Development of automated transport system

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Abstract

We have developed an automated transport system for construction sites, manufacturing plants, and distribution warehouses, such as an automated transport trolley, an automated transport forklift, and a transport management system. It can be instructed by a tablet to make a delivery and it can move autonomously along a given route by self-localization using LiDAR. In addition, a camera sensor can recognize the pallet or roll box pallet for loading and unloading. We have operated the automated transport trolley in construction sites and tested the automated transport forklift in distribution warehouses. In this paper, we report on the transport system and the result of operation and testing.

Keywords –

Automated transport trolley; Automated transport forklift; AMR; LiDAR; Camera sensor; Path planning

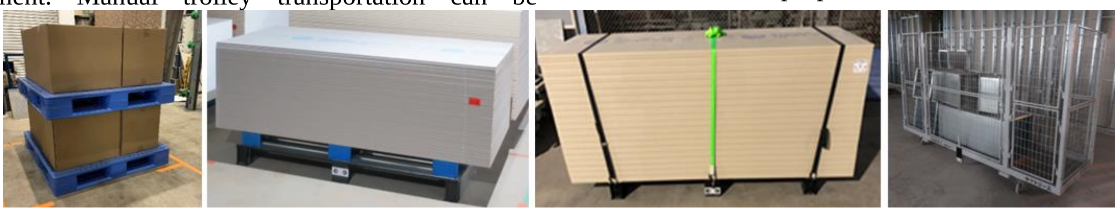
1 Introduction

Materials are transported in manufacturing plants, construction sites, and distribution warehouses using equipment such as trolleys and forklifts. Material handling operations are becoming increasingly mechanized and automated in manufacturing plants and distribution warehouses, where specialized equipment is often introduced. In facilities requiring flexibility in equipment to handle small lots of many different products, however, dedicated equipment is often not applicable. Reliance on manual labor is expected in construction sites due to the difficulty of installing equipment. Manual trolley transportation can be hazardous and physically demanding, especially when handling heavy items, posing caught-in or load collapse risks. Even when forklifts or other vehicles are used, the work also involves dangers such as collisions and load collapse, requiring the operator's attention and concentration. In order to improve the safety and productivity of these transport operations and to save the workforce, we have developed a system to transport materials automatically.

It is said that the first transport robot [1], appeared in the 1950s. Since then, various transport trolleys have been developed [2]-[5], but many are optimized for specific facilities, such as receiving loads from production lines or towing dedicated carts or basket trolleys. Few automated transport trolleys can load and unload pallets placed on the ground or handle harsher environments than factories or warehouses, and most have limited travel speeds. Forklifts have also been studied [6][7], but they mostly move on predetermined routes and require guides like fixed frames due to their low tolerance to material misalignment, or the predetermined stacking height, leaving little room for flexibility.

Given this background, automating transport operations requires capital investments, such as changing the work method by installing specialized equipment rather than automating the current work processes without changing them.

In the construction, there were examples of automation by installing facilities such as line tape and material storage before 2000, but they were not suitable for construction sites where work progressed day by day. Since 2010, LiDAR and camera sensors have been developed, and a method of movement without the facilities has been proposed, but it was not suitable for



(a) Pallet (b) Skid pallet (c) Cribbing (d) Roll box pallet

Figure 1 Packing mode

construction sites where the environment was changing and difficult to mapping and detect the self-position, and it was not an environment in which anyone could give work instructions.

To solve this problem, we have developed a more general-purpose transport system that requires minimal modification or expansion of facilities and equipment. The general transport work often uses transport equipment such as (a) pallets, (b) skid pallets, (c) cribbing, and (d) roll box pallet, as shown in Figure 1. Storage spaces, racks, and elevators are often designed according to the equipment standards. We developed two transport robots: automated transport trolley (Robo-Carrier) and automated transport forklift (Robo-Carrier Fork). These transport robots use LiDAR (Light Detection and Range) sensors for self-position detection and use camera sensors to detect objects such as materials, eliminating the need for building the environment, such as transport guides and equipment for specific materials. In addition, automating the elevator system at construction sites enables automatic material transportation to designated floors. We have operated automated transport trolleys at multiple construction sites and tested automated transport forklifts at logistics facilities. This paper describes the transport system and robots and reports on the results of operation and testing.

