

# Unmanned Vehicle Transportation System Using Pair of Thin Robots

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## ABSTRACT

An unmanned vehicle system that transports cars in place of humans was devised. To enable application to a wide range of vehicle types including those without automated driving functions, vehicle transportation robots that are not constrained by car body performance are used for vehicle transportation. Additionally, in order to transport vehicles even in limited indoor and urban spaces, the system employs a pair of robots that move freely underneath the target vehicle, lift up the tires of the vehicle at the same time, and cooperate to achieve free omni-directional transportation. A prototype of the vehicle transportation robot was developed to verify system feasibility. Operation verification experiments were conducted using the developed prototype in a limited space, and confirmed realization of the desired transport operation.

## 1. Introduction

Honda has proposed the statement to “serve people worldwide with the ‘joy of expanding their life’s potential’” in its 2030 Vision<sup>(1)</sup>. Cars are convenient tools that expand the potentials of life and satisfy travel needs easily and quickly. However, the use of cars also involves various labors that are not directly related to travel, such as parking, refueling, and charging.

Specifically, some 30% of all drivers feel they are not adept at or experience anxiety when parking<sup>(2)</sup>. In addition, over half of novice drivers feel that driving in parking lots or garages is dangerous<sup>(3)</sup>. Thus, the act of parking is a psychological obstacle to traveling by car. Around 30% of all traffic accidents in Japan occur in parking lots<sup>(4)</sup>, so these feelings of being not good at or having anxiety about parking also appear in the actual state of traffic accidents.

Valet parking (VP) is widespread in Europe and the United States as a service that takes care of parking. In VP, the driver leaves their car key with an attendant (valet) who parks the car and then delivers the car to the entrance for departure. While VP is a convenient service for drivers, it is no different from personal parking, and operates only in limited environments such as high-class restaurants and hotels.

Vehicles equipped with parking-assist functions that assume use near parking slots have already been

commercialized as a means of directly assisting parking, and are helping to reduce the psychological burden on drivers as well as accidents in parking lots<sup>(5)</sup>.

Automated valet parking (AVP) that combines automated operation and VP is also attracting increasing attention. In AVP, the user drives to an AVP-compatible parking lot reserved in advance, exits the vehicle at a location convenient for access to adjacent facilities, etc., and requests automated parking using a terminal such as a smartphone, at which time the service parks automatically by unmanned operation without presence of the driver<sup>(6)</sup>. Active efforts are underway to develop AVP technology, but some reports also say that it will take decades for the level 4-equivalent automated driving cars required for AVP to spread around the world<sup>(7)</sup>.

In response to this issue, practical operation has begun of large-sized vehicle transportation robots intended for use mainly in large-scale outdoor parking lots such as those found at airports<sup>(8)</sup>. By using robots, all the necessary functions and infrastructure can be provided on the facility side, enabling automated parking even for vehicles without automated driving functions.

Meanwhile, systems intended for use in small indoor or urban spaces where parking is a challenge and only a few vehicles can be parked have yet to be practically applied. Factors for this include challenges in robot miniaturization and precise control. The authors have therefore devised

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an unmanned vehicle transportation system that can be operated even in small spaces.

This paper describes the system concept, the development of a prototype of the vehicle transportation robot that plays a central role, and operation verification experiments using the prototype to transport a mock-up vehicle for the purpose of verifying system feasibility.

Figure 1 shows the prototype of the developed vehicle transportation robot.



Fig. 1 Prototype of robot

## 2. Development Goals

Figure 2 shows an example of application of an unmanned vehicle transportation system that assumes AVP able to operate even in a small space.

The driver can easily board and exit the vehicle and

load luggage by leaving the vehicle in the expansive boarding and exiting space. After the driver exits the vehicle, the robots automatically recognize the vehicle type, size, and position, and cooperate as a pair to transport the unmanned vehicle to the parking area. As there is no need for boarding and exiting space in the parking area, high-density placement can be performed by commands from the management server. When departing the parking lot, the vehicle is transported to the boarding and exiting space according to the driver's command. This series of operations helps to reduce the labor and stress of parking, while increasing parking efficiency and safety.

The devised unmanned vehicle transportation system was developed with the following two goals in order to realize this type of service and provide a more comfortable car life for people.

- (1) Capable of operation in a small space
- (2) Capable of application to diverse vehicle types

## 3. Concept of Vehicle Transportation System

### 3.1. Basic Concept

Figure 3 shows the concept scheme of vehicle transportation operation using robots. When performing transportation with a single robot, the robot itself must be larger and operation in a small space is challenging. Therefore, a system was adopted wherein a pair of robots move freely underneath the target vehicle, lift up the tires of the vehicle at the same time, and cooperate to perform free omni-directional transportation.

