Development of A Mobile Robot pulling An Omni-directional Cart for A Construction Site

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Abstract -
We have been researching a mobile robot that pull a cart with equipment to improve productivity at construction sites. In this field of research, a cart having front wheels as swivel wheels and rear wheels as rigid wheels have been used. However, at the construction site, in many cases, wheels of a cart have only swivel wheels in order to easily transport them in a narrow space. We aimed to be able to transport a minimum width of 1200 mm by pulling this cart by a robot. However, when this cart is pulled using a simple 1-axis connection, there is no guarantee that a cart will follow the same trajectory as a robot. For example, a cart will move significantly out of the trajectory of a robot as it turns a curve. At this time, it is expected that a cart will collide with the building under construction or the materials placed on the site. This paper describes the results of a theoretical and experimental confirmation of the features of a cart and examination of its solution.

Keywords -
AGV; Mobile robot; Omni-directional cart

1 Introduction

In Japan, the workers involved in the construction industry are aging. It is expected that many workers will retire in 10 years and there will be a shortage of workers. Therefore, in this research, we decided to aim at improving the productivity of the construction site by automating the transfer work by pulling a cart with a mobile robot. We assumed that we would transport the aisles of Japanese buildings, and targeted aisles of 1200 mm or more. Therefore, the robot needs to use a small size.

There are several methods for transporting materials by a robot. For example, there is a method in which a robot pulls a cart with materials[1][2][3]. In this case, the robot can be made smaller and lighter than the material. Therefore, there is a possibility of traveling on the target passageway. On the other hand, it is necessary to control the traveling of a robot in consideration of the movement of a cart. There is a method to put materials on a robot[4]. In this case, controlling the running of a robot is simple. However, in order to realize stable running, the weight of the robot needs to be larger than the weight of the material, and a robot tends to be large. Therefore, it may not be possible to travel on the target passage. For the above reasons, the method of pulling a cart was selected in this research.

Figure 1. A mobile robot.

In order to control the traveling of a robot, it is necessary to theoretically verify the motion characteristics of a cart. There are theoretical researches about a cart with front wheels as swivel wheels and rear wheels as rigid wheels[5][6][7][8][9]. On the other hand, an omni-directional cart which is a slewing wheel for all the wheels is used in a construction site. The reason is that the materials are manually transported even in a narrow way. There are few theoretical researches on this cart. In this research, this omni-directional cart is connected to a robot to improve the convenience. However, when this cart is pulled using a simple 1-axis connection, a cart deviates from the trajectory of a robot. Therefore, it is expected that a cart will collide with surrounding buildings and materials. In order to reduce such a risk, this research theoretically examined the movement of a cart during a curve. In addition, in order to confirm that this theoretically result is useful, we conducted a traction experiment and compared the results.

2 A mobile robot

This chapter describes a robot. A robot used in this research are shown in the Figure 1 and the specifications are shown in the Table 1. This robot is jointly developed by Tokyu Construction Co.,Ltd. and THK Co.,Ltd. A bumper and an LRF（Laser Range Finder） are installed in front of the robot to automatically stop working when

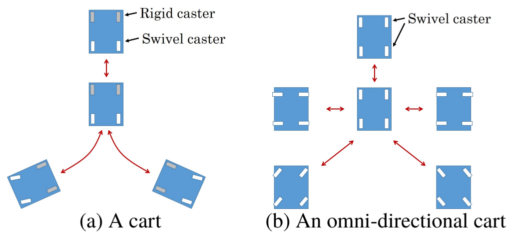


Figure 2. The motion characteristics of a cart.

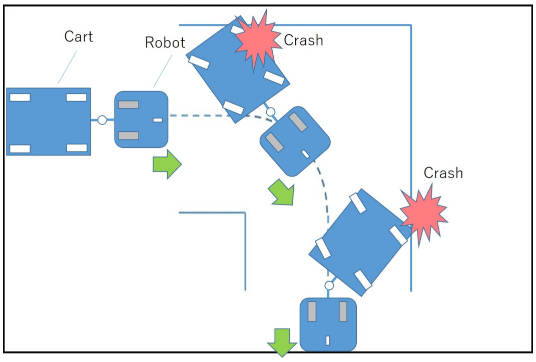


Figure 3. Behavior of an omni-directional cart on curve.

an operator or an obstacle approaches. A cart connects to the back of this robot.

3 An omni-directional cart

A cart with only swivel wheels has the characteristics of being able to move in all direction. Therefore it is hereinafter referred to as an omni-directional cart. On the other hand, a cart with front wheels as swivel wheels and rear wheels as rigid wheels is hereinafter referred to as cart. First, the motion of characteristics of an omni-directional cart are described in this chapter. Second, the results of theoretically examining the motion of a cart when traveling on a curve are described.