2 Transport System

2.1 System Overview

As shown in Figure 2, the transport system consists of a server called an integrated management system, a user interface tablet terminal, an automated transport trolley and forklift as transport robots, and a construction elevator specifically for construction sites.

The integrated management system receives the operation instructions from the user via the tablet terminal, generates the operation commands, and sends them to the transport robots. In addition, it receives the operation status of the transport robots and sends the status information to the tablet terminal. The integrated management system is connected to transport robots and tablet terminals via public networks or Wi-Fi.

2.2 Route Map

The worker uses the tablet terminal to register the transport work to be carried out as a task. The tablet displays a site plan and a route map, as shown in Figure 3, which includes the paths of the transport robots, material storage locations, elevators, and vehicle waiting areas. The route map shows a straight line connecting the pathways along which the transfer robot can travel and the site's material storage areas

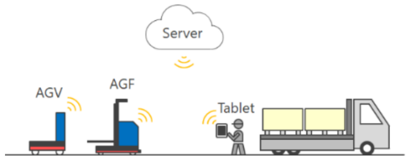


Figure 2 Transport system overview

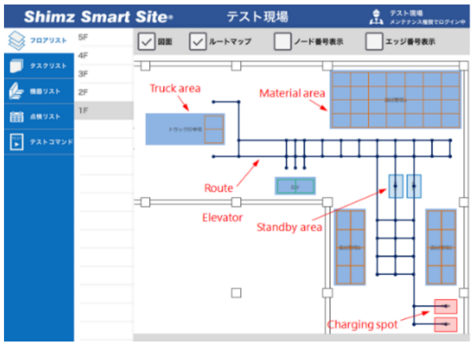


Figure 3 Route map

Figure 4 Task list

and vehicle waiting areas. A vertex or intersection of the pathways is called a node, and the straight line connecting the nodes is called an edge. The robot's orientation for loading and unloading materials can be specified for each storage location. For stacked storage, the number of stacks can be specified at the same location, and for racks, the number of materials and their respective heights can be specified. In addition, multiple storage areas can be grouped as an area so that the destination of materials can be indicated collectively as an area instead of specifying each storage area. This route map can be drawn by CAD add-in software, and program code can be generated. Codes saved on the server can be displayed on the tablet.

2.3 Task Registration and Operation Instructions

For material transport instructions, select the type of material, destination floor, destination area, etc., and register them as a task. At the time of execution, pressing the play button in the task list, as shown in Figure 4, sends operation instructions from the integrated management system to the transport robots and construction elevators.

The motion instructions for the transfer robots include moving, loading, unloading, etc., and instructions sent to the construction elevators are grouped into tasks, such as opening/closing doors, moving floors, etc. The integrated management system sends the order and timing of sending motion instructions according to the status of the transport robots and construction elevators and sends commands in a timely manner.

2.4 Path Finding

Once a command is executed, the system searches for a travel route to the destination on the route map. Transport robots can move forwards, backwards, and even sideways and perform actions like rotating and turning. Since it is also essential to align the orientation of the vehicle body for the material storage area, it is necessary to find not only the path it travels but also which direction and method to travel along the edge, such as forward/backward or sideways, and which actions to perform at the nodes, such as spinning, turning, and maintaining the direction. To ensure the appropriate orientation of the transport robot, every possible route, including actions, is calculated to select the shortest travel-time route. When multiple robots are active in the same route map, based on the theory of multi-agent path planning [8], the expected passing time of each node is calculated, and one node is reserved for one vehicle to avoid collision. The other vehicle searches for a route to avoid collision by calculating a route that does not pass the reserved node at that time, as shown in Figure 5. The integrated management system monitors the positions of the robots during movement and, if interference between vehicles is predicted, re-executes the path finding and changes the route as necessary.

