

# Control of Lifting Desired Number of Steel Plates and Automatic Crane Operation

Hong-Ju KIM, Seok-Kyun HWANG and Jin S. LEE

Department of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea. E-mail: mirror@postech.ac.kr, rookie@postech.ac.kr, jssoo@postech.ac.kr

(Received on July 15, 2002; accepted in final form on October 3, 2002)

This paper presents an automation scheme for an overhead magnet crane that is a critical component of thick steel plate storage yard automation. First, the load cells and magnetic flux sensors are introduced to detect the number of steel plates lifted using the magnet crane. Then a voltage control algorithm to lift the ordered 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 in POSCO's No. 2 thick steel plate storage yard.

KEY WORDS: overhead magnet crane system; magnet voltage control; load cell; magnetic flux sensor; on-line tuning look-up table.

## 1. Introduction

Automating the operation of thick steel plate storage yards is an important priority in factory automation. There are many aspects of thick steel plate storage yard automation to consider, but magnet crane control units are probably the most important. When the steel plates arrive at the storage yard, they are removed from the roller, stacked for temporary storage, rearranged between stacks according to customer demands, and moved from the stacks to be loaded onto trucks for shipping. All of these operations are carried out by an overhead magnet crane as shown in **Fig. 1**. The overhead crane is similar in its structure to three axes gantry-type robots. The crane body moves along side rails and the crab moves along the crane body to position the trolley at the desired stack position. The trolley moves up and down to lift or discharge the plates.

Before magnet crane systems were automated, the operation of each magnet crane was primarily controlled by a crane operator in the operation room with the assistance of a guide in the yard. The guide tells the crane operator where to lift the steel plates and how many plates to lift using a wireless communication unit. After obtaining such information, the crane operator moves the crane to the ordered location and, to lift the given number of plates, applies an estimated amount of voltage based on experience. When the plates are lifted, the guide counts the number of lifted plates by sight and signals the counted number to the operator by hand. If the number of the lifted plates is greater than the ordered one, the operator will attempt to correct the number of plates by slowly decreasing the voltage and dropping the plates one by one. If the number of lifted plates is smaller than the ordered one, the operator will start over the process by placing the plates back on the

stack and reapplying a greater amount of voltage. Once the ordered number of plates is lifted after trial and error, the guide leads the operator to the designated location to discharge the plates. However, this guide-assisted magnet and crane operation suffers from drawbacks. First, the working environment in the storage yard is not user-friendly. There is too much dust; the plates make big noises when dropped on the stacks; if any hardware faults occur while carrying the plates, workers in the steel yard could be in serious danger. Second, since this operation requires a guide and an operator, it is not cost-effective. To stay competitive in the international market, measures are required to reduce labor costs while increasing productivity. To this end, automation of magnet crane operations is proposed to replace operators and guides.

The automated crane system is operated as follows. The crane controller mounted in the operation room first receives the job order file from the ground station. The file contains the ordered number of plates and each plate's information such as weight, width, length, and destination. The computer system then reads the job order, and moves the crane to the ordered position by sending appropriate commands to the motor drive. Next, it calculates the right amount of voltage based on the proposed algorithm, and drives the magnets by sending the voltage 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 load cells with the weight calculated from the process computer located at the ground station. If the counted number of plates is not the same as the ordered one, the computer system automatically tries to decrease or increase the amount of voltage according to the counted number of plates. If the ordered number of plates is lifted correctly, then it moves the crane to the designated position.

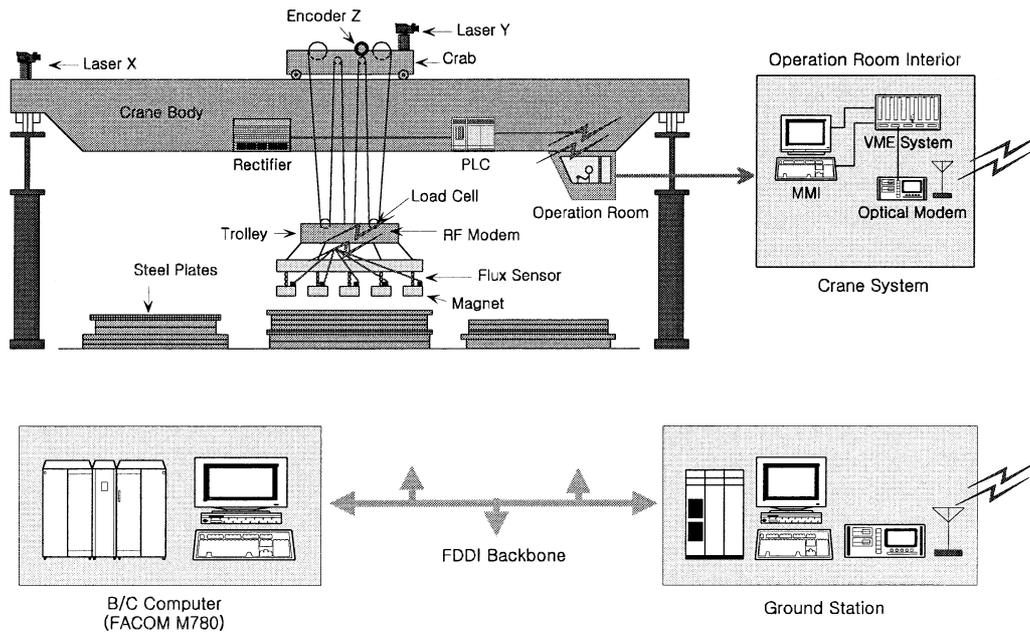


Fig. 1. The overhead magnet crane system.

