Development of Automatic Operation System of Transfer Cranes

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Transfer cranes have been used for not only in container yards but also in steel mill yards. As conditions of use in both areas have become severe, and also the automation level required has become higher, we have developed a high level automation system for transfer cranes in order to respond to these requirements. This automatic transfer crane operation system has following characteristics.
(1) Transfer crane scheduling system with high efficiency, (2) Autosteer system of transfer cranes with precise position sensing system using image processing and a feedback control system, (3) Automatic container handling system with precise position control, precise anti-sway control, and container stacking guide, (4) Back up system using gyrocompass for autosteer control in case of obscured lines. In this paper we will introduce an outline of these points and our philosophy. In the last stage we will discuss some points about future trends.

1. Introduction
Tire-mount transfer cranes have the merit of obviating the need for rails, but require straight traveling control. For this reason, autosteer control for straight traveling was developed and marketed at an early stage. However, in the system developed initially, the detection of deviation from a straight line was done by detecting the magnetic field produced when an A.C. current was passed through an electric cable under the ground, and control was provided simply by feedback control of the distance and angle of the deviation. In view of providing aid to the operator’s operation, this control had a reasonable effect, but involved the following problems: (1) The work of laying the electric cable under the ground was required and once the cable was installed, it could hardly be moved. (2) Adequate accuracy could be guaranteed at constant traveling velocities on flat ground, but sometimes could not do so under conditions where the ground was inclined or trolleys were operated concurrently. With the increasing number of transfer cranes inside container yards and in the face of the present shortage of skilled operators, and the requirement for high efficiency in container handling, as a result, the requirement for the automation of operation of transfer cranes has increased, giving rise to a demand for unmanned systems in the near future.

2. Trend of container yard rationalization
The interrelationship of the container handling system as a whole in a container yard is shown in Fig. 1. For rationalization of container handling in a container yard, proceeding with the automation of individual components of the system, while matching or balancing them as a whole, is important. The plan to attempt their automation may be as shown in Fig. 2.

To realize automation of these system components, it is essential to proceed with the automation of all container cranes, chassis and transfer cranes, the main transfer equipment in a container yard using the transfer crane system. In particular, an attempt to convert the individual equipment into unmanned units has recently been undertaken. A container equipped with AGV has been developed and commercialized as equipment to replace the chassis. With regard to container cranes, an automation system has been commercialized, which enables high precision anti-sway control and positioning control, following the job sequence instructed by the central control room. To achieve high efficiency of the container yard as a whole, the efficient arrangement of transfer cranes is important. This requires a smaller number of transfer cranes to do efficient work in the automated container handling scheduling. Also, stable and high-accuracy traveling control in all unfavorable circumstances is necessary. At the same time, comprehensive elevation of the level of automation of these works is required.

3. Container handling scheduling
Among the container handling work done by transfer cranes, the shipping work is subjected to the strictest time schedule and therefore it should be given the highest priority. Since normally several transfer cranes are assigned to one container crane the object containers are first divided into groups corresponding to the scheduled number of cranes. At this time, they must be assigned so that not only the number of containers handled in each group is the same, but the total working time is minimized and the scheduled container handling sequence by the container crane shall be followed. Then, determining that the transfer cranes correspond to the

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respective container groups set up in this way is the second step. It is impractical to make calculations on the basis of all transfer cranes and all groups of containers combined and therefore a method of assigning them in the sequence of accessibility of each container to be handled was employed as a simplified method, though this could not give the truly optimum results.

If other containers are stacked on the object containers to be handled, their removal needs to be minimized. To overcome this difficulty, a scheduling system was devised by developing and employing a heuristic algorithm with the number of removals as the score, thereby enabling the determination of the optimum container handling sequence that would minimize the container handling time. A general idea of the scheduling system adopted for the realization of the above-mentioned object is shown in Fig. 3.

4. Autosteering (Transverse deviation control while traveling)

4.1 Basic concept and modeling

Tire-mount transfer cranes tended to meander owing to dented tires and on their accounts, autosteering control was commercialized at an early stage. However, with a control performance as low as ±150 mm, it could hardly meet recent strict operation requirements. In this situation, a system that would meet the following requirements has been sought:

(1) It shall operate with a control performance within ±100 mm and within ±30 mm after stopping.