3 Automated Transport Robot

3.1 Automated Transport Trolley

As shown in Figure 6, the automated transport trolley is equipped with a mechanism to lift the material to its bed by the fork. It can transport flat-laid cargo and is primarily intended for use in construction sites. Its specifications are: load capacity 1,000 kg, body dimensions W1,400mm x L2,000mm x H1,930mm, body weight 1,160kg, and lithium-ion rechargeable battery-powered. The wheels consist of two drive steering wheels and two caster wheels, with the drive steering wheels being independently controllable. This allows the robot to move forwards, backwards, turn, and move sideways and rotate. The lower part of the fork has a scissor-type load-bearing mechanism, allowing it to support the weight of materials on the ground. This can eliminate the need for a counterweight, making the body lighter than a conventional forklift with a capacity of 1 ton. As a result,

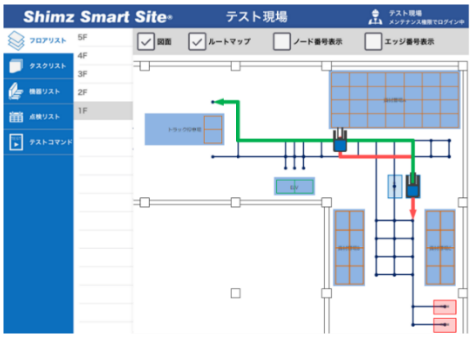


Figure 5 Multi-unit routing

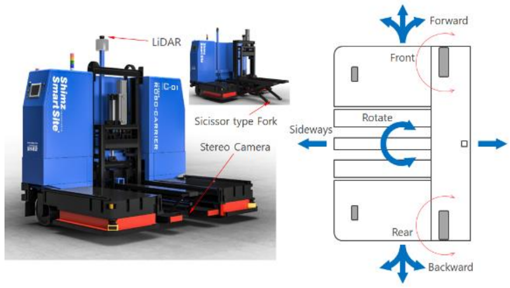


Figure 6 Automated transport trolley

it can be used on floors with general structures, such as construction sites. However, since the wheels need to roll under the fork, using skid pallets without bottom boards is necessary instead of standard pallets. During loading operations, a contact sensor located at the base of the fork can detect when the fork is fully inserted into the material.

3.2 Automated Transport Forklift

As shown in Figure 7, the automated transport forklift is based on a reach-type forklift as the base machine. It can unload trucks, stack materials, and load them onto racks at logistics facilities, manufacturing plants, and construction sites. Its specifications are: load capacity 1,000 kg, lifting h eight 3,000 mm, body dimensions W1,290mm x L2,450mm x H2,530mm, body weight 2,550kg, and lead-acid battery-powered. The wheels consist of one rear drive steering wheel and two front steering wheels, each independently controllable. It can move forwards, backwards, and sideways, and turn and spin. In addition, translation and rotation can be

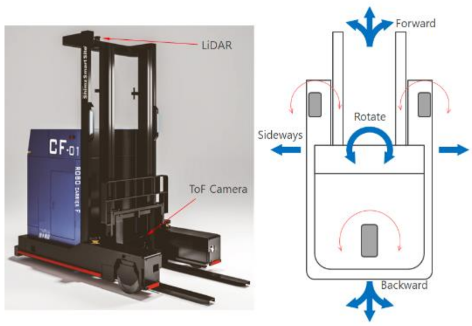


Figure 7 Automated transport forklift

controlled simultaneously when driving or positioning, eliminating the need to turn the vehicle body around. Due to space constraints, there may not be enough space for turning around at construction sites, and a small turning radius for changing direction is a significant advantage.