Progress on the automation of overhead magnet crane operations has been reported.<sup>1-4)</sup> In contrast to these reports, this paper introduces an algorithm for counting the number of plates attached to the magnets and a voltage prediction technique for lifting the given number of plates, and presents a complete automated crane system.

The overall automation system consists of several sub-units: the counting unit for counting the number of plates attached to the magnets, the voltage control unit for determining the amount of voltage to lift or discharge the desired number of plates, the position tracking and the motor control unit of the crane, and the ground station unit for managing the storage yard map.

In detecting the number of plates, two sensors are introduced: load cells<sup>5)</sup> and magnetic flux sensors.<sup>2)</sup> The load cell-based detection unit uses eight load cells to measure the weight of the attached plates and compares the measured weight with the weight calculated from the ground station. The flux sensor-based detection system uses flux sensing electromagnets mounted on each magnetic core to detect the magnetic flux change of the lifting magnet and deduce the number of plates attached to the magnet. The automatic voltage control algorithm is developed by using the model of the magnets and the plates attached to the magnet<sup>7)</sup> and the online tuning look-up table. The crane system hardware is arranged to realize each function of the subunits. The computer system of the crane is based on the VMEbus backplane and uses VRTXsa (Versatile Real Time Executive Scalable Architecture) as the real time operating system.<sup>6)</sup>

The remainder of this paper is organized as follows. Section 2 presents sensor units that detect the number of steel plates. Section 3 presents the voltage control systems and Sec. 4 describes the hardware and software components of the crane system. Finally, Sec. 5 concludes this paper.

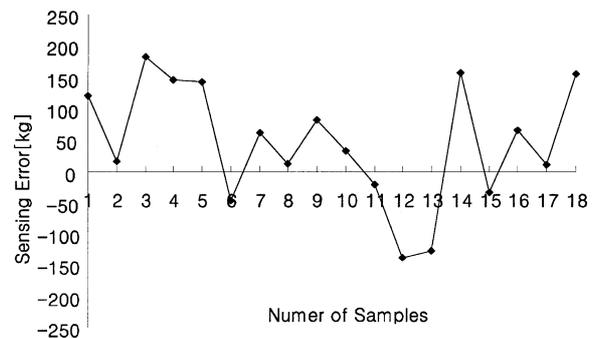


Fig. 2. Profile of sensing errors acquired at POSCO's steel plate storage yard.

## 2. Systems and Algorithms for Detection of the Number of Steel Plates

### 2.1. Load Cells

A load cell is classified as a force transducer that converts force or weight into an electrical signal. Multiple strain gauges, which will change the resistance values when stress is applied, are usually used to form four legs of a Wheatstone-bridge configuration. When stress is applied to the bridge, the output voltage is proportional to the force on the cell. This output is then amplified and processed by electrical circuitry and the resulting weight value is sent to the VME computer via an RS422 serial line.

The measured weight values could suffer from significant errors due to considerable sensor noises particularly when the crane swings back and forth during operation. To minimize these errors, eight pin type load cells have been installed on the pulley axes of the wire ropes and their outputs are summed and then averaged over a set period. With this arrangement, the errors never exceed 200 kg as shown in Fig. 2. The number of plates can then be determined by comparing the stored weight values in the ground computer with the averaged weight values of the load cells.

Now, let the weight  $M$  measured by the load cells be

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

where  $N$  is the total number of plates attached to the magnets,  $m_j$  denotes the weight of the  $j$ th steel plate given by the ground station and  $\Delta m_j$  is the measurement error of  $m_j$ .  $N$  is then determined when the total measurement error up to  $N$  plates becomes less than half of the weight of the lightest steel plate of the first  $(N+1)$  plates, or when

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

Note here that  $m_1, m_2, \dots, m_N$  are the weights of plates already attached to the magnets and  $m_{N+1}$  is the weight of the top plate on the stack.