(2) It shall be applicable to traveling while changing the lane and require no civil engineering work.

(3) It shall be controlled with high accuracy, even when the ground is inclined, or when it travels with a load, or if the traveling operation is done while trolleys are traversing.

(4) It shall have the required control performance even when accelerating or decelerating, or when traveling at a constant velocity, or when stopping.

(5) It shall have a control interlocked with the gantry positioning control.

The autosteering control is achieved by the velocity difference between the front and rear driving wheels. Hence, by controlling this velocity difference, the distance and the angle of deviation from the traveling line may be controlled.

Model equations are given in Eq. (1).

\[
\begin{align*}
\frac{dV_c}{dt} &= (T_A - R_A) + (T_B - R_B) - F_3
\end{align*}
\]

\[
\begin{align*}
I \frac{d^2 \theta}{dt^2} &= - (T_A - R_A) l_4 + (T_B - R_B) l_6 + C_A (\beta_A + \delta_A) l_6 - C_B (\beta_A + \delta_B) l_6
\end{align*}
\]

\[
\frac{V_c}{\gamma} = - (\dot{\theta} + \beta)
\]

Where, \( m_c \) denotes crane mass; \( V_c \) traveling velocity; \( T_A \) and \( T_B \), driving forces of the front and rear driving motors; \( R_A \) and \( R_B \), resistance forces imposed on the front and rear driving wheels; \( F_3 \) and \( F_2 \), disturbing forces caused by gravity due to ground inclination in the traveling direction and in the direction at a right angle; \( \theta \), the angle the crane makes with the line; \( \beta \), \( \delta_A \), and \( \delta_B \), the angles the crane’s orientation makes with the traveling directions; \( L_6 \), moment of inertia centering on the center of gravity of the crane; \( l_4 \) and \( l_6 \), the lengths of the arms from the center of gravity to the driving wheels; \( \delta_A \) and \( \delta_B \), alignment of wheels; and \( C_A \) and \( C_B \), cornering forces.

4.2 Autosteering control

From the model described in Section 4.1, the state of a transfer crane is determined by its traveling velocity, distance, angle and angular velocity of deviation and velocity difference between the front and rear driving wheels. Since constant
velocity traveling is its basic condition, first the system is linearized with its velocity as constant, yielding the state equation as shown by Eq. (2). The target is to keep the traveling velocity constant, while maintaining the deviation, angle and angular velocity of deviation and velocity difference at 0. By applying regulation theory, the optimum feedback control system will be built up by Eq.(3).

$$X = Ax + Bu \quad X' = (x \quad \theta \quad \dot{\theta})$$

$$A = \begin{bmatrix} 0 & V_0 & 0 \\ 0 & 0 & 1 \\ 0 & -k(l_2^2 + l_3^2) & l_0 \end{bmatrix}$$

(2)

$$B^T = \begin{bmatrix} 0 & 0 & -k-l \end{bmatrix}$$

$$u = \mathcal{J}V$$

$$J = \int [(A^TQA + u^TRu)dt$$

$$u = F \cdot X$$

(3)

Where, $F$ is the optimum feedback gain and $Q$ and $R$ are weighing coefficients of performance index $J$. High accuracy has been realized as a gain scheduling type auto-steering system based on the application of feedback gains differing at the constant velocity time and at the time of acceleration or deceleration. Measurement results of auto-steering with real cranes are shown in Fig 4.