3.3 Equipment Configuration

As shown in Figure 8, the control equipment configuration of the automated transport trolley and forklift consists of an integrated control PLC (Programmable Logic Controller) that performs control calculations and a vehicle control PLC that performs steering, driving, and lifting operations according to commands from the former. The system consists of a communication device to receive commands from a server, SLAM (Simultaneous Localization and Mapping) controller and LiDAR sensor to obtain the self-position, and a camera controller and camera sensor to acquire material information. The automated transport trolley uses a stereo camera, and the forklift uses a TOF (Time of Flight) camera. The integrated control PLC and vehicle control PLC share status information. Based on the operation instructions from the server, the integrated control PLC performs calculations of instruction values required for wheel steering angle, travel speed, lift movements, etc., using information such as self-position from the SLAM controller and material coordinates from the camera controller. The calculated results are instructed to the vehicle control PLC, which sends operation commands to the motor driver and lift to perform driving control and loading/unloading operations. The vehicle control PLC manages safety sensors, and in case those safety devices are activated, it executes emergency stops or temporary halts based on its determination. The integrated control PLC shares the current operating status with the vehicle control PLC and sends the status information, including its current position, to the server.

3.4 Self-Position Detection

A LiDAR sensor for self-position detection is mounted on top of the vehicle for autonomous driving. This sensor measures the shape of surrounding objects in a building in a 270-degree horizontal plane. Generally, a map for self-position estimation is created from the measurement data, but in this system, map data is generated based on CAD data of architectural drawings. Among the architectural drawings, the system uses two superimposed drawings, one containing structural elements such as columns and beams and finishing materials such as interior walls and doors, and the other containing temporary equipment such as construction elevators. This drawing data is converted to map data using dedicated software, eliminating the need for prior

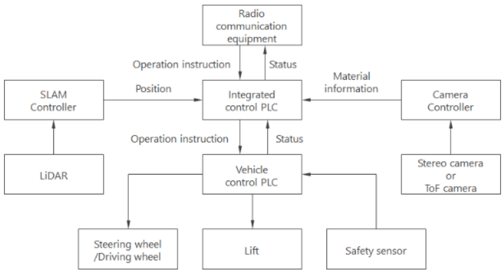


Figure 8 In-vehicle equipment configuration

map creation and origin alignment tasks. In addition, objects that are not included in the drawing data may be measured at the site. If these objects occupy a large proportion of the area, errors may occur in self-position estimation, so the system has a function that overwrites the map data with data obtained from measurements to generate a map according to the site environment. This enables travel control by obtaining information on the planar position and direction of the vehicle body.

3.5 Material Position Detection

Travel control based on self-position estimation enables the robot to travel autonomously within the site, but when loading and unloading materials, the materials are not always in the proper position, so alignment with the object is necessary. To insert the fork appropriately without causing collapses or collisions, the transport robots have camera sensors that detect the position of materials, allowing them to face the material in the correct position. The transport trolley uses a stereo camera, while the forklift uses a ToF camera, so the basic system differs. The trolley's camera, which detects dedicated markers on the pallets, is installed at the fork storage position underneath the body. The marker is attached to the center front of the pallet, as shown in Figure 9. Although there are other methods like affixing markers at both ends of the pallet [9][10], a small marker is placed in the center of the pallet to ensure they fit accurately within the camera's field of view even when the vehicle is close to the pallet. By detecting markers with a stereo camera, the robot can detect the planar position of the pallet.

The camera sensor of the automated transport forklift is mounted at the base of the fork. The ToF camera, as shown in Figure 10, can acquire 3D data of the target material. From the data obtained, the fork pockets of the pallet can be detected, as shown in Figure 11. It detects the space below the material for basket trolleys and

Figure 9 Skid pallet marker

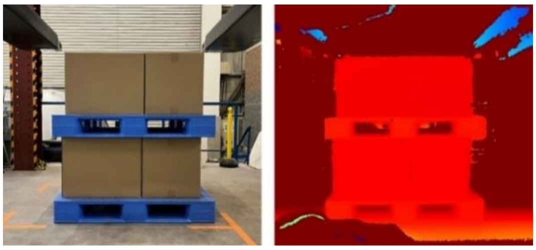


Figure 10 Data captured by the ToF camera

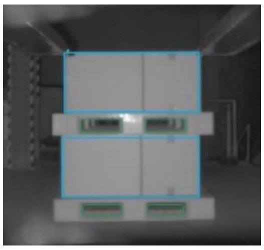


Figure 11 Pallet and material detection

similar items. Furthermore, information on rotation around the vertical axis can be obtained from the depth distance in the flat area of the material or pallet. The camera sensor allows the vehicle to face the material's center. It can also recognize stacked materials and detect the top part of the load, enabling operations like stacking multiple materials or taking materials from the top of a stack.

