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Cooperative control of multiple modular mobile systems with active-caster omnidirectional drive mechanisms

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In this paper, an "active-caster" omnidirectional wheel mechanism is introduced. The original type of the active caster was invented more than twenty-five years ago, and various types of active casters were developed by the author's group, some of which are described in this paper as well. Unlike other omnidirectional wheels such as Mecanum Wheel or Universal Wheel, active casters do not need freely rotating parts. An active caster is an orientable wheel with a normal tire, the steering and wheel shafts of which do not intersect like a normal passive caster. The wheel and steering shafts are driven by the respective motors to perform the omnidirectional movement of the robot.

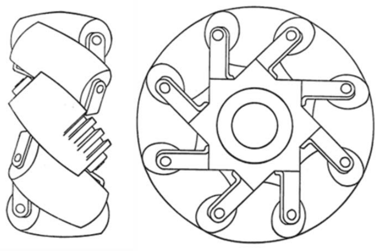
To apply this technology to various fields, many types of active casters have been developed. For example, a two-wheeled active caster was developed to avoid redundant actuation, dual-wheeled active caster—to reduce turning friction, and differential-drive-type active caster—to improve the operating rate of the actuators.

A cooperative transporting system with multiple two-wheeled mobile robots is presented as a future work that realizes the omnidirectional transportation of large objects with multiple mobile robots. Each mobile robot is controlled to perform the active-caster motion during the transporting task, and it can move independently in the same manner as a two-wheeled robot. This configuration increases flexibility in object transport applications.

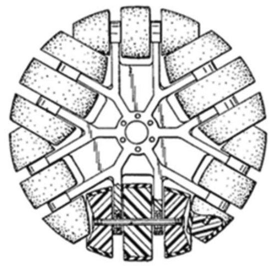
1. Introduction

The mechanisms to move on floor surfaces using wheels have been known since ancient times. For example, an automobile type steers the front wheels and obtains a driving force from the rear wheels, and a wheelchair type independently drives the wheels arranged on the left and right sides. These two types of systems are dominant in common mobility systems.

However, an omnidirectional mobile system that can move instantly in all directions is effective for special applications in places, such as factories or



(a) Mechanum Wheel (USP3,876,255)



(b) Universal Wheel assembly(USP4,715,460)

Figure 1: Wheels for omnidirectional motion.

crowded environments. An omnidirectional mobile robot uses an omnidirectional wheel to perform such movements. Mechanum Wheel [1] is equipped with many barrel-shaped rollers on its rim, as shown in Fig. 1(a). Each roller can rotate passively about its axis, and each rolling direction is 45° to the axis of the main wheel. The free rollers allow the wheel to move passively in the lateral direction of the roller contacting the ground at that moment. As the motor rotates the wheel axle in a normal manner, an active traction force is generated along the direction of the roller axis. Universal Wheel [2] (Fig. 1(b)) has many free peripheral rollers; however, the direction of each roller axis is perpendicular to the wheel axis. The location of the point of contact is always stable with respect to the vehicle body.

Omnidirectional motion of a vehicle can be achieved by arranging three or more wheels [3]. As this robot can control each mobile vector independently in two directions on a plane and a rotation vector about the vertical axis, that is, a three-dimensional vector, it can characteristically generate extremely flexible motions (known as holonomic and omnidirectional motions). However, these wheel mechanisms have various drawbacks such as many-component wheel composition and complicated structure. Moreover, the load-carrying capacity cannot be easily increased because the ground contact area is small and vibrations occur owing to the switching of the ground contact point between the rollers. In addition, the step-climbing ability significantly deteriorates depending on the direction of movement. These types of robots have been limitedly used in industrial applications because of these drawbacks; however, they are often used in specific applications, such as soccer robots, owing to their good controllability.

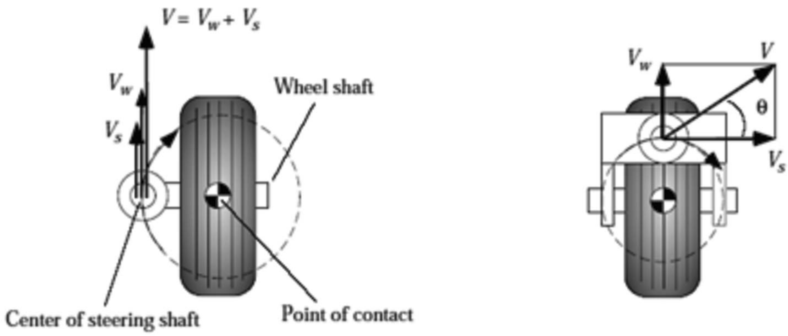
Wheel mechanisms aimed at omnidirectional movement have been extensively studied, and many types of mechanisms have been invented and proposed [4–7]. However, these mechanisms are similar in principle to the aforementioned omnidirectional wheels. That is, they actively generate a driving force in one direction from the wheels, but passively roll in the orthogonal direction. Thus, most of the moving mechanisms have the above-mentioned inherent defects. To solve the aforementioned problems fundamentally, a novel concept has been proposed by the author's group for generating an omnidirectional motion with a caster-like drive wheel with a normal tire [8].

