Design of an Automated Mobile Rack Using Repetitive Control Method

Hwanseong Kim, Yunsu Ha, and Kyoungmi Cheon

***Abstract*—Non-rail mobile rack, which is used for cargo storage, can improve the storage capacities of logistics centers. Furthermore, it has the advantage that it can be used in traditional logistics centers without making any changes or renovation, such as installing rails.**

However, when the rack is operated by separated drive actuators mounted on the left and the right wheels, precise position control of the wheels is necessary even if the unbalanced cargo weight on the rack would affect the control. Therefore, internal synchronization control for position tracking between the left and right wheels on the non-rail mobile rack is necessary in this study. In addition, external synchronization control for realizing the same straight movements between mobile racks is necessary.

For the internal and the external synchronization control, we propose a synchronization control algorithm based on the repetitive control theory. An internal synchronization control algorithm with repetitive control theory requires the application of the robust servo control method owing to parameter variations. In this case, we can set up the gains for the robust servo control system by considering the cargo variations on the mobile rack. Furthermore, for developing the external synchronization control algorithm, we use a double repetitive control system to perform synchronization control between mobile racks. The efficiency of the proposed control algorithm will be verified by simulation and experimental results. The proposed algorithm can be easily applied in the industry.

***Index Terms*—Non-rail, mobile rack, synchonization, repetitive control.**

I. Introduction

The 21st century is also called the “digital revolution” era after its rapid transition into scientific and informationized society with fast development in IT(Information Technology). In logistics industry, the automatic system based on IT is being widely used to minimize the cost in logistics. Logistics management system is also being developed for cheap and fast logistics services.

Moreover, the development in logistics management system enables multiple small orders for online and home shopping to be done quickly and accurately and also contributing to the logistics service demands in high value-added products such as pharmaceuticals. However, the current advanced equipment as well as the logistics equipment (the hardware of the logistics management system) are relying on imported products which are expensive.

Recently, the necessity to actualize the technology to improve the logistics operation in terms of rapidity, flexibility and lightness considering the variety of cargo and the frequent shipping & receiving is increasing in South Korea. Also, it’s necessary to develop comprehensive facilities that can store, categorize, ship and receive variety of products other than just storing products. These kinds of facilities can reduce the manpower at logistics center by 50% and improve efficiency at storing, thus reducing the floor space up to 40% overall [1].

Currently, there are issues about fixed shelf not being space-efficient and there are not many cases in which related products released from Japan, Europe and South Korea have been used in logistics center. Also, the mobile racks from the market in South Korea are limited on forward and backward mobile motors and related safety devices only.

Therefore, in this study, the structure and condition of non-rail mobile rack that can be installed in wide range of forms is analyzed. Through this, the property of corresponding system is known form the mathematical modelling. Assuming the 3-tiers pallet stacking, linear differential equation and state equation are derived considering the weights of cargo and mobile rack base and related matters for mathematical modelling of mobile rack.

Later, robust servo control system that is immune to parameter variation is designed and its simulation is reviewed for the synchronization controller of mobile racks. Also, designing the repetitive controller and verification by simulation for synchronization drive control of mobile rack’s left and right motor is necessary. After this, synchronization control algorithm using servo control system and repetitive control method is proposed and its effectiveness is verified through simulation and experiments.

II. Modeling of Mobile Rack

A. Mobile Rack Model

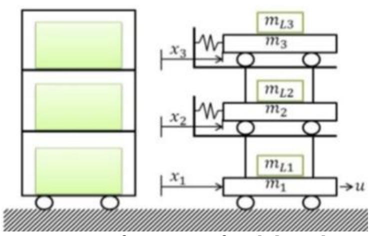

Fig. 1. Configuration of mobile rack.

In this paper, 3 tiers pallet mobile rack will be considered with motor driven and geared type power transmitter. The

Manuscript received November 11, 2016; revised April 3, 2017. This work was supported by Transportation & Logistics Research Program (Grant No: 79281) funded by Ministry of Land, Infrastructure and Transport Affairs of the Korean government.