### 4.4 Control in more severe environments

Disturbances to the traveling control of transfer cranes include disturbances by forces and structural disturbances. Disturbances by forces include eccentric load due to the trolley position and ground inclination, etc. Structural disturbances result from fitting error of sensors or inclination of the crane body, etc. Where the ground is inclining in the front-rear direction, the aforementioned disturbances are found to comprehensively affect the transfer crane traveling at constant velocity under linear feedback control, as expressed by Eq.(4).

$$x_0 = -\frac{1}{b} \left[ \frac{V_0}{r_1} \left( \frac{k}{r_1} - k_a \right) + \frac{2}{(k_a + k_b)} \right]$$

$$\frac{1}{2} \left( -F_2 + k_a \delta_a + k_b \delta_b - 2(k_a + k_b) \partial \delta_a \right)$$

$$\delta_a = \frac{-1}{k_a + k_b} \left( -F_2 + k_a \delta_a + k_b \delta_b \right)$$

Where, $x_0$ and $\delta_a$ are the distance and angle of deviation; $a$ and $b$, feedback gains; $V_0$, traveling velocity; $r_1$ and $r_2$, tire diameters; $F_2$ gravitational disturbances due to ground inclination; $\delta_a$ and $\delta_b$, errors in fitting tires; $k_a$ and $k_b$, coefficients; and $\cos \delta_a$, error in fitting sensors.

These characteristics pose no problem under stable traveling conditions, but there is a possibility of controllability deteriorating at the time of stopping and restarting. On this account, control is provided in such a way that first of all the inclination may be eliminated at the time of stopping and restarting.

### 4.5 Gyro traveling

The deviation sensor of the image processing system works on the premise that a white or black line is drawn along the traveling road. This line is sometimes erased in some areas due to traveling of trailers, etc. In order to make the auto-steering control possible, even in places where the line is erased, a system to effect backup by use of optical fiber gyro is employed. When a gyro is used, a separate sensor to detect the distance of deviation at the time of starting is always required, and because of the drift, traveling control cannot be done for a long period of time with the gyro on its own; compensating sensors need to be installed at every set interval in the traveling section. A stable and high precision control could be realized, using a mutual compensation method in which the image processing system was employed as a standard sensor for compensation.

### 5. Automatic operation system

#### 5.1 Gantry positioning control

A transfer crane under auto-steering control needs to be subject to gantry positioning control at the target bay position. This method comprises calculating the difference between the target position, as given, and the present position, reducing the velocity to the target velocity determined for each crane, as the remaining distance has reached the preset distance, and making the final positioning by inching control. Approximate position detection is done by means of an encoder and final position detection is done by the image processing system, detecting the marker on the ground by use of the CCD camera. By this system, a gantry positioning control accuracy of ±0.3 mm has been achieved.

Additionally, the following three systems were prepared for
5.2 Container positioning control

For the handling of object containers, it is important to perform the positioning control of containers or spreaders in as short a time as possible, for which the following techniques are necessary:

(1) Anti-sway control of load
(2) Trolley positioning control
(3) Optimum control for the shortest route of the load
(4) Anti-sway control for skew
(5) Automatic container grounding control

The anti-sway control of load on a transfer crane was conventionally performed by use of auxiliary rope control, but an attempt to change it into electric anti-sway control has started, leading to the realization of a totally automated system. A stacking guide has been developed to avoid shifting between upper and lower containers, in the case of grounding containers automatically when stacking them. Its external appearance is shown in Fig. 5.

5.3 System configuration

An example of system configuration for the automatic operation of transfer cranes is shown in Fig. 6.

Using a 32-bit microcomputer (Intel 80386) as its center, this system is used in common with the automatic operation system of container cranes, to attain standardization as well as realizing high-speed processing. With radio or floppy disk-based connection for communications with the central control room, the job sequence in the work schedule and the container stacking information in the container yard are input. Subsequent work instructions may also be provided from a touch operation panel.

The touch operation panel is shown in Fig. 7. The anti-sway control makes use of an electric anti-sway control using an optimum regulator system. As the sensors for this purpose, an electric sway sensor of the image processing type and a tachogenerator for the detection of traversing velocity were used.

6. Conclusion

An automatic operation system of transfer cranes in a container yard has been outlined. The techniques described...
above are part of the development of an unmanned system; requiring minimum operator intervention, they can attain high efficiency whatever the operators' skill. For an unmanned system which may be said to be the final target, the following two factors seem to offer the most vital theme:

1. Detection of the position of the object containers to be handled (on ground area)
2. Ensuring safety with emphasis on lane changes and during traveling

A detailed study is afoot and, it is believed that this will pave the way for their realization in the near future.

References

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