2. Active caster

Conventional casters operate passively and are not used as driving wheels. Rather, if the steering and wheel rotation shafts are spaced apart, like the caster, the vehicle moves sideways when the direction of the wheel is changed; therefore, driving with such wheels has been avoided so far. However, considering this phenomenon in reverse, the possibility of driving becomes apparent. That is, the fact that the vehicle body moves when driven using the steering shaft indicates that the vehicle can be moved using the steering shaft operation. This implies the occurrence of "motion interference." In contrast, another motion cannot be controlled with one motion without "motion interference." When the caster structure is considered based on this concept, there are various directions in which the steering shaft is separated from the wheel shaft. Fig. 2 shows an example of two types of directions: immediately beside the wheel and along the rolling direction of the wheel. The velocity vector V_s that moves the upper vehicle by the rotation of the steering shaft and the velocity vector V_w that moves the vehicle when the wheel shafts rotate are shown. However, it can be seen that both directions coincide in Fig. 2(a), and they are orthogonal to each other, as shown in Fig. 2(b). Orthogonality means that motion vector V oriented in an arbitrary direction can be generated by independently changing the magnitude of each vector. The structure shown in Fig. 2(b) is similar to that of a normal caster; however, based on this principle, a study was initiated to realize omnidirectional movement by independently controlling the drive of the wheel and steering shafts.

3. Control of the active caster

Controlling caster-type wheels requires technically complex motion planning. This is because, in general, the direction of the wheels is carefully planned for wheel control. If the control is not performed with high precision, the vehicle turns around, resulting in inconsistencies in motion, such



(a) Lateral offset (b) Longitudinal offset

Figure 2: Orientable off-centered wheels.

as the wheels pushing and pulling each other. However, based on the considerations in Section 2, a velocity-generation-based method for controlling the steering shaft is devised. That is, the target velocity vector is decomposed into the steering and wheel directions. It is intended to drive the wheel and steering shafts so as to satisfy the respective target velocity components. This relation is the kinematics of the wheels and is consequently expressed in Eq. (1).

$$\begin{bmatrix} \omega_w \\ \omega_s \end{bmatrix} = \begin{bmatrix} \frac{\cos\theta}{r} & 0 \\ 0 & \frac{\sin\theta}{s} \end{bmatrix} \boldsymbol{V} \tag{1}$$

Here, ω_w and ω_s are the angular velocities of the wheel and steering shafts, respectively; r and s are the wheel radius and caster offset (separation distance between the wheel shaft and the steering shaft), respectively; and V represents the required command velocity vector. θ included in the matrix on the right side represents the direction of the command velocity vector with respect to the rolling direction of the wheel. By driving the wheel and steering shaft motors based on these kinematics, a velocity vector with an arbitrary direction and magnitude can be generated at the position of the steering shaft center, regardless of the direction of the wheel.

The absolute angle of the wheel relative to the vehicle should be measured for calculating the ratio of the component decomposition of the velocity vector (rather than for controlling the angle). The angle measurement was performed continuously, and the value of θ in Eq. (1) was regularly updated. Fig. 3 shows a conceptual diagram depicting the movement of the wheel according to this control law. In initial state $\boxed{\text{A}}$, the velocity is

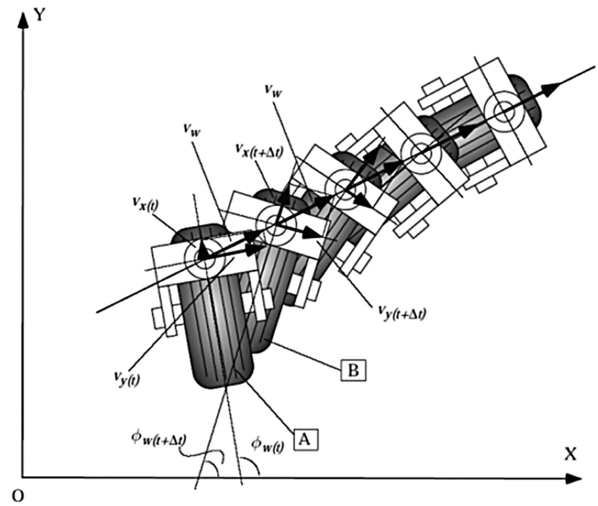


Figure 3: Motion of the active caster.