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doi: 10.18178/ijmmm.2018.6.2.362

weight of mobile rack will be changed by the weight of cargo and its distribution on the rack. Also, the model of mobile rack is considered by using the drawing of mobile rack and it will be shown in Fig. 1.

Based on the concept of mobile rack, the mathematic equation eq. (1) will be induced by using differential equation, where the stiffness coefficient of post and weight of cargo also considered [2]-[4].

$$\begin{gathered} m_{1L3}\ddot{x}_1 + k(x_1 - x_2) + B\dot{x}_1 = u \\ m_{2L3}\ddot{x}_2 + k(x_2 - x_1) + k(x_2 - x_3) = 0 \\ m_{3L3}\ddot{x}_3 + k(x_3 - x_2) = 0 \end{gathered} \tag{1}$$

where, $m_{1L3} = m_1 + m_{L1} + m_2 + m_{L2} + m_3 + m_{L3}$, $m_{2L3} = m_2 + m_{L2} + m_3 + m_{L3}$, $m_{3L3} = m_3 + m_{L3}$, $k = 2\left(\frac{3EI}{L^3}\right)$, and E is stiffness coefficient, $I = \frac{d_2 d_1^3 - (d_2 - d_t)(d_1 - d_t)^3}{12}$ is geometrical moment of inertial, $d_1 = d_2$ is the thickness of post beam.

B. State Equations for Mobile Rack

From the above differential equation (1), a state equation can be obtained as Eq. (2) [5, 6].

$$\begin{gathered} \dot{x}(t) = Ax(t) + Bu(t) \\ u(t) = Cx(t) \end{gathered} \tag{2}$$

where,

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{-k}{m_{1L3}} & \frac{k}{m_{1L3}} & 0 & \frac{-B}{m_{1L3}} & 0 & 0 \\ \frac{k}{m_{2L3}} & \frac{-2k}{m_{2L3}} & \frac{k}{m_{2L3}} & 0 & 0 & 0 \\ 0 & \frac{k}{m_{2L3}} & \frac{-k}{m_{3L3}} & 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{m_{1L3}} \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix}$$

In this paper, the parameter of mobile rack will be considered to design the controller as in Table I.

TABLE I: PARAMETER VALUES OF MOBILE RACK

Parameters	Values
m_1	50 [kg]
m_2	25 [kg]
m_3	25 [kg]
m_L	6,000 [kg]
L	1.3 [m]
E	2.05×10^{15} [kg f/m^2]
d_1	0.85 [m]
d_2	0.55 [m]
d_{t1}	0.32 [m]
d_{t2}	0.23 [m]

III. DESIGN OF SYNCHRONIZATION CONTROLLER

In logistics center, the job schedule will be adjusted by cargo staking condition and loading/unloading job orders. Also the dimension of mobile rack will be selected by considering the main cargo characteristics of customer. At this time, the total weight of mobile rack and its weight distribution will be important role. Also the mobile rack have to be controlled by considering job schedule and its operation conditions.

Also, the mobile rack cannot be controlled by conventional servo control algorithm due to the heavy weight change [12]. To synchronize the mobile rack control, sliding mode controller based on GA is suggested [7], but it is not useful to apply the mobile rack system.

Thus, a simple program for PLC or industrial computer would be required in this paper. In this paper, we will propose a simple algorithm for designing the synchronization controller by using robust servo controller and repetitive algorithm.

A. Design of Robust Servo Controller

First of all, we propose a simple robust servo control by considering the variation of cargo weight. In the design of robust servo control, the inner model have to be considered by target reference model or perturbation model as in Fig. 2 [8].

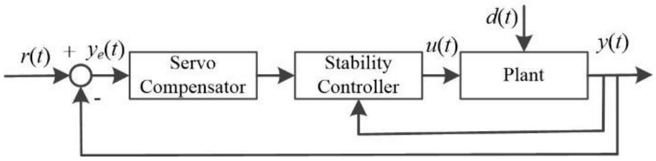

Fig. 2. Servo system considering parameter variations.