3.1 Characteristics of an omni-directional cart

The motion characteristics of a cart are shown in the Figure 2-(a), and the motion characteristics of an omni-directional cart are shown in the Figure 2-(b). From a Figure 2-(a), a cart can move in a front-back direction, but cannot move in a lateral direction unless wheels skid. When moving diagonally, there is a characteristic that a curve is drawn. However, as shown in a Figure 2-(b), an omni-directional cart can move in the lateral direction in addition to the front-back direction. These features of an omni-directional cart benefit when traveling in a narrow space on a construction site. When this cart is pulled using a simple 1-axis connection, a cart moves in all directions. It means that a cart will move significantly out of the trajectory of a robot as it turns a curve. For example, when connecting a cart as shown in a Figure 2-(a), a cart can move in the same trajectory as a robot. This is because the inertial force acting on a cart during the curve balances the frictional force generated on a rigid wheel and the road surface. On the other hand, when using a cart shown in the Figure 2-(b), the direction of the wheel changes, so the frictional force with the road surface becomes very small. Therefore, it is expected that a cart will swing outward due to inertial force as shown in Figure 3. At this time, it is expected that a cart will collide with the building under construction or the materials placed on the site.

Table 1. Specification of a robot.

Size	W600mm × D800mm × H400mm
Weight	120 kg
Speed(MAX)	0.5 m/s
Running time	8 hours

3.2 Motion model of a cart

The motion of an omni-directional cart on the curve was theoretically examined. In this research, it is assumed that a robot travels at a constant velocity $\dot{\phi}$ on a curve with radius r at coordinate x-y. A omni-directional cart is towed using a simple 1-axis connection. The model of this system is shown in Figure 4.

The force balance for a robot is expressed by the following equation.

$$M_1\ddot{x} = F_x - T_x \tag{1}$$

$$M_1\ddot{y} = F_y - T_y \tag{2}$$

The force balance for a cart is expressed by the following equation.

$$M_2\frac{d^2}{dt^2}(x + l_2 \sin\theta) = T_x \tag{3}$$

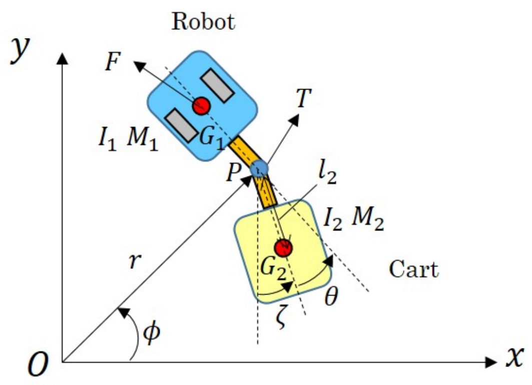
$$M_2\frac{d^2}{dt^2}(y + l_2 \cos\theta) = T_y \tag{4}$$

$$I_2\ddot{\theta} = T_y l_2 \sin\theta - T_x l_2 \cos\theta \tag{5}$$

Transform Equation (1) and (2).

$$T_x = -M_1\ddot{x} + F_x \tag{6}$$

$$T_y = -M_1\ddot{y} + F_y \tag{7}$$



M_1 : The mass of a robot. [kg]
I_1 : The moment of inertia of a robot. [kg・m^2]
F : The tractive force of a robot. [N]
M_2 : The mass of a cart. [kg]
I_2 : The moment of inertia of a cart. [kg・m^2]
T : The force exerted on a cart by a robot. [N]
l_2 : The PG$_2$ distance. [m]
θ : Relative angle between robot and cart. [rad]
ζ : The direction of a cart. [rad]
r : The turning radius of a robot. [m]
ϕ: The angle of P. [rad]

Figure 4. A Model of the system.

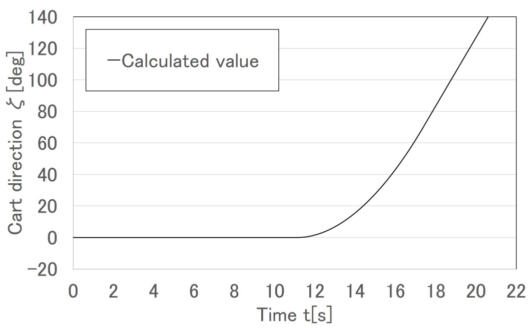


Figure 5. Direction of an omni-directional cart on the curve (Calculated value).

Table 2. Specification of the calculation.

M_2	150 kg
I_2	142 kg·m^2
l_2	0.90 m
r	2.00 m
$\dot{\phi}$	0.25 rad/s

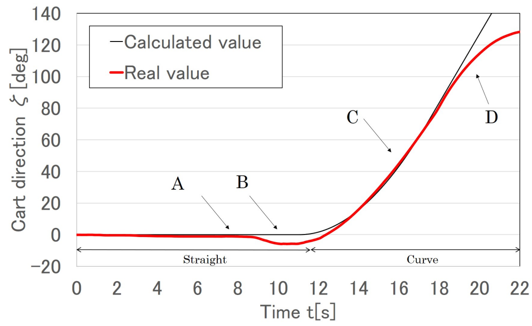


Figure 6. Direction of an omni-directional cart on the curve (Calculated value vs Real value).