decomposed into the wheel rolling direction and the lateral direction with respect to the command velocity vector, which is set to move in a direction different from that of the wheels. At that time, the driving of the wheel and steering shafts is initiated. At position B of the wheel, after a short time, the posture changes from initial position A. Thus, the angle at that moment is measured and updated, and the driving of the wheel and steering shafts is performed at a new velocity ratio. By repeating this process, the direction of the wheel gradually moves such that it follows the target trajectory while generating the command velocity in the central position of the steering shaft. Fig. 4 shows the simulation results, in which the control operation is calculated in detail. As shown in the figure, the direction of the wheel is reversed on the way, and a motion that converges in the direction of the target velocity is generated. This is exactly the behavior observed in a passive caster, and it has been confirmed that this behavior, which appears to be complicated, can be generated by a simple control law, as shown in Eq. (1).

Thus, omnidirectional motion can be realized without using omnidirectional wheels. A two-wheeled robot [9] and a three-wheeled robot [10] were manufactured based on a single-wheeled mechanism design. Fig. 5 shows an overview of the three-wheeled robot prototype.

An omnidirectional mobile robot using this form of active caster was commercialized as an XR4000 robot by Nomadic Technology for a certain period from 1997, and it was used in studies of mobile manipulators [11].

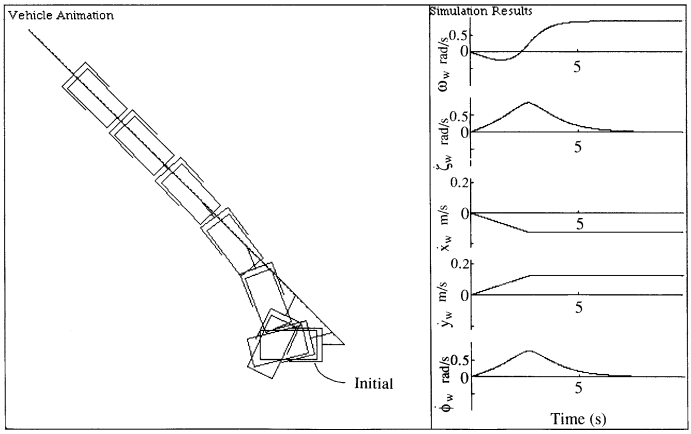


Figure 4: Simulation of active caster motion.

(a) Wheel mechanism (b) Omnidirectional robot overview

Figure 5: Three-wheeled omnidirectional robot.

4. Variety of the active caster mechanism

Based on the principle of active casters explained in the previous section, active casters were proposed with various improvements such that they could be applied to various systems. Representative examples are provided below.

4.1. Two-wheeled active caster

At least two drive wheels are required to create a mobile robot by using active casters. As each wheel requires wheel and steering motors, at least four motors are required to be mounted on the entire robot. As the robot has three degrees of freedom on the floor surface in total, that is, x and y in the longitudinal and lateral directions and angle θ about the vertical axis, one degree of freedom in the actuation is redundant. Therefore, the motor should be controlled for high-precision coordination. In the case of a three-wheeled robot, six motors are mounted; thus, the number of redundant degrees of freedom is three. To solve this redundancy problem, an active caster system capable of omnidirectional motion with three motors having the same degrees of freedom as those of the vehicle has been devised [12].

According to this structure, the steering shaft, arranged at a position spaced forward from the midpoint of the two wheels, is further independently driven, in addition to the independent driving of the two parallel wheels. The three degrees of freedom of a vehicle moving on a plane are controlled by three motors in total. The control law is as follows.

$$(2) \qquad \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\theta - \frac{rs}{W}\sin\theta & \frac{r}{2}\cos\theta + \frac{rs}{W}\sin\theta & 0 \\ \frac{r}{2}\sin\theta + \frac{rs}{W}\cos\theta & \frac{r}{2}\sin\theta - \frac{rs}{W}\cos\theta & 0 \\ \frac{r}{W} & -\frac{r}{W} & 1 \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \\ \omega_S \end{bmatrix}$$

Thus, the driving velocity of the three motors can be calculated by the command of the motion of the planar three degrees of freedom, thereby avoiding the redundancy of the degrees of freedom of the drive. In this way, the control method becomes simple. In other words, high-precision cooperative control is not required for avoiding inconsistencies.

However, an omnidirectional mobile system of this form is suitable for a robot body, the horizontal cross-sectional shape of which is close to a circle or a square, to perform a continuous multirotating motion at the upper part of the drive mechanism. Taking advantage of this property, an omnidirectional wheelchair has been developed [13]. In addition to the basic form of the two-wheeled active caster, the driving forces of the left and right wheels are also transmitted to the omnidirectional wheels arranged in parallel to the left and right front wheels. The step-climbing ability of this four-wheel drive (4WD) is greatly improved.