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

```

INPUT       $M, m_1, m_2, \dots, m_{(N_{\max}+1)}$ 
OUTPUT      $N$ 
Step 1     Set  $M_s=0; m_0=0$ 
Step 2     for  $i=0, 1, \dots, m_{N_{\max}}$  do
              Set  $M_s=M_s+m_i; N=i$ 
              if  $abs(M-M_s) < \frac{1}{2} \min(m_1, m_2, \dots, m_{i+1})$ 
                then
                  OUTPUT ( $N$ )
                STOP,
    
```

where  $N_{\max}$  is the maximum number of plates the magnet crane can lift. If there are more plates than  $N_{\max}$ , then  $m_{(N_{\max}+1)}$  is of course the weight of the  $(N_{\max}+1)$ th plate. But if there are only  $L$  plates, where  $L \leq N_{\max}$ , then  $m_{L+1}, \dots, m_{(N_{\max}+1)}$  are all set to infinity. In step 2, the loop starts from  $i=0$  to account for the case when there are no lifted plates. Let's assume that  $N$  is the number of the attached plates. Then, at  $i=N-1$ , we have  $|M-M_s| = \left| \sum_{j=1}^N (m_j + \Delta m_j) - \sum_{j=1}^{N-1} m_j \right| = |m_N + \sum_{j=1}^N \Delta m_j| < (1/2) \cdot \min(m_1, \dots, m_N) \leq (1/2) \cdot m_N$  from which we obtain  $(-3/2) \cdot m_N < \sum_{j=1}^N \Delta m_j < (-1/2) \cdot m_N$  and Eq. (1) does not hold. But at  $i=N$ , Eq. (1) is satisfied and this fact confirms that  $N$  is indeed the number of lifted plates. Since most of the thick steel plates produced in POSCO (Pohang Iron & Steel Co.) weigh over 400 kg, the above detection algorithm identifies the attached number of steel plates very accurately.

**2.2. Magnetic Flux Sensors**

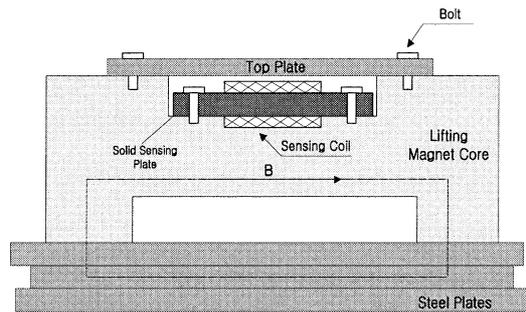
As mentioned in Sec. 2.1, the measurement accuracy of the load cells is good enough to detect the number of most plates. In some cases, however, part of the steel plates may not be fully attached to the lifting magnets; the load cells cannot detect this situation and it may cause the plates to fall while they are carried to the destination. To prevent this from happening, auxiliary sensors can be mounted on each lifting magnet so as to detect this undesirable situation. If the lifting magnets are placed on the steel plates and excited with voltage or current sources before lifting the steel plates, the magnetic flux in the core of the lifting magnet

can be determined by the magnetic reluctance of the magnetic circuit formed by the core and the attached steel plates. When the steel plates are lifted, they are attached to the surface of the magnet pole and the flux does not change. But in case of the partially-attached condition, part of the steel plates is separated from the surface of the pole and causes significant flux change in the core of the lifting magnets. The partially-attached situation can be easily detected by observing the voltage or current change in the sensing coil, whenever it is placed in the core of the lifting magnet. To place the sensing coil in the core of the magnet, a hole is made in the top surface of the lifting magnet as shown in Fig. 3(a). Then an I-shaped 5 mm thick plate wound with a sensing coil is inserted into this hole. Once this sensing plate is properly positioned, a top plate with 15 mm thickness covers the hole on the surface of the lifting magnet. With this set-up, a magnetic circuit with an AC signal source is formed by the core, the sensing plate and the top plate. Then the magnetic field intensity  $B_c$  in the core is given by

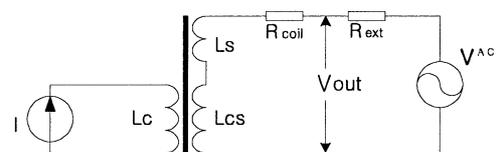
$$B_c = \frac{\mu_c N_c I}{l_c} \cdot \left( 1 + \frac{\mu_c l_p S_c}{\mu_p l_c S_p} \right)^{-1} \dots\dots\dots(2)$$

where  $\mu$  is the permeability;  $N_c$  is the number of turns in the coil winding;  $I$  is the current that flows through the coil;  $l$  is the length of the flux path;  $S_c$  and  $S_p$  are respectively the flux path cross-sectional areas of the core and the attached steel plates. When the sensing coil is excited with an AC voltage source  $V^{AC}$  through a large resistor  $R_{ext}$ , then the AC current  $I^{AC}$  becomes  $V^{AC}/I^{AC}$ , where  $R^{AC} = R_{coil} + R_{ext}$  and  $R_{coil}$  is the internal resistance of the core coil. From the equivalent magnetic circuit as shown in Fig. 3(b), the flux sensor output  $V_{OUT}$  is calculated as

$$V_{OUT} = \omega L_T I^{AC} + R_{coil} I^{AC} \dots\dots\dots(3)$$



(a) Schematic diagram of a flux sensor



(b) Equivalent magnetic circuit of (a)

Fig. 3. Schematic diagram of a magnet, a flux sensor and an equivalent circuit.

where  $\omega$  is the angular velocity and  $L_T$  is the sum of the self inductance of the sensing coil  $L_s$  and the mutual inductance  $L_{cs}$  between the sensing coil and the magnet core coil. Consequently, it follows that

$$L_T = L_{cs} + L_s = \frac{N_s B_c S_s}{I_c} + \frac{N_s B_s S_s}{I^{AC}} \dots\dots\dots(4)$$

where the subscripts c and s denote the core coil and the sensing coil respectively, and  $N_s$  is the number of turns of the sensing coil.  $L_s$  is constant for an AC voltage source, but from Eqs. (2) and (4),  $L_{cs}$  varies in proportion to the thickness of the plates attached to the magnet.  $L_T$  thus depends on  $B_c$  due to the first term of Eq. (4) and so does  $V_{OUT}$ . According to Eq. (3), the output  $V_{OUT}$  increases as more plates are attached to the magnet.