[Theorem 1] [8]: For the time invariant system with n system order, m input order and p output order, robust servo control is exist if and only if

$$rank \begin{bmatrix} A & B \\ C & 0 \end{bmatrix} = n + p \tag{3}$$

Eq. (2) for the model of mobile rack satisfy the [Theorem 1]. So, the robust servo controller can be designed as following steps [8].

[Step 1] Consider the following augmented system

$$A_e = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix}, B_e = \begin{bmatrix} 0 \\ I_m \end{bmatrix}, D_e = \begin{bmatrix} I_n \\ 0 \end{bmatrix}, C_e = \begin{bmatrix} C & 0 \end{bmatrix} \tag{4}$$

[Step 2] Set the weighting matrices Q_e and R_e, where Q_e is $(n+m)$ order non-positive symmetric matrix and R_e is m order positive symmetric matrix. And we can set as $Q_e = C_e^T C_e$

[Step 3] Solve the following Riccati equation P_e

$$A_e^T P_e + P_e A_e + Q_e - P_e B_e R_e^{-1} B_e^T P_e = 0 \tag{5}$$

[Step 4] Calculate optimal gain

$$F_e F_e = R_e^{-1} B_e^T P_e \tag{6}$$

[Step 5] Obtain optimal control gains K_1 and K_2

$$F_e Z^{-1} = (K_1 \quad K_2) \tag{7}$$

where, $Z = \begin{bmatrix} A & B \\ C & 0 \end{bmatrix}$

[Step 6] Calculate control input $u(t)$ by using optimal control gains

$$u(t) = -K_1 x(t) + K_2 \int_0^t u_e(t)dt + K_1 x(0) \tag{8}$$

In the mobile rack model, the optimal control gains K_1 and K_2 will be obtained as

$$K_1 = [59.04 \;\; 0.11 \;\; 0.05 \;\; 6.41 \;\; 3.76 \;\; 1.88] \tag{9a}$$
$$K_2 = 1.7321 \tag{9b}$$

By using obtained optimal control gains in Eq. (9), the robust servo controller can be constructed and its simulation results is shown in Fig. 3 [9, 10]. Here, the results show the overshot results for cargo weight, but it will be reduced by adjusting the weighting matrices Q_e and R_e, respectively. Also the results will be improved by using repetitive algorithm.

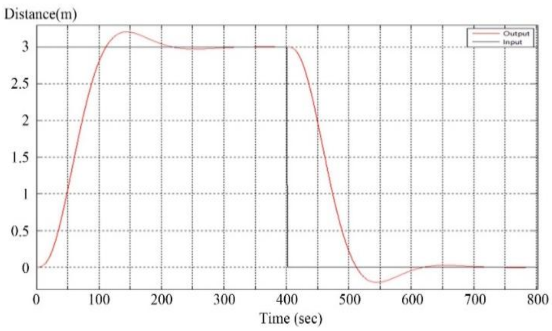

Fig. 3. Step response of robust servo control system.

B. Design of Repetitive Servo Controller

The repetitive control system as in Fig. 4 makes a compensator which have a fixed L period by internal model principle [11]-[14] for tracking the given periodic reference or rejecting the external disturbance with fixed period.

If a model which based on the internal model principle is inserted into the inside of closed-loop control system, the control system can tracks a reference signal with a period L or rejects a disturbance with a period L.

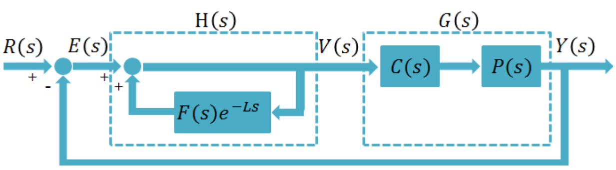

Fig. 4. Repetitive control system.

A periodic function with a period of L can compensate error on every period L after memorizing each corresponding function data. We call this periodic compensation function as the repetitive control system [11]-[14].