Certain studies [13] used a mobile mechanism based on the basic structure of a two-wheeled active caster shown in Fig. 6. Another example that has been put to practical use is the TOYOTA personal robot. [14]

4.2. Dual-wheel active caster

The active caster, described in Section 4.1, has two wheels that are driven independently of each other, but the single-wheel active caster described in

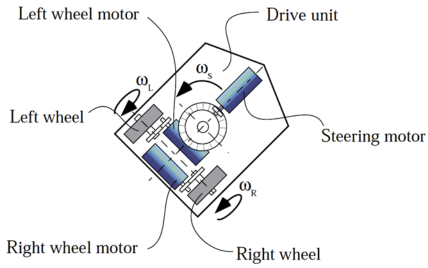
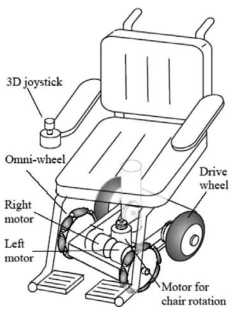


Figure 6: Two-wheeled active caster.

Figure 7: Motion of the two-wheeled active caster.



(a) Concept sketch

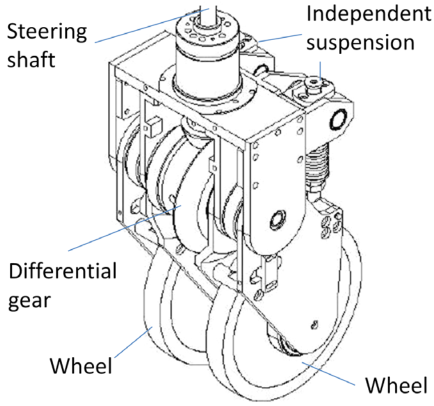
(b) Prototype overview

Figure 8: 4WD omnidirectional wheelchair.

Section 2 has a dual-wheel form. A mechanism that drives with a single motor via a differential mechanism has been developed [15] and [16]. This dual-wheel design is also found in passive casters, and the caster operation is smoothened by reducing the steering torque when turning the wheels. Moreover, it has the advantage that the diameter of the wheel can be increased owing to its design.

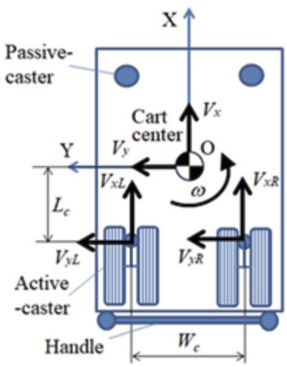
Fig. 10 shows a cart equipped with dual-wheel active casters [17]. This cart can control the transmission/disconnection of the motor power to the wheels via an electromagnetic clutch, and when the power is cut off, it can be pushed and pulled by humans as a normal passive cart. Thus, it can

(a) Prototype wheel overview

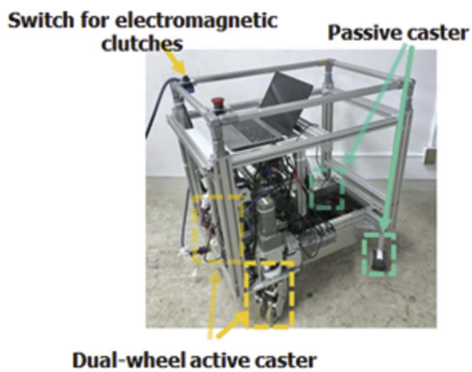


(b) 3D drawing

Figure 9: Dual-wheel active caster.



(a) Cart kinematics



(b) Omnidirectional cart prototype

Figure 10: Cart with dual-wheel active casters.

be expected to be used in human/machine cooperative work. A kinematic model of the cart according to the two-wheeled active caster is shown in Eq. (3). The dual-wheel active caster is studied for many applications [18–24].

$$
\begin{bmatrix} V_x \\ V_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\theta_R & -\frac{s}{2}\sin\theta_R & \frac{r}{2}\cos\theta_L & -\frac{s}{2}\sin\theta_L \\ \frac{r}{2}\sin\theta_R & \frac{s}{2}\cos\theta_R & \frac{r}{2}\sin\theta_L & \frac{s}{2}\cos\theta_L \\ \frac{r}{W}\cos\theta_R & -\frac{s}{W}\sin\theta_R & -\frac{r}{W}\cos\theta_L & \frac{s}{W}\sin\theta_L \end{bmatrix} \begin{bmatrix} V_{xR} \\ V_{yR} \\ V_{xL} \\ V_{yL} \end{bmatrix} \tag{3}
$$