Two magnetic flux sensors are installed on each magnet of the G2 crane at POSCO's No. 2 thick steel plate storage yard. Each G2 crane comes with five lifting magnets, so there are ten flux sensors installed on each crane. For sensor durability and cabling efficiency, a module was designed, through which the crane controller acquires sensor outputs. The output of the sensor is in the range of 0–10 V and is converted to a digital value from 0 to 4 096. **Figure 4** shows a sensor profile measured from the G2 crane with three magnets. When the plates are fully attached to the magnets, the sensor outputs increase and become stable once the transient period is over. Because the VME system can receive 10 outputs per second, it takes about three seconds for the output to be stable. The sensor output difference between the initialization and the attachment depends on the number of plates attached to the magnets. This difference enables the crane controller to determine either a 'partially-attached' or 'fully-attached' condition as well as the number of attached plates.

**3. Magnet Voltage Control**

**3.1. Modeling**

**Figure 5(a)** shows a conceptual drawing of the magnet with the attached steel plates and the flux path that passes through them. The magnet crane lifts the steel plates 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 the flux that stores energy in the magnetic field. The minimum amount of current required to lift the steel plates is that which produces enough magnetic force to overcome gravitational force.

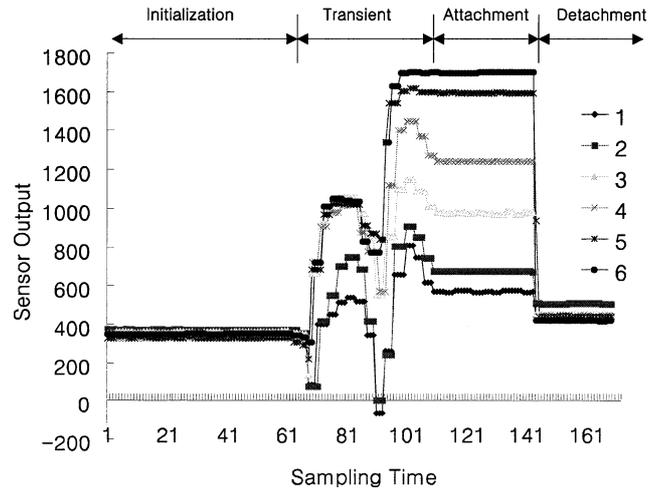
According to Poynting's theorem,<sup>7)</sup> the stored magnetic energy  $E_m$  becomes

$$E_m = \frac{1}{2} \int_{vol} B \cdot H dv \dots\dots\dots(5)$$

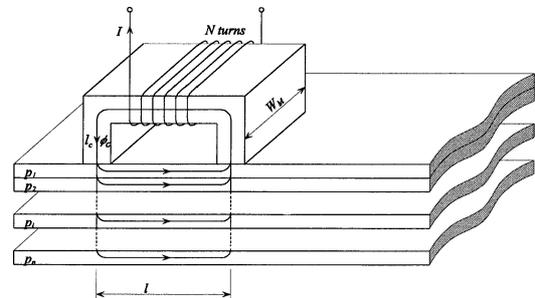
and substituting  $B = \mu_0 H$  and  $\phi_g = BS_g$  into Eq. (5) yields

$$E_m = \frac{\phi_g^2 l_g}{2\mu_0 S_g} \dots\dots\dots(6)$$

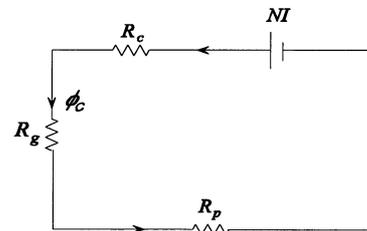
where  $\mu_0$  is the air permeability;  $\phi_g$  is the flux that passes through the air gap;  $l_g$  is the air gap distance;  $S_g$  is the cross-