From Equation (3) and (4), the following Equation can be obtained.

$$M_2(\ddot{x} - l_2 \sin\theta\dot{\theta}^2 + l_2 \cos\theta\ddot{\theta}) = T_x \tag{8}$$

$$M_2(\ddot{y} - l_2 \cos\theta\dot{\theta}^2 + l_2 \sin\theta\ddot{\theta}) = T_y \tag{9}$$

Substitute Equation (8) and (9) into Equation (5).

$$M_2 l_2 \cos\theta\ddot{x} - M_2 l_2 \sin\theta\ddot{y} + (I_2 + M_2 {l_2}^2)\ddot{\theta} = 0 \tag{10}$$

Transform Equation (10) with respect to $\ddot{\theta}$.

$$\ddot{\theta} = -\frac{M_2 l_2}{I_2 + M_2 {l_2}^2}(\ddot{x}\cos\theta - \ddot{y}\sin\theta) \tag{11}$$

To analyze the motion of a cart, we should solve Equation(11) for θ. However, it is difficult to get analytical solution because this equation is non-linear. Therefore, we analyze it numerically by the Euler method. The pitch width is

$$\Delta t = t_{n+1} - t_n \tag{12}$$

and we can get numerical solution as follows.

$$\dot{\theta}_2(t_{n+1}) = \dot{\theta}_2(t_n) + \ddot{\theta}_2(t_n)(t_{n+1} - t_n) \tag{13}$$

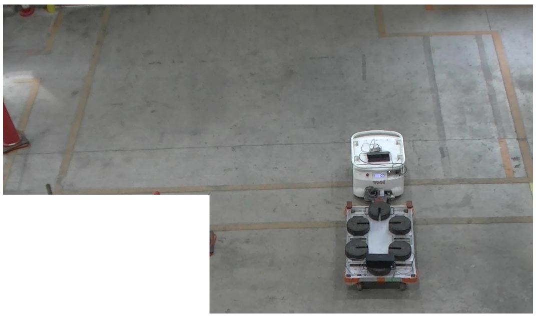
$$\theta_2(t_{n+1}) = \theta_2(t_n) + \dot{\theta}_2(t_n)(t_{n+1} - t_n) \tag{14}$$

When initial conditions are following Equations.

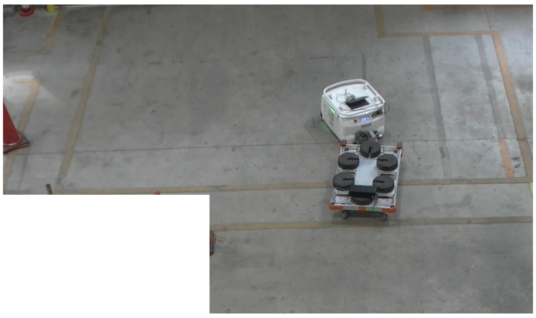
$$\dot{\theta}_2(t_0) = \dot{\theta}_2(0) = 0 \tag{15}$$

$$\theta_2(t_0) = \theta_2(0) = 0 \tag{16}$$

The motion of the robot is expressed by following equations.



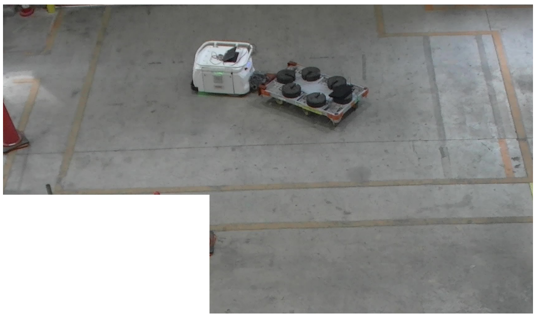
(a) t=8[s]



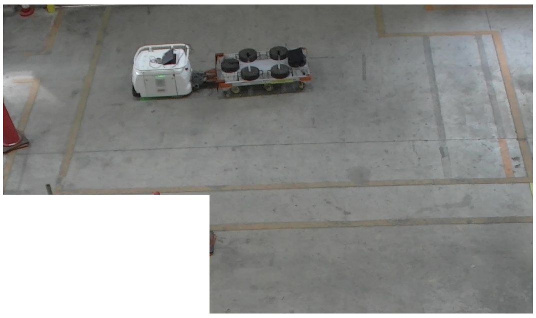
(b) t=10[s]

(c) t=12[s]