4.3. Differential-drive active caster

All the active casters described so far drive the steering shaft with their respective motors. The steering shaft motor almost stops when the direction change of the wheels ends, and the wheels move along a long linear motion. Because the mass of the steering motor is carried by the wheel motor, the operating efficiency of the actuator decreases, and the motor becomes large. To solve this problem, a differential drive mechanism is devised in which the two mounted motors are operated in both rotational movements of the steering shaft and wheel. The wheel structure is shown in Fig. 11. This structure does not incorporate the conventional differential gear mechanism developed previously [25]. Rather, it functions as a differential drive using a gear-coupling method that drives the wheel on both sides with separate gears. With this structure, a design that simplifies the mechanism can be realized because it can be configured with a few gears. Fig. 12 shows a prototype wheel with this design. It is an extremely simple, symmetrical structure that transmits the power of the motor provided in the upper part to one side of each wheel. With this structure, the velocity difference between the two motors results in the wheel rotation, and the average velocity results in the steering shaft rotation. Therefore, the rotation operation of both motors contributes to the rotation of the wheels and steering; thus, the operating efficiency of the motor can be increased. Consequently, driving using a small motor becomes possible. The kinematic model of the wheel is

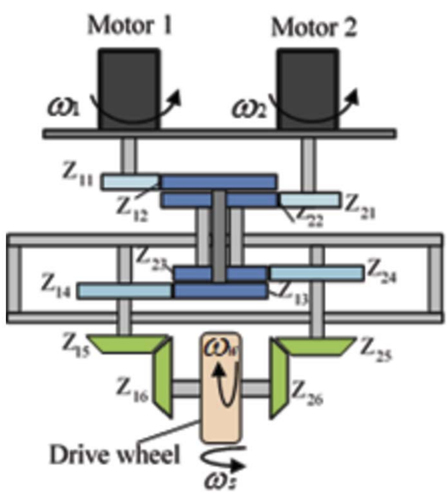


Figure 11: Gearing of the differential drive active caster.

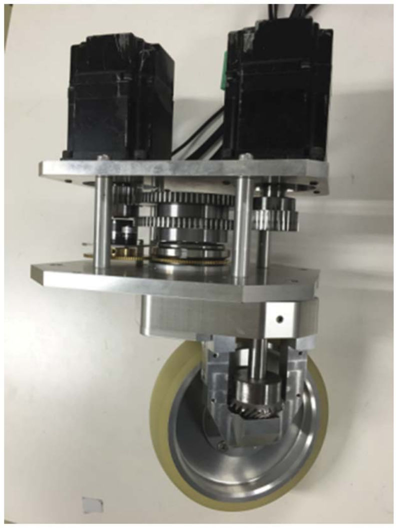


Figure 12: Prototype of the differential drive active caster.

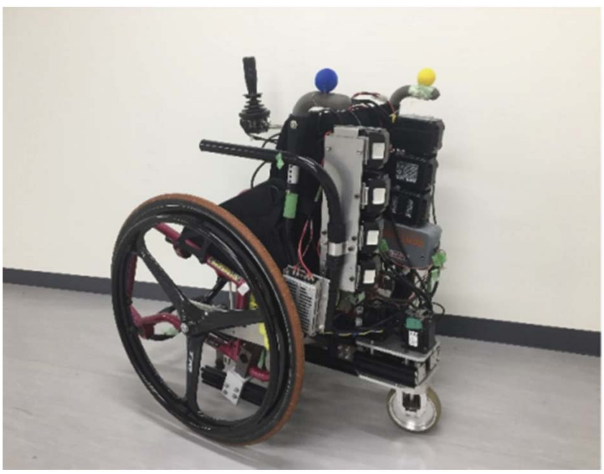


Figure 13: Wheelchair with a differential active caster drive system.

expressed by Eq. (4). Fig. 13 shows a wheelchair equipped with the proposed differential active caster.

$$\begin{bmatrix} \omega_w \\ \omega_s \end{bmatrix} = \begin{bmatrix} \frac{1}{2G} & \frac{-1}{2G} \\ \frac{-1}{2} & \frac{-1}{2} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} \tag{4}$$

5. Modular mobile system

5.1. Concept of the cooperative transportation system with multiple modular mobile robots

Thus far, various types of active casters researched and developed in the past have been described, but the common feature is that wheel control is highly independent. As mentioned in Section 2, a single-wheel mechanism can completely control the velocity vector given to one point (fixed point of the steering shaft) of the robot body. Thus, the operation of other wheel mechanisms is required "to prevent the distance between the steering shafts from changing." Therefore, each wheel mechanism is considered to be independent and modularized to construct a cooperative transport system. Fig. 14 shows a conceptual diagram. Each mobile robot has two parallel wheels that perform normal left and right independent drives. Therefore, the mobile robot moves like a normal two-wheeled robot. Moreover, when transporting a large object, each mobile robot supports the object. At this time, the mobile robot rotatably holds the legs of the transported object not at the midpoint of the two parallel wheels but at a position spaced forward. By doing so, it achieves a form similar to that of a two-wheeled active caster. That is, the two parallel wheels are located at a position apart from the steering shaft (in this case, the leg of the object). Therefore, the reverse operation of a caster can be realized by driving the two wheels as per the control method of the active caster, achieving holonomic omnidirectional transportation of objects.