**Fig. 4.** Output profile of No. 1 flux sensor measured with 8 mm plates.



**(a) Flux path of the magnet and steel plates**



**(b) Equivalent circuit of (a)**

**Fig. 5.** The simplified flux path of steel plates attached to a magnet and its equivalent circuit.

sectional area of the flux path. Since the change in flux between the magnet and the plates is caused by a virtual differential displacement  $dl_g$ , the change of stored magnetic energy becomes

$$dE_m = 2 \frac{dl_g}{2\mu_0 S_g} \phi_g^2 \dots\dots\dots(7)$$

where the coefficient 2 reflects the fact that the magnetic force is generated at both ends of the magnet shoe. Dividing  $dE_m$  by  $dl_g$  determines the force  $F_m$  which is large enough to lift the plate:

$$F_m = \frac{dE_m}{dl_g} = 2 \frac{1}{2\mu_0 S_g} \phi_g^2 \geq g\rho \sum_{i=1}^n t_i W_i L_i \dots\dots\dots(8)$$

where  $g$  is the gravitational acceleration;  $\rho$  is the density of the steel plates;  $t_i$ ,  $W_i$  and  $L_i$  are respectively the thickness,

the width and the length of the  $i$ th plate.  $\phi_g$  is then obtained from Eq. (8) as

$$\phi_g \geq \sqrt{\mu_0 S_g g \rho \sum_{i=1}^n t_i W_i L_i} \dots\dots\dots(9)$$

Note here that  $\phi_g$  is equal to  $\phi_c$  which is the flux that passes through the magnet core.

From the equivalent magnetic circuit as shown in Fig. 5(b), we obtain

$$N_c I = (R_c + R_g + R_p) \phi_c \dots\dots\dots(10)$$

where  $N_c$  is the number of turns in the coil winding;  $I$  is the current that flows through the coil;  $R_c$ ,  $R_p$  and  $R_g$  denote respectively the reluctance values of the core, the plates and the air gap. Substituting  $\phi_c$  obtained from Eq. (9) into Eq. (10) yields the required coil current  $I$  as

$$I \geq \frac{1}{N_c} (R_c + R_g + R_p) \sqrt{\mu_0 S_g g \rho \sum_{i=1}^n t_i W_i L_i} \dots\dots\dots(11)$$

Currently, the actuators of the magnet crane use voltage sources as power sources and thus the computer system gives a voltage command  $V$  to the rectifier to generate the actuating current. Since  $I = V/R_a$  where  $R_a$  is the actuator reluctance, Eq. (11) can be rewritten as

$$V \geq \frac{R_a}{N_c} \left( \frac{l_c}{\mu_c S_c} + \frac{2l_g}{\mu_0 S_g} + \frac{l_p}{\mu_p S_p} \right) \sqrt{\mu_0 S_g g \rho \sum_{i=1}^n t_i W_i L_i} \dots\dots\dots(12)$$

where  $S_c$ ,  $S_p$  and  $S_g$  are respectively the cross-sectional areas of the core, the plates and the air gap and  $l$  is the length of the flux path.

**3.2. Implementation**

$\mu_0$ ,  $l_c$ ,  $l_g$ ,  $l_p$ ,  $S_g$  and  $S_c$  in Eq. (12) are constants and so are  $2l_g/(\mu_0 S_g)$  and  $\sqrt{\mu_0 S_g g \rho}$ ; On the other hand,  $\mu_c$ ,  $\mu_p$  and hence  $l_c/(\mu_c S_c)$  can be considered as constants around the operating point because  $B$  and  $H$  are linearly related in the vicinity of a specific operating point. But  $S_p$  in the term  $l_p/(\mu_p S_p)$  is equal to  $\sum_{i=1}^n t_i W_M$ , where  $W_M$  is the minimum width of the magnet and the plates. Considering these facts, Eq. (12) can be written as:

$$V \geq \left( C_1 + C_2 \frac{1}{\sum_{i=1}^n t_i} \right) \sqrt{\sum_{i=1}^n t_i W_i L_i} \dots\dots\dots(13)$$

where  $C_1$  and  $C_2$  are the constants that hold in the vicinity of operating points or for the plates with similar sizes. Hence  $C_1$  and  $C_2$  can be determined by measuring voltages for two different plates with similar length, width, and thickness.

In real operation,  $C_1$  and  $C_2$  are determined by using the experimentally determined **Table 1**. The plates used in Table 1 are standard plates with the same width and length but with different thickness values. The selected values are 2400 mm in width and 6800 mm in length, which are denoted by  $W_c$  and  $L_c$  respectively. Table 1 records the mini-

**Table 1.** The minimum voltage to lift the set number of plates with set thickness value.

$n \setminus t(mm)$	6	8	10	12	15	20	30	40	50
1	7	9	10	12	20	25	40	45	50
2	11	18	30	31	40	50	220	220	220
3	23	34	35	55	220	220	X	X	X
4	30	50	55	220	220	X	X	X	X
5	42	80	220	220	X	X	X	X	X
6	60	220	220	X	X	X	X	X	X
7	140	220	X	X	X	X	X	X	X
8	220	X	X	X	X	X	X	X	X
9	220	X	X	X	X	X	X	X	X

um voltage values required to lift the set number of standard plates. The plates of 6, 8, 10, 12, 15, 20, 30, 40 and 50 mm thickness values are common at POSCO's thick steel plate storage yard and the maximum thickness value that the magnet flux can manage with maximum 220 V voltage is 50 mm. Consequently, the maximum number of plates  $n_{max}$  that the magnet crane can lift can be easily calculated. For example,  $n_{max}$  is 8 for plates with 6 mm in thickness and it is 6 for plates with 8 mm in thickness.