3.6 Travel Control

When the transport robot moves, the integrated management system sends the node coordinates of the travel path, the orientation of the robot, and the passing method at the node. When traveling a straight line connected by two pointsP_i, P_{i+1}, the system controls the robot to follow this line. As shown in Figure 12, the robot's self-position (X_C, Y_C, θ_C) and the distance d_n from the target line can be expressed using the line equation as:

$$d_n = \frac{aX_C + bY_C + c}{\sqrt{a^2 + b^2}} \tag{1}$$

$$\begin{cases} a = -Y_{i+1} + Y_i \\ b = X_{i+1} - X_i \\ c = X_i Y_{i+1} - X_{i+1} Y_i \end{cases} \tag{2}$$

and the angular difference between the vehicle and the target line can be expressed as:

$$(\gamma - \theta_C) \tag{3}$$

Using the translational control input gain K_{dp}, and rotational control input gain $K_{\theta p}$, and the translational control input φ_d and rotational control input φ_θ are expressed as:

$$\varphi_d = -K_{dp} \tan^{-1}\left(\frac{d_n}{1000}\right) + (\gamma - \theta_C) \tag{4}$$

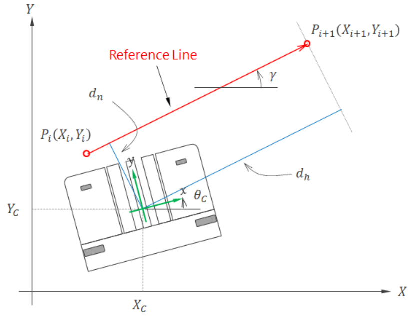


Figure 12 Line tracking control model

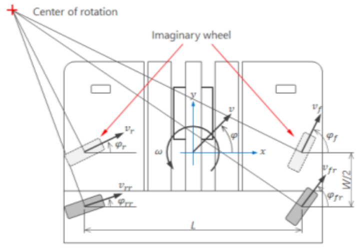


Figure 13 Steering angle calculation model for trolley

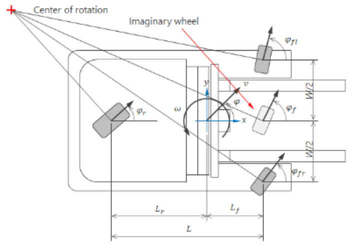


Figure 14 Steering angle calculation model for forklift

$$\varphi_\theta = K_{\theta p}(\gamma - \theta_C) \tag{5}$$

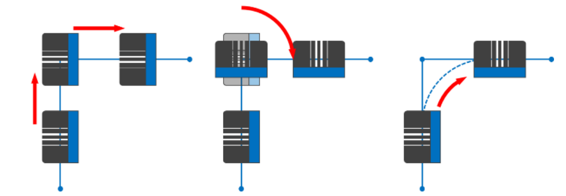
Here, $\tan^{-1}$ is used in Equation (4) to prevent large control inputs proportional to position deviation by asymptotically approaching $\pi/2$ because the control input is handled in the steering angle dimension. As a result, when the distance is greater than a certain level, an almost maximum rudder angle is input.

Here, when the distance between the target coordinate point P_{i+1} and the line perpendicular to the target straight line is d_h, the following equation is obtained:

$$d_h = \sqrt{(X_{i+1} - X_C)^2 + (Y_{i+1} - Y_C)^2 - d_n^2} \tag{6}$$

The speed is decelerated in steps according to the distance to the destination by calculating the speed sequentially during driving, and the stopping and turning operations are performed.