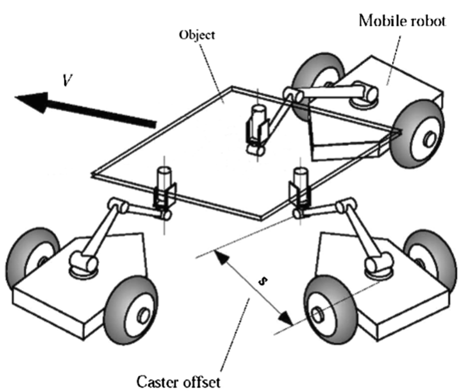


Figure 14: A Concept schematic of a modular mobile system.

This type of transport system has already been studied. A mobile platform with multiple active caster modules has been proposed [26]. The number of modules can be varied based on the platform size (from 2 to n). However, in this system, each module cannot move independently from the mobile platform, and the mounting position of the active caster module must be defined in advance. An omnidirectional mobile robot with active split offset casters was studied in [27]. This system was applied to a mobile platform of a wheelchair and demonstrated successful omnidirectional movements on the asphalt pavement. This system allows the installation of two active caster modules, but the configuration of the platform and the location of the modules must be defined in advance.

In our research, a two-wheeled mobile robot is used as the active caster module to improve the flexibility of the transport system. A microcomputer board, sensors, motors, and a battery are installed on the mobile robot, and omnidirectional transportation is achieved by communicating with other robots and a host computer. Therefore, each mobile robot can move independently when transporting a task is not required. Additionally, when an object is too heavy for a robot team with a predetermined number of mobile robots, an additional robot(s) can join for assistance.

5.2. Simulation study and prototyping

Fig. 15 shows a schematic model of the proposed omnidirectional transportation system using two robots [28]. The two-wheeled robots are connected to a large object via passively rotatable connecting rods. Note that the rod is

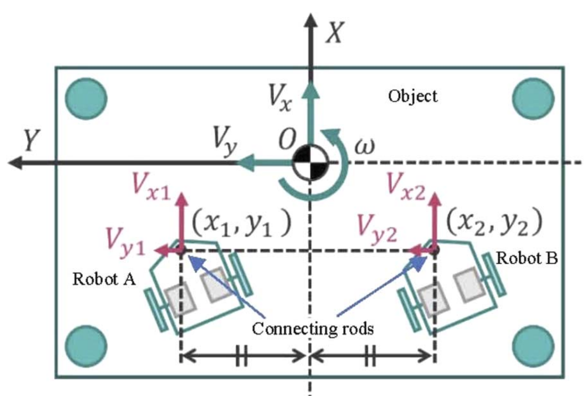
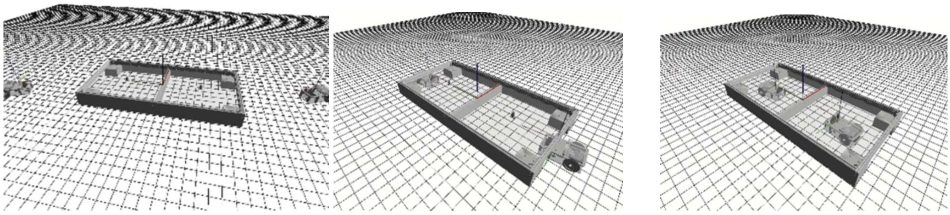


Figure 15: Model of the omni-directional cart with two mobile robots.



(a) Approaching an object (b) Entering bottom space (c) Docking completed

Figure 16: Simulation of the two robots dock to a large object.