Using Table 1, we can calculate the minimum voltage  $V_n$  required to lift  $n$  plates, each with thickness  $t_i$ , width  $W_i$ , and length  $L_i$  for  $i=1, \dots, n$  as follows. We first calculate the mean thickness  $t_a$  of these plates and determine the column index  $k$  that renders  $t_a$  to be in  $(t_k, t_{k+1})$ , where  $t_k$  and  $t_{k+1}$  are the sample thickness values in the top row of Table 1. Then,  $C_1$  and  $C_2$  can be calculated by choosing  $v_{nk}$  and  $v_{n(k+1)}$  from Table 1, where  $v_{ij}$  is the voltage value of the  $i$ th row ( $i=1, 2, \dots, 8, 9$ ) and the  $j$ th column ( $j=1, 2, \dots, 9$ ). From Eq. (13), we have  $v_{nk} = (C_1 + C_2 \cdot (1/nt_k)) \sqrt{W_c L_c nt_k}$  and  $v_{n(k+1)} = (C_1 + C_2 \cdot (1/nt_{k+1})) \sqrt{W_c L_c nt_{k+1}}$ , from which we obtain

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{nt_k} \\ 1 & \frac{1}{nt_{k+1}} \end{bmatrix}^{-1} \begin{bmatrix} \frac{v_{nk}}{\sqrt{W_c L_c nt_k}} \\ \frac{v_{n(k+1)}}{\sqrt{W_c L_c nt_{k+1}}} \end{bmatrix} \dots\dots\dots(14)$$

Note here that it is also possible to calculate  $C_1$  and  $C_2$  by selecting  $v_{nk}$  and  $v_{(n+1)k}$ . In this case,  $C_1$  and  $C_2$  are derived as

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{nt_k} \\ 1 & \frac{1}{(n+1)t_k} \end{bmatrix}^{-1} \begin{bmatrix} \frac{v_{nk}}{\sqrt{W_c L_c nt_k}} \\ \frac{v_{(n+1)k}}{\sqrt{W_c L_c (n+1)t_k}} \end{bmatrix} \dots\dots\dots(15)$$

Finally,  $V_n$  is calculated from Eq. (13) by using  $C_1$  and  $C_2$  determined either from Eq. (14) or from Eq. (15). Because  $V_n$  is the minimum voltage required to lift  $n$  plates, the recommended voltage  $V_R$  to lift  $n$  plates is selected as

$$V_R = \frac{V_n + V_{n+1}}{2} \dots\dots\dots(16)$$

Note in Table 1 that the entry  $v_{(n_{max}+1)k}$ , which is 220 V, is intentionally added for each column in order to calculate  $V_R$  to lift  $n_{max}$  plates. The above algorithm has been tested on the G2 crane in the POSCO storage yard and the success rate of lifting the correct number of plates on the first trial was 100% when we deal with plates with thickness values greater than or equal to 10 mm, but was relatively poor for plates with thickness values less than 10 mm. A more refined look-up table was therefore required especially for plates with thickness values less than 10 mm. To this end, Table 1 is first augmented with other standard plates and **Table 2** is generated. These plates are ones that are produced in POSCO and with 14, 16, 18, 22, ..., 46, 48 mm thickness values. Table 2 is simply an expanded version of Table 1 in that it includes these other standard plates in the table. Because the experimental data are not available for these plates, the minimum voltage entries corresponding to them are then calculated by using Eqs. (13) and (14). As with Table 1, we use Table 2 to calculate the minimum voltage  $V_n$  required to lift  $n$  plates, each with different dimension.

In case the crane fails to lift the exact number of plates by using Table 2, we tune the table on-line as follows. When the number of lifted plates  $N$  is larger than that of ordered plates  $n$ , the reference voltage  $V_R = (V_n + V_{n+1})/2$ , which is meant to lift  $n$  plates, actually lifted  $N$  plates. Hence, the entries  $v_{Nk}$  and  $v_{(N+1)k}$  must be replaced with  $v_{nk}$  and  $v_{(n+1)k}$  to lift  $N$  plates:

$$v_{Nk} \Leftarrow v_{nk}, v_{(N+1)k} \Leftarrow v_{(n+1)k} \dots\dots\dots(17)$$

This change must also be reflected on the intermediate entries  $v_{nk}, \dots, v_{(N+1)k}$ , which can be adjusted by using Eqs. (13) and (15). Equation (15) was used here instead of Eq. (14) because the column entries in Table 2 need to be updated. When  $n \geq 2$ , the reliable entries  $v_{(n-1)k}$  and  $v_{Nk}$  are selected to calculate  $C_1$  and  $C_2$  in Eq. (13) as