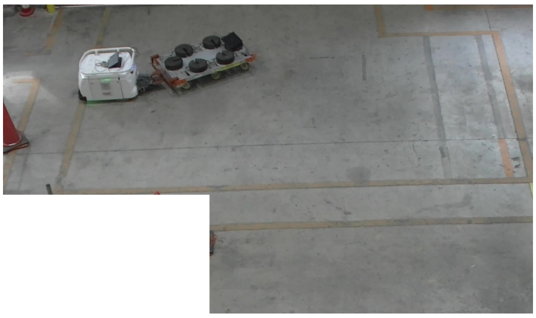
(d) t=14[s]



(e) t=16[s]



(f) t=18[s]



(g) t=20[s]

(h) t=22[s]

Figure 7. Behavior of a cart during experiment.

$$x = r\cos\phi \tag{17}$$

$$y = r\sin\phi \tag{18}$$

The second derivative of Equation (17) and (18) is as follows.

$$\ddot{x} = -r\dot{\phi}^2\cos\phi \tag{19}$$

$$\ddot{y} = -r\dot{\phi}^2\sin\phi \tag{20}$$

Robot turns at a constant speed.

$$\ddot{\phi} = 0 \tag{21}$$

A cart direction ζ is expressed by the following Equation.

$$\zeta = \phi - \theta \tag{22}$$

We performed a simulation as shown in Figure 3, and assuming first a straight(0s~12s), next a curved at 90deg (12s~18s), and finally a straight(18s~22s). The parameters used the conditions in the table 2. The result of the simulation is shown in the figure 5. It was theoretically found that the direction of a cart gradually increased as the curve started, and a cart sways over 90 deg at t=17s.

4 Comparison of a pulling experiment and a simulation result

An omni-directional cart was connected to the robot and the behavior of a cart on the curve was observed. In this chapter, the conditions of the experiment and the experimental results are explained.

4.1 Experimental conditions

In this experiment, a robot and an omni-directional cart were connected by a simple 1-axis connector. The experimental conditions were the same run as the simulation under the table 2. An IMU(Inertial Measurement Unit) was attached to the back of a cart. This sensor is equipped with geomagnetic sensor and can measure the direction ζ of the cart.

4.2 Experimental results and consideration

The experimental results are shown in Figure 6. Furthermore, the state of the experiment is shown in Figure 7. For comparison, Figure 5 is overlaid on Figure 6. In Figure 6, we divided into 4 sections and compared a experimental result with a simulation result. That is, Section A (0s~9s): Straight, Section B (9s~12s): Transition from straight to curve, Section C(12s~18s): Curve, Section D(18s~22s): Transition from curve to straight.

At first, the experimental value and the calculated value were almost the same in the section A(Figure 7-(a)). Next, there was a difference between the experimental and calculated values in the section B(Figure 7-(b)). Since the connecting point between a cart and a robot (Figure 4 - point P) is away from the robot's reference point (Figure 4 - point G_1), it is considered that the turning of a robot moved the connecting point to the outside and the direction of a cart changed. The experimental value and the calculated value were almost the same in the section C(Figure 7-(c)~(f)). Finally, there was a difference between the experimental and calculated values in the section D(Figure 7-(g)~(h)). As a result of confirming the actual operation of a robot and a cart, it was found that the cause was that a robot and a cart mechanically contacted with each other and the movement of a cart was suppressed. Such a phenomenon may damage a robot or cause a cart to collide with surrounding materials and buildings.

We considered that there are three ways to solve this problem. The first is a method of attaching a rigid wheel to an omni-directional cart. However, this method may lose convenience at a construction site. Moreover, an accident may occur due to forgetting to attach the parts. The second method is to add a spring/damper to the connecting device. By this method, there is a possibility that the behavior of a cart swinging outward can be suppressed. The third is a method of devising the traveling control of a robot. For example, it is conceivable that the inertial force can be reduced by decelerating as much as possible during a curve, and the swing of a cart can be suppressed.

5 Conclusion

In this research, we aimed to improve the productivity of a construction site by automating by pulling a cart with a robot. When pulling a cart by a robot, it was important to develop it in consideration of the motion of a cart. For this reason, first, we theoretically examined the motion characteristics of an omni-directional cart when traveling on a curve. As a result, it was found that the direction of a cart gradually increased as it began to curve and swayed outward. Next, we conducted the pulling experiment and observed the behavior of a cart. As a result, it was found that the same tendency as the theory was shown in the curve section. On the other hand, after the end of the curve, there was a discrepancy between the calculated value and the experimental value due to the touch of a cart. In order to solve the problem of an omni-directional cart that a robot greatly deviates from the trajectory of a robot in the curve, a method of attaching a swivel wheel to an omni-directional cart, a method of adding a spring/damper to the connecting device, and a method of driving control of a robot was considered. In the future, we will set the target trajectory of a cart based on this calculated value and examine these methods.

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