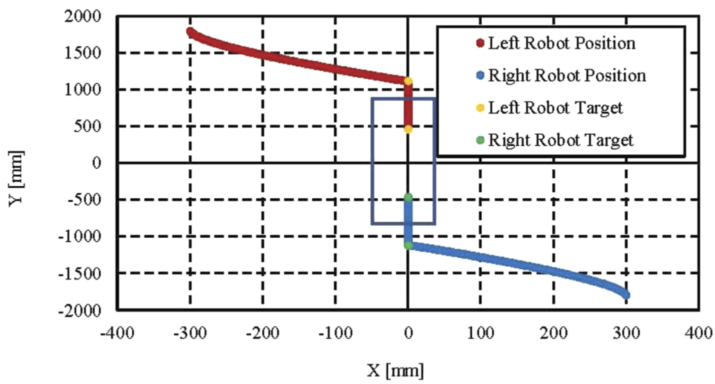
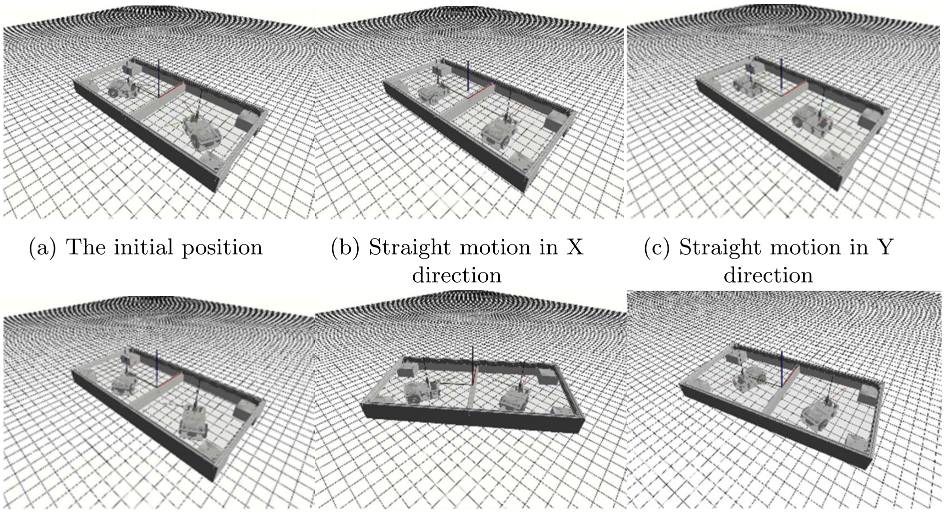


Figure 17: Simulation result of the robot control for docking (Trajectories of the two robots).

fixed to the robot body not at the midpoint of the two drive wheels but at the offset position to the front of the mobile robot. The distance between the midpoint of the wheels and the center of the rod is regarded as the caster offset.

In this study, independent and semi-stand-alone robot control is considered together with the omnidirectional transportation of a large object. In other words, each robot can move independently from a large object and other robots to go to the home position, a charging station, etc. When a cooperative transformation task is requested, two or more mobile robots approach and dock to a large object for transporting it to the desired position.

Fig. 16 shows the simulation result of the docking motion of the two robots, where each mobile robot approaches a large object with independent control after finding a respective docking position (a hole on the bottom of the object). Fig. 17 shows the trajectories of the two robots. In the simula-



(a) The initial position
(b) Straight motion in X direction
(c) Straight motion in Y direction
(d) Straight motion in 45deg.
(e) Spin turn
(f) Translation motion with rotation

Figure 18: Simulation of omnidirectional movement control.

tion, the two robots were able to reach the docking positions and successfully stopped.

After the docking task, the two robots transported the large object by cooperative omnidirectional motion based on the active caster control, in which each mobile robot was regarded as a two-wheeled caster. Fig. 18 shows screenshots of the simulation animation. In the simulation, translation motions along the X-direction, Y-direction, and 45° from the X-axis were performed, followed by spin-turn and translation motion with rotation. Plots of the position and orientation of the object are shown in Fig. 19. As can be observed, the proposed system realizes a continuous series of omnidirectional motions.

To verify the operation of the proposed system in a real-world scenario, a prototype mobile robot was designed and built. Fig. 20 shows an overview of the prototype. The dimensions of the mobile robot are 345 mm (L) × 240 mm (W) × 140 mm (H), and its weight is approximately 5 kg (no battery), with a 0.67 kg Li-ion battery pack for power tools. A 2D-LiDAR was installed on the mobile robot to measure the environment of the robot for path planning, performing the docking task, and measuring the relative position and angle of an object.

Pictures are shown in Fig. 21 to illustrate the docking scenario. Note that the object consists of aluminum frames with a clear acrylic top plate

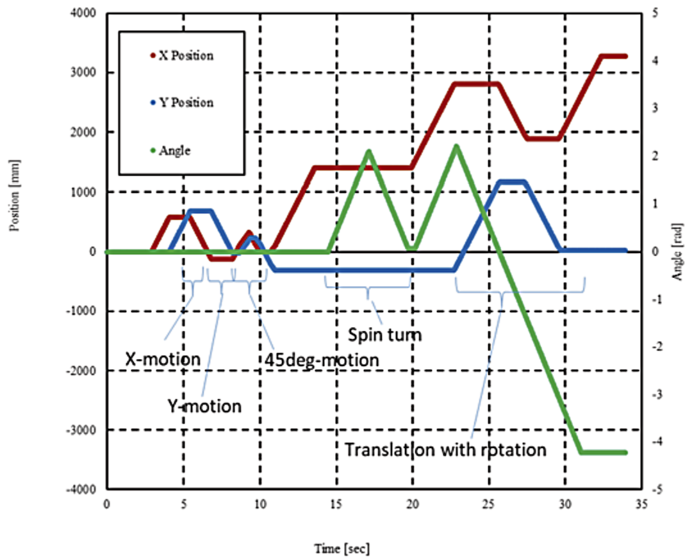


Figure 19: Simulation result of the omnidirectional cart transportation by two mobile robots.