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{(n-1)t_k} \\ 1 & \frac{1}{Nt_k} \end{bmatrix}^{-1} \begin{bmatrix} \frac{v_{(n-1)k}}{\sqrt{W_e L_e (n-1)t_k}} \\ \frac{v_{Nk}}{\sqrt{W_e L_e Nt_k}} \end{bmatrix} \dots\dots\dots(18)$$

and  $v_{(n+j)k}$  for  $0 \leq j \leq N-n-1$  are then updated as

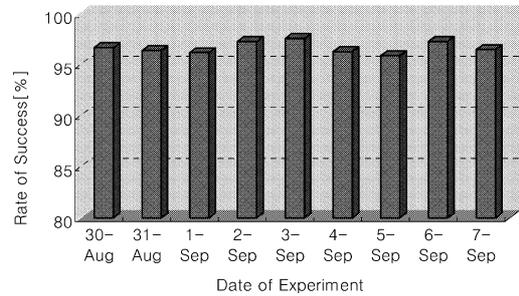
$$v_{(n+j)k} \Leftarrow \left( C_1 + C_2 \frac{1}{(n+j)t_k} \right) \sqrt{W_e L_e (n+j)t_k} \dots\dots(19)$$

In case  $n=1$ , Eq. (18) can not be used to calculate  $C_1$  and  $C_2$  due to the term  $1/((n-1)t_k)$ . Thus,  $C_1$  and  $C_2$  are calculated as in Eq. (15) by choosing  $v_{Nk}$  and  $v_{(N+1)k}$ , and  $v_{(1+j)k}$  for  $0 \leq j \leq N-2$  are then updated as in Eq. (19).

When the number of lifted plates  $N$  is less than that of ordered plates  $n$ , the entries  $v_{Nk}$  and  $v_{(N+1)k}$  are replaced with  $v_{nk}$  and  $v_{(n+1)k}$  as in Eq. (17). Since  $v_{Nk}$  and  $v_{(N+1)k}$  are already updated, the intermediate entries  $v_{(N+2)k}, \dots, v_{(n+1)k}$  must be adjusted by using Eqs. (13) and (15). By using  $v_{(N+1)k}$  and  $v_{(n+2)k}$ ,  $C_1$  and  $C_2$  in Eq. (13) are calculated first

**Table 2.** The expanded minimum voltage look-up table.

$n \setminus t(m)$	6	8	10	12	14	...	46	48	50
1	7.0	9.0	10.0	12.0	17.5	...	48.1	49.0	50.0
2	11.0	18.0	30.0	31.0	37.2	...	220.0	220.0	220.0
3	23.0	34.0	35.0	55.0	168.8	...	X	X	X
4	30.0	50.0	55.0	220.0	220.0	...	X	X	X
5	42.0	80.0	220.0	220.0	220.0	...	X	X	X
6	60.0	220.0	220.0	X	X	...	X	X	X
7	140.0	220.0	X	X	X	...	X	X	X
8	220.0	X	X	X	X	...	X	X	X
9	220.0	X	X	X	X	...	X	X	X



**Fig. 6.** Initial success rate.

as

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{(N+1)t_k} \\ 1 & \frac{1}{(n+2)t_k} \end{bmatrix}^{-1} \begin{bmatrix} \frac{v_{(N+1)k}}{\sqrt{W_e L_e (N+1)t_k}} \\ \frac{v_{(n+2)k}}{\sqrt{W_e L_e (n+2)t_k}} \end{bmatrix} \dots\dots(20)$$

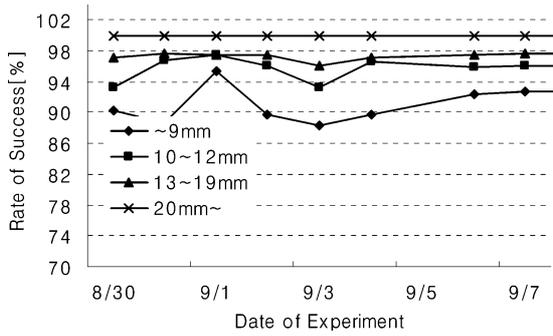
and  $v_{(N+2+j)k}$  for  $0 \leq j \leq n-N-1$  are then updated as

$$v_{(N+2+j)k} \Leftarrow \left( C_1 + C_2 \frac{1}{(N+2+j)t_k} \right) \sqrt{W_e L_e (N+2+j)t_k} \dots\dots\dots(21)$$

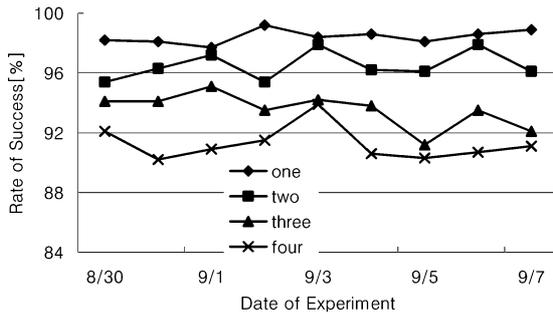
The algorithm has been applied to the G2 crane for nine days from Aug. 30, 2002 to Sep. 7, 2002 and the results were collected and the initial success rate were also recorded. The initial success rate was approximately 95% as shown in **Fig. 6**. Compared with an experienced operator's success rate of 70%, these results are quite promising. From **Figs. 7(a)** and **7(b)**, the success rate becomes lower as the plates become thinner and as the number of plates increase. But thin plates are also difficult for the operators to deal with and these results are superior to that of the operators.