Fig. 2 shows the block diagram of a typical repetitive control system in which $P(s)$ is the transfer function of the plant to be controlled, and $C(s)$ is the controller designed to stabilize the closed loop system. The repetitive control system in Fig. 4 can be rewritten as eq. (10).

$$H_F(s) = \frac{1}{1 - F(s)\, e^{-Ls}} \tag{10}$$

In Fig. 4, $G(s)$ which have a compensator and control functions is given as eq. (11)

$$G(s) = P(s)C(s) \tag{11}$$

The repetitive control system in Fig. 4 will stable under the following conditions

(i) $[1 + G(s)]^{-1} G(s)$ is a stable function and there is no pole-zero cancellation between $P(s)$ and $C(s)$.

(ii) $Q_F(s) \approx F(s)[1 + G(s)]^{-1}$ is satisfied $\|Q_F(s)\| < 1$

where, condition (i) equals that the control system is internally stable. Also condition (ii) can be rewritten as

$$||(1 + G(s))^{-1}|| \approx \sigma[1 + G(j\omega)]^{-1} = \frac{1}{\sigma[1+G(j\omega)]^{-1}} \tag{12}$$

where, if the value of $[1 + G(j\omega)]^{-1}$ is smaller, then the $|F(j\omega)|$ will be bigger, i.e. , the repetitive control system with high tracking performance can be obtained. That is means that the wider bandwidth of $F(j\omega) \approx 1$ can make small steady state error. So, if $F(s)$ is selected with the above conditions, then the tracking performance can be improved.

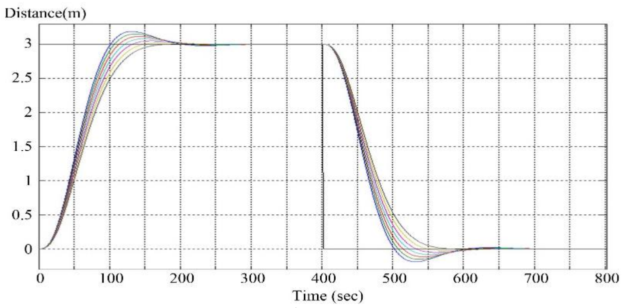

Fig. 5. Step response of repetitive control system.

In this paper, the simulation results is obtained by using 5 times repetitive control system and it is shown in Fig. 5. In the results, the overshoot showed in first period will be disappeared in 5th period.

C. Synchronization Controller Using Repetitive Control Method

To construct the synchronization control system, we decide the master and slave mobile rack and we set up the reference input for mobile rack movement. For the master mobile rack, we insert reference input and make a synchronization control for slave mobile rack to follow the master's reference inputs.

For this, we distinguish the inner synchronization and outer synchronization. The inner synchronization make synchronize the each wheels for mobile racks. And outer synchronization make synchronize the slave to follow the master mobile rack.

In simulation, 1 mobile rack is assumed for master and other 3 mobile rack are assumed for slave. The synchronization control algorithm is constructed as in Figure 6, where inner and outer synchronization controllers include the repetitive algorithm.

By using synchronization control algorithm, single mobile rack will be controlled for tracking the reference. For the simulation, with/without synchronization algorithm will be compared, respectively.

Fig. 7 and Fig. 8 show the simulation results with/without repetitive control algorithms, respectively. By adjusting parameters for simulation, the cargo weight can be changed in left and right side of mobile rack for weight unbalancing. Thus, we can see its effects on the beginning the simulation.