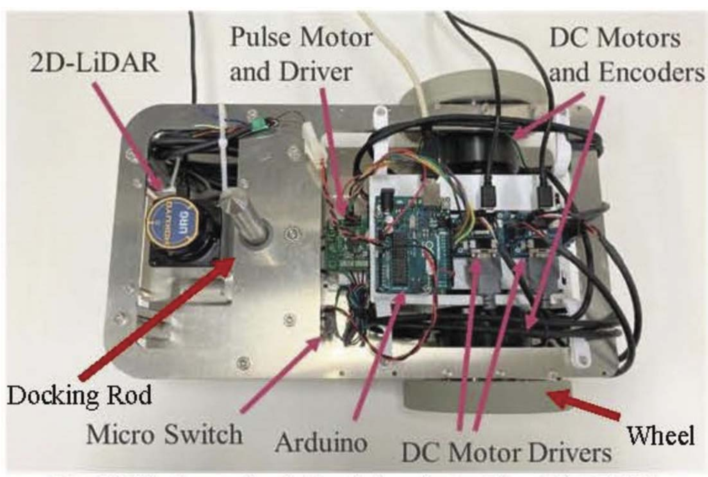
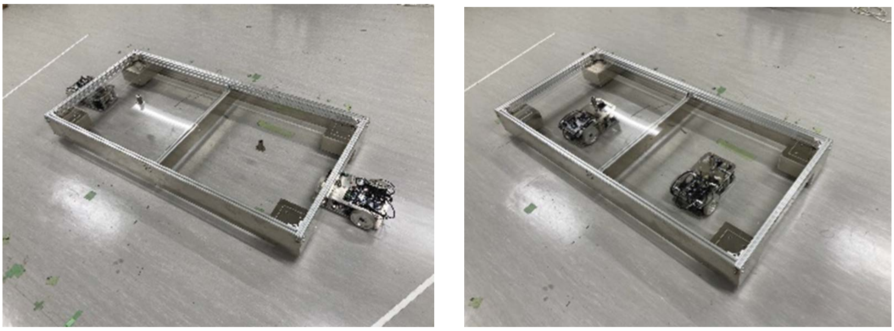


Figure 20: The two-wheeled mobile robot with a 2D-LIDAR.

to show the robot's behavior. The two sides of the object frame have gates for entering the robot into the object frame. Each robot finds a gate using 2D-LiDAR and measures the relative position and orientation of the object



(a) The object frame with robots entering

(b) Docking two Robots to the object

Figure 21: Prototype of two mobile robots and an object frame.

to complete the docking task. After docking, the two mobile robots act as active casters for omnidirectional transportation of the large object. The proposed system, by which a large object is transported by two or more mobile robots with independent control, is unique and has features that are not present in the literature. To realize the scenario above, control algorithms and communication protocols will be developed in the next stage of the research.

6. Conclusion

This paper summarizes the research on omnidirectional mobile systems that have been developed by the author's group for many years and describes the current and future prospects as well. The core of this technology is to realize omnidirectional movements by actively driving the steering and wheel shafts of the caster-shaped wheel, in which the steering and wheel axes do not intersect. The system is called as "active caster" that solves the problems present in mecanum wheels and universal wheels, such as vibrations, noise, and inaccurate motion.

A single-wheeled active caster was first introduced as a fundamental configuration, followed by a two-wheeled active caster to avoid redundant actuation by reducing the required number of motors from four to three. The dual-wheeled active caster was developed to reduce turning friction, whereas the differential-drive-type active caster contributed to improving the operating rate of the actuators. Because various active casters are available, users can select the best configuration according to the application requirements.

Herein, a corporative omnidirectional transporting system is proposed, in which multiple two-wheeled mobile robots carry a large object by performing active caster motion for omnidirectional motion. In the simulation study, two mobile robots approach and dock an object. After docking, the two mobile robots perform active caster motion for the omnidirectional transportation of the object.

The aim of the proposed system is to realize a more flexible cooperative transport system than existing systems. Each robot moves independently unless a cooperative task is performed. When a large object has to be moved, the number of cooperating robots is determined according to the size and weight of the object, which can be flexibly and dynamically changed, for example, by joining or leaving halfway.

To realize this concept in a real-world scenario, prototype mobile robots were designed and built together with a large experimental object. Control algorithms and communication protocols for the prototype will be developed in the future to realize this concept.

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