergency, the extreme limit switches on the 3 axis will automatically stop the operation.

d. Detection unit
refer the section 2.

e. Current control unit

- *PLC for driving current*: the PLC for driving current gives the amount of voltage in the digital form from 0 to 2200 to the rectifier drive which drives the relay related to the voltage source.
- *Algorithm of decision of the initial current*: refer the section 3.
- *Current control in case of retrying*: this routine begins to operate when the number of the lifted plates is different from that of the ordered plates. After driving the amount of current according to the proposed current control algorithm, the plates are lifted to a height of 30 cm and then the number of plates is counted. When more number of plates is lifted, the amount of the current is decreased gradually with checking that the plate is dropped. As soon as the plate is dropped, the current is increased. This procedure is repeated until the number of the lifted plates corresponds with the ordered number. Conversely, when the number of the lifted plates is fewer than the ordered number, the amount of the current is increased and lifts one more time. For the two cases, the look-up table is on-line tuned.

f. Process monitor unit
Process monitor controls the whole operation and handles the crane in place of an operator. According to results of the detection algorithm and the current control algorithm, it monitors the next steps.

5. CONCLUSION

In this paper, an automation system of an overhead magnet crane is presented. The two important issues of the automation system are presented,that is, the detection of the number of the steel plates attached to the lifting magnets and the current control of the lifting magnets. And hardware and software configuration is presented. The proposed automation system has been installed at POSCO's No. 2 thick steel plate yard and has been in operation since last 2 years. Without operators and assistants, the automated system has been reliably operating in poor environment of the field and has saved on the labor as 6 less operators and assistants per crane.

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