Since the driving wheels of the automated transport trolley are located off the center of the vehicle, the two virtual wheels placed in the center of the vehicle are considered, as shown in Figure 13, to simplify the calculation and provide symmetry. For the calculated control inputs, when the rudder angle of the front and rear virtual wheels is φ_f, φ_r, the rudder angle of the virtual wheels when moving forward is as follows:



(a) Posture keep (b) Spin (c) Turn

Figure 15 Node passing method

$$\begin{cases}\varphi_f = \varphi_d + \varphi_\theta \\ \varphi_r = \varphi_d - \varphi_\theta\end{cases} \tag{7}$$

the rudder angle of the virtual wheel when moving backward is as follows:

$$\begin{cases}\varphi_f = \varphi_d - \varphi_\theta \\ \varphi_r = \varphi_d + \varphi_\theta\end{cases} \tag{8}$$

The actual rudder angles of the vehicle's driving wheels $\varphi_{fr}, \varphi_{rr}$ are calculated as:

$$\varphi_{fr} = \tan^{-1}\left(\frac{2L\sin\varphi_f\cos\varphi_r}{2L\cos\varphi_f\cos\varphi_r + W\sin(\varphi_f - \varphi_r)}\right) \tag{9}$$

$$\varphi_{rr} = \tan^{-1}\left(\frac{2L\cos\varphi_f\sin\varphi_r}{2L\cos\varphi_f\cos\varphi_r + W\sin(\varphi_f - \varphi_r)}\right) \tag{10}$$

In this way, the control system can track the target in a straight line. In the case of sideways movement, two wheels are driven separately, but the control input is calculated in the same way as above, and the straight-line tracking control is performed based on the speed difference of each driving wheel based on the sum of the translation control input and the turning control input. However, since translation and turning are dependent, it takes time to converge compared to traveling.

Similarly, the automated transfer forklift is modeled using virtual wheels, and how to calculate control inputs is the same as for the trolley. As shown in Figure 14, the steering angle of the virtual wheels during forward movement is

$$\begin{cases}\varphi_f = \varphi_d + \tan^{-1}\left(\frac{2L_f}{L}\tan\varphi_\theta\right) \\ \varphi_r = \varphi_d - \tan^{-1}\left(\frac{2L_r}{L}\tan\varphi_\theta\right)\end{cases} \tag{11}$$

and the steering angle of the virtual wheels when moving backward is

$$\begin{cases}\varphi_f = \varphi_d - \tan^{-1}\left(\frac{2L_f}{L}\tan\varphi_\theta\right) \\ \varphi_r = \varphi_d + \tan^{-1}\left(\frac{2L_r}{L}\tan\varphi_\theta\right)\end{cases} \tag{12}$$

Where, the $\tan^{-1}$ term is corrected for the misalignment of the center of rotation due to the geometric relationship between the front and rear wheels. Similarly, if the steering angle of the actual wheels is $\varphi_{fr}, \varphi_{fl}$,

$$\varphi_{fl} = \tan^{-1}\left(\frac{2L\sin\varphi_f\cos\varphi_r}{2L\cos\varphi_f\cos\varphi_r - W\sin(\varphi_f - \varphi_r)}\right) \tag{13}$$

$$\varphi_{fr} = \tan^{-1}\left(\frac{2L\sin\varphi_f\cos\varphi_r}{2L\cos\varphi_f\cos\varphi_r + W\sin(\varphi_f - \varphi_r)}\right) \tag{14}$$

The rear wheel steering angle is obtained using the virtual wheels. Since all three wheels of an automated transport forklift can be steered, translation and turning can be controlled independently, even when traveling sideways.

As shown in Figure 15, there are three types of node passing methods: (a) maintaining posture, (b) spinning, and (c) turning. In maintaining posture, the robot stops at a node and steers the wheels to change the direction of travel from traveling forward to traveling sideways. In spinning, the robot stops at the node and rotates in place to a predetermined angle. In turn, the robot follows an arc connecting two straight lines to pass the node. Turning is the quickest way to pass through the three passing methods, while spinning takes the most time.