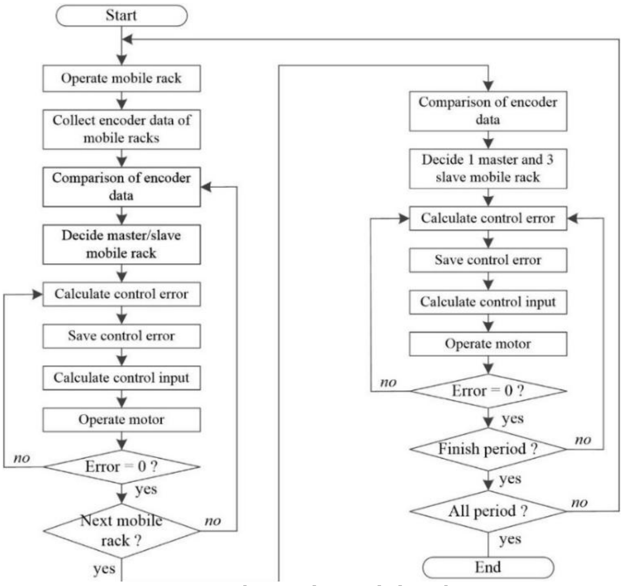

Fig. 6. Synchronized control algorithm.

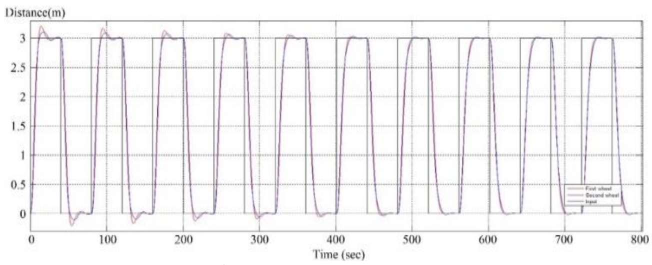

Fig. 7. Control response of repetitive controller without synchronized control algorithm.

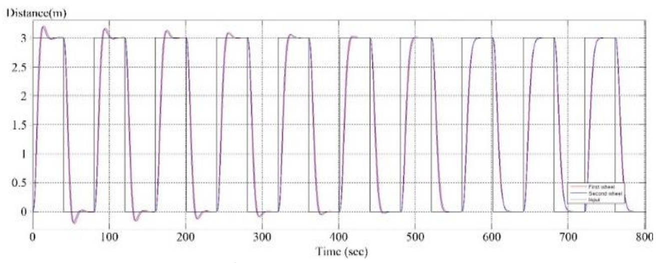

Fig. 8. Control response of repetitive controller with synchronized control algorithm.

Fig. 9 and 10 show the results of before and after synchronization control. As you can see in Fig. 9, the controller error is reduced by repeating the control period, but still there is control error.

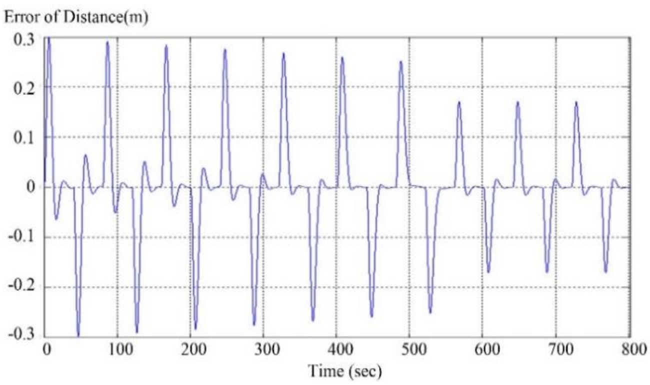

Fig. 9. Control response of repetitive controller without synchronized control algorithm.

However, Fig. 10 shows the simulation results for synchronization controller with inner loop. We can verify that the control error gradually reduced by repetitive control algorithm and the overshoot also is disappeared for 10 control period. And the error will be reduced about 43% by using synchronized control algorithm.

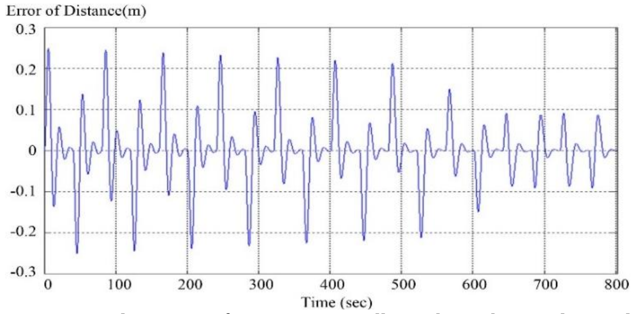

Fig. 10. Control response of repetitive controller with synchronized control algorithm.