**4. Hardware and Software Configuration of the Crane System**

POSCO's storage yard for thick steel plates is shown in **Fig. 8**; it is about 83 200 m<sup>2</sup> in area and has a storage capac-



(a) Initial success rate with respect to thickness



(b) Initial success rate with respect to the number of plates

Fig. 7. Initial success rate.



Fig. 8. View of POSCO's No. 2 steel plate storage yard.

ity of 146 000 tons. There are 1 086 places to stack steel plates, each of which is about 4.5 m in width and 6 m in length. There are 23 overhead magnet cranes, each of which covers an area of about 30 m in width and 150 m in length. Under automated crane operation, the crane controller installed in the operation room serves the role of both crane operator and assistant. The controller system is VMEbus-based and consists of a CPU board, two serial communication boards, and a DIO (digital input/output) board. The VM40 CPU board which is equipped with an MC68040 (25MHz) processor with 4MB DRAM, 2MB SRAM, and 4MB FLASH ROM has the VRTXsa real-time operating system kernel installed, and runs the application programs. Two VMOD-2 boards with eight serial ports interface with the sensors. These serial communication ports receive crane positions from laser sensors, communicate with the ground station, the crane motor, and the magnet voltage control PLC, receive height information of the two grabs from the



Fig. 9. Lifting the plates about 30 cm above the stack.

encoders, interface with the LCD, and receive keyboard inputs and magnetic flux sensor outputs. RS422 protocol is used on full-duplex mode at 19 200 bps without parity check. The DIO board is used for device fault LEDs, and the emergency buzzer.

The ground station manages overall crane work schedules in the thick steel plate storage yard, sends yard map and stacked plate information to the crane controller, and receives crane position, device fault information, and others from the crane controller. The ground station communicates with the crane controller by using an optical modem and the RS422 communication port connects the VME system to the optical modem.

The positions of the crane in the two dimensional plane parallel to the ground are measured by lasers, and the distance from the crane to the lowered lifting magnet is measured by the encoder. The command to move the crane is first given to the PLC and the corresponding current command is given to the motor drive. By reading data from the lasers and the encoders continuously, the crane controller controls crane positions with high accuracy. Once the distance between the current position and the target position is determined, the crane controller sequentially sends acceleration commands from the start until the crane reaches 10% of the distance, maintains constant speed until it reaches 90% of the distance, then issues deceleration commands until it reaches the destination. In case of emergency, the emergency switches installed on all three axes will automatically stop the operation.

Once the reference voltage to drive the magnet is calculated by the proposed algorithm, the PLC gives this amount of voltage to the rectifier drive. Then the plates are lifted to about 30 cm above the stack as shown in Fig. 9. The detection algorithm introduced in Sec. 2 counts the number of lifted plates. If the detected number of plates is the same as the ordered one, the flux sensors confirm the number and if the plates are fully attached, then the crane moves the plates to the destination position. When an excessive number of plates is lifted, the crane controller gradually decreases the amount of voltage to drop the plates one by one. As soon as the expected number of plates is dropped, the voltage is quickly increased so that the remaining plates are kept attached. Conversely, when the number of lifted plates is less

than the ordered one, the controller lowers the trolley to place the lifted plates back on the stack, increases the amount of voltage and lifts more plates, and checks if the correct number of plates are attached. For both cases, the look-up table is tuned on-line with and these results are superior to that of the operators.

## 5. Conclusion

In this paper, an automatic operation scheme of overhead magnet crane is presented for the thick steel plate storage yard. Two important features of the presented automation system are: the detection unit of the number of steel plates attached to the lifting magnets and the voltage control mechanism of the lifting magnets. The hardware and software configurations are also presented. The proposed automation system has been installed at POSCO's No. 2 thick steel plate yard and has been in operation for about three years. Without operators and assistants, the automated sys-

tem has been operating reliably in a harsh field environment and reduces up to 6 human operators and assistants per crane.

## REFERENCES

- 1) S. Y. Park, J. S. Lee, J. Y. Choi and B. H. Park: Automatic Current Control of Magnet Cranes for Steel Plate Yard Automation, IFAC Control Engineering Practice, No. 6, Elsevier Science Ltd., Oxford, (1998), 1193.
- 2) B. K. Kang, S. D. Kim and J. S. Lee: *Sens. Actuators A*, **65** (1998), 203.
- 3) J. S. Lee and B. H. Park: The field application of study of sensing the number of plates and control systems, Tech. Report, RIST, (1994).
- 4) B. G. Kang and J. S. Lee: The development of magnetic sensor for plate control, Tech. Report, RIST, (1996).
- 5) K. Bethe: *Sens. Actuators A*, **52** (1996), 99.
- 6) MICROTEC, *VRTXsa* Programmer's Guide, Microtec Research, Santa Clara, CA, (1996).
- 7) W. T. Scott: *The Physics of Electricity and Magnetism*, 2nd Ed., John Wiley & Sons, New York, (1996).