3.7 Material Positioning Control

The self-position estimation using LiDAR has an error of approximately ±50mm and ±1deg. It is necessary to allow some errors when traveling. For tasks like loading and unloading, where positioning relative to the material is critical, a camera sensor is used to ensure accuracy to prevent misalignment of materials. As shown in Figure 16, the camera sensor provides a target coordinate $P_V(X_V, Y_V, \theta_V)$ for a pallet or other target. This provides a perpendicular line from the center surface of the target object, and by controlling the machine to follow this line, it can face the object's center.

For the automated transport trolley, the trolley moves sideways, when the sensor located at the base of the fork detects contact with a material, the robot stops moving forward and places it onto the vehicle by lifting, moving back, and lifting down the fork. This action allows the material to be taken in, and the reverse action allows it to be unloaded.

For the automated transport forklift, as shown in Figure 17 left side, after moving to the front of the material storage area, the lift is raised, assuming that the material is stacked, and the top edge of the material is searched with a camera sensor. When the top edge is detected, it aligns the lift to the height of the fork pocket, aligns the body in front of the material while detecting the position and rotation of the pallet, and picks up the

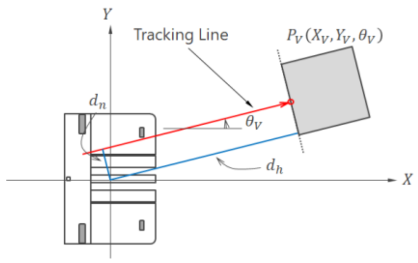


Figure 16 Positioning control with the camera sensor

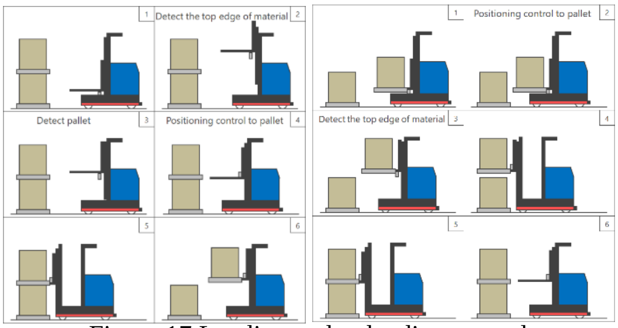


Figure 17 Loading and unloading control

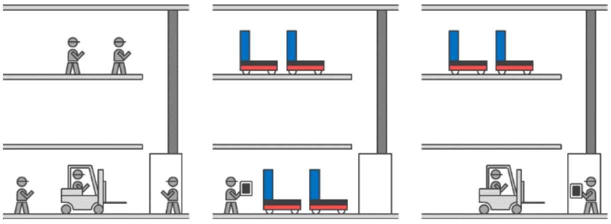

(a) Manual (b) Automated (c) Hybrid

Fig.18 Transportation structure

material. The pick-up task is completed as follows: the robot moves forward while extending out the fork, stops when the sensor at the fork base detects contact with the material, lifts the fork until the sensor on the top surface of the fork detects contact with the material, stops the lift, then moves the fork back, and moves backward.

For unloading, as shown in Figure 17 right side, it detects the lowest pallet in the storage area, detects the position and rotation of the pallet, and aligns the body in front of the material. After that, it searches the top edge of the material and lifts the load higher than it to some extent before placing the load on it. If no material is in the storage area, the robot places the load directly on the space. The unloading task is completed as follows: the robot moves forward to a predetermined distance while moving the fork forward, stops, lifts the fork down, and after the sensor on the fork top detects the separation from the material, stops the lift, moves the fork back, and moves backward. These operations enable placing flat or stacking materials.

In the case of a material rack, the robot receives information on the height of the material storage area from the integrated management system, and the lift is raised to a predetermined height in advance to perform loading and unloading tasks.

4 Testing and Operation

4.1 Operation of Automated Transport Trolleys

An automated transport trolleys was applied to a construction site, and many materials were transported. We are transported at night when no workers are present, rather than during the daytime when there is heavy worker traffic, because safety laws and rules have not yet been established. While this ensures safety, it is also more efficient because the transport area is larger, elevators can be occupied in an environment where no workers are present.