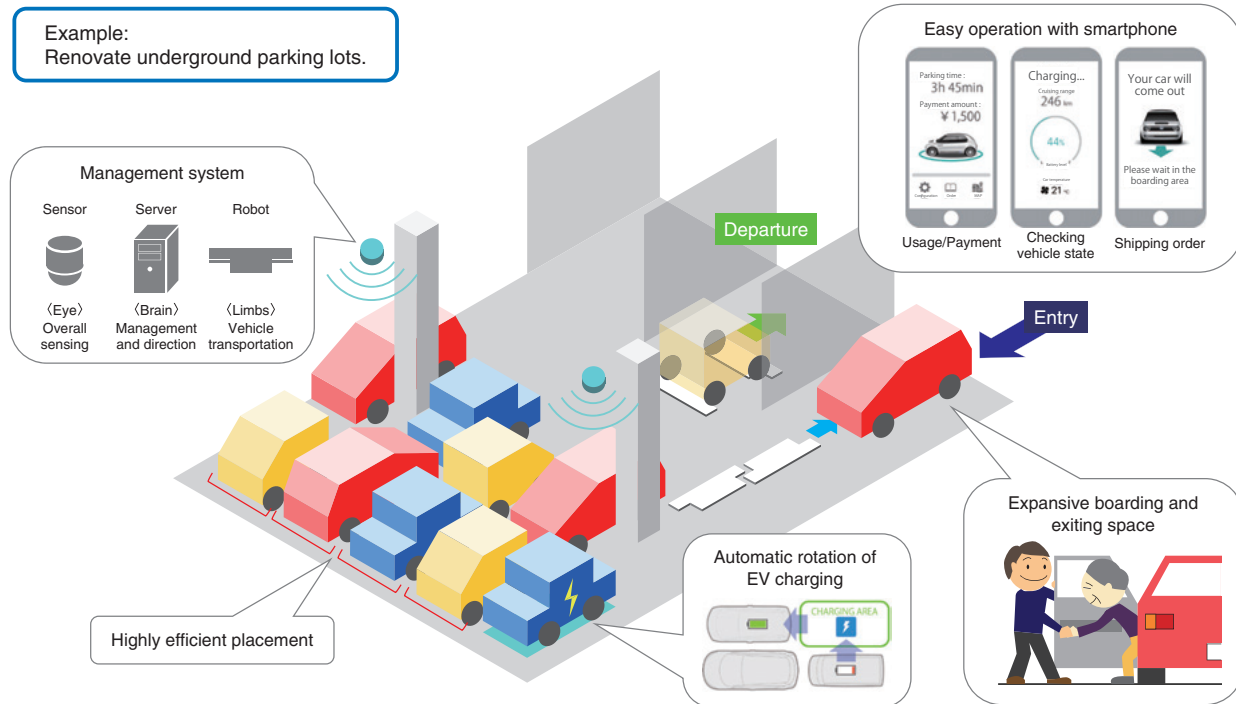


Fig. 2 Image of AVP operation using robots

### 3.2. Operation in a Small Space

When transporting a vehicle, the robots fit underneath the vehicle so the original vehicle size is maintained as shown in Fig. 3. When operating alone, space is saved by moving and storing the robots using the space underneath vehicles and other narrow dead space as shown in Fig. 4. In addition, as cars generally change direction by turning the front wheels and there is a limit to the steering angle, multiple switchbacks are needed depending on the destination, making it unsuited for movement in a small space. The robots are therefore equipped with an omni-directional movement mechanism that enables operation such as moving sideways and turning in place, realizing operation with a high degree of freedom independent of the movement capabilities of the car in a small space.

### 3.3. Application to Various Vehicle Types

The developed robot is intended to support vehicles from general Japanese Kei small cars to large vehicles. Transportation of a wide variety of vehicles calls for a system that can flexibly respond to differences in vehicle type and size. This section describes the vehicle lift up system and design requirements that enable application to various vehicle types.

#### 3.3.1. Lift up method

Vehicle lift up is performed using pairs of arms mounted on the robot as shown in Fig. 5. After the two robots enter underneath the vehicle, the arms are rotated 180 degrees on a horizontal plane for each tire on the left and right, and the tires are clasped between the rotation arms and fixed arms to lift up the vehicle. The arms have a structure where the outer circumferences of the arms rotate freely to reduce the

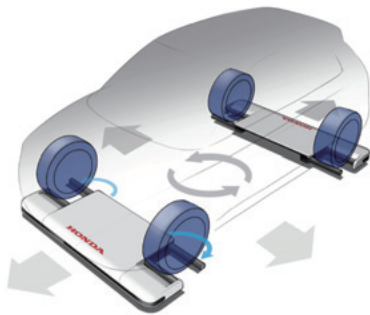


Fig. 3 Concept scheme of transportation by robots

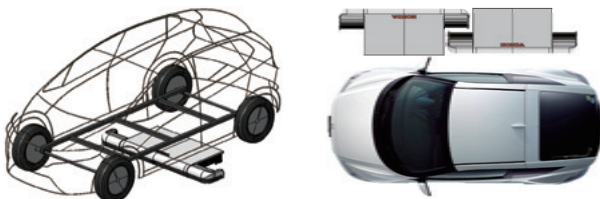


Fig. 4 Efficient use of space

contact friction with the tire as shown in Fig. 6.

Furthermore, even if deviation occurs in measurement or operation, rotational force is produced on the robot body by the arm that contacts the tire first, so the robot is aligned to a position parallel to the axle as shown in Fig. 7, enabling robust lift up.

#### 3.3.2. Design requirements

This clause describes the requirements for robots to be applied to various vehicle types, in reference to the Road Transport Vehicle Law and safety standards in Japan, and the approach toward those requirements.

While no clear safety standards are established for tread width, the Road Transport Vehicle Law stipulates a total width of 1480 mm or less for Japanese Kei small cars, 1700 mm or less for vehicles with a class code beginning with “5,” and 2500 mm or less for vehicles with a class code beginning with “3,