IV. Experimental Results

A. Configuration of Experimental

In this section, we will verify the simulation results by using experiment of mobile racks. For configuration of experimental, we set 4 mobile rack up with 1/8 scale of real size as shown in Fig. 11.

The base module of mobile rack will be divided into two parts; drive part and control part. Also the mobile rack include 4 motors and wheels with 2 tiers pallet.


Fig. 11. Experimentation equipment.

The experimental equipment also includes PC for design the control gain and collect encoder data from Arduino Due by using Xbee communication. We use an Arduino Due to control the mobile rack by sending PWM input signal to DC servo motor driver [15], [16]. To check encoder data, the interrupt digital input is used to count the encoder pulse from DC motor.

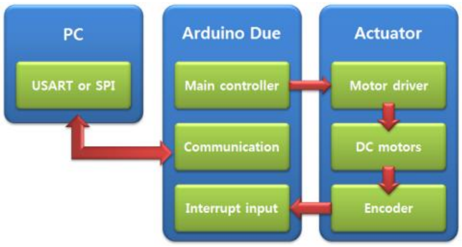

Fig. 12. System configuration of experimental model.

B. Experimental Results

In this experiment, the mobile rack with unbalanced load one side will be used for operation between fixed distances. Figs. 13 and 14 show the control error which obtained by encoder for synchronization control before and after, respectively.

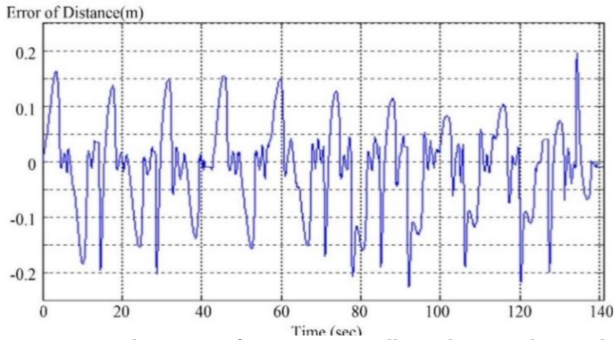

Fig. 13. Control response of repetitive controller without synchronized control algorithm.

Without synchronization controller, the irregular convergence of control error in Fig. 13. Also we can see that the control error is still big in forward and backward movements.

However in Fig. 14, the initial control error is similar to the result of Fig. 13, but the control error is gradually reduced by repeating the control period. Also the deviation of control error is small for forward and backward movements.

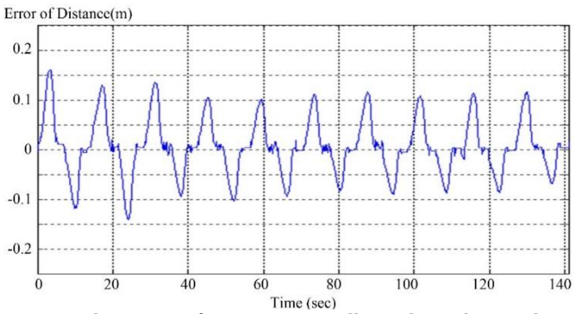

Fig. 14. Control response of repetitive controller with synchronized control algorithm.

V. Conclusions

In this paper, we proposed a synchronization control algorithm based on repetitive control method for internal and external synchronization about non-rail mobile rack. Also, the stabilization controller of this repetitive control method is designed using robust servo control system immune to parameter variation.

The effectiveness of synchronization controller is verified considering the robust servo control system which is not affected to the variation of cargo weights. And also the repetitive control method and driving wheel using mathematical modeling and the repetitive driving strategy by using simulation.

By using the designed the controller verified by simulation, the error of experimental collected within +12[mm] in the experiment using a model about 1/8 of actual size. However, the vibration from the electric power transmitter and lower part of the frame of the mobile rack used in this experiment affected the experimental errors. Henceforward, the development of designing the control system with improved electric power transmitter and flexible structure of the model is necessary.

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