Conventional transport operations, materials are brought in by truck on the first floor, they are loaded onto the elevator using a forklift. The elevator is operated to move to the upper floors, and an operator is required because the elevator is for construction work. On the upper floors, due to floor weight restrictions, forklifts are not generally used, and hand lifts or dollies are used to remove materials from the elevator and place them in the storage area. As shown in Figure 18, (a) manual work often requires a total of five workers: one forklift operator, one loading operator on the first floor, one elevator operator, and two workers on the upper floor. In contrast, (b) when an automated transport system is used, one system operation manager and two to four automated transport trolley are used: one to two on the loading floor and one to two on the upper floors.

The time required for manual transfer was 24 pallets/hour, or 2.5 minutes per pallet, while that for the automated transport system was 12 pallets/hour, or 5 minutes per pallet. Therefore, although automatic transfer takes longer than manual transfer, it requires only one person, thus saving labor. The number of pallets transported per person is approximately 5 pallets for manual transport and 12 pallets for automated transport, resulting in a higher workload per person. On the other hand, the automated transport system requires the cost of automated transport trolleys and automated elevator equipment. The cost of an automated transport trolley is about the same as the cost of a worker, but the full cost of the elevator automation system is additional. Therefore, the cost can be reduced by using manual operation of the elevator. In addition, since forklifts are generally located on the first floor, the work on the loading floor can be done manually. As shown in Figure 16(c), if only unloading on the upper floor is automated as a hybrid system of automated and manual work, work can be performed by two people: one forklift operator and one elevator operator who also manages the system operation. Under this system, work can be performed at a rate of 20 pallets/hour, 3 min./pallet. This is a cost-effective balance between the speed of manual work and the manpower savings of automated transport.

Manual loading and unloading requires many people to load and unload the elevator. On the other hand, automated transport reduces the number of workers, but it is slower than manual transport. Having only one automated transport trolley on a floor causes significant delays, so having two trolleys on a floor is more efficient. This reduces the time delay for unloading on the upper floor compared to manual operation. However, loading on the first floor is more efficient without automation because of the time difference compared to manually operated forklifts.

4.2 Testing of Automated Transport Forklifts

The automated transport forklifts were tested in a test site and logistics facility, moving stacked materials, materials stored in racks, and unloading materials from trucks. In the truck unloading test, pieces of material loaded on a truck were taken out from the left and right sides and stacked in two or three stages at a storage area. The automated transport forklift took 45 minutes for this task, while a manually operated forklift took about 20 minutes, depending on the operator's skill level. The work time is roughly twice as long as that of a forklift operated by a person. At the logistics facility, the prescribed transportation was performed while moving over distances of several tens of meters. Although the loading and unloading operations took longer with the robot, there was little difference in the travel time. Therefore, when the traveling distance is long, the performance difference between humans and robots is further reduced.

5 Conclusion

We built a transport system to automate transport work on site, where the management system, operation terminals, and transport robots all work together to automate the transfer of materials. The system has been proven applicable even in environments without adequate facilities, such as construction sites. Although the work of a single transfer robot is slower than that of a human operator, production efficiency can be increased by operating multiple robots with fewer personnel. Transport robots follow predetermined routes and perform searches and positioning in front of the material during loading and unloading, while the human operator flexibly selects a route according to the surrounding conditions, checks material conditions in advance, adjusts the height and position and makes decisions. This makes a difference in work speed. In some cases, due to safety concerns, the traveling speed limit is applied to automated transfer robots. While there is ample room for further improvement, achieving the same operation time as humans with current technology is challenging, and operating multiple units with a small workforce is the current solution.

Automation enables efficient use of production time, improves safety and productivity, and helps solve problems such as labor shortages. However, changing jobs from performing material transportation to operating transport robots will change the human resources required, so personnel development, training, and system usability will also become essential. In terms of operation, it will be necessary to build work processes and facility layouts to incorporate the automated transport system, indicating the necessity for solutions and improvements in both technology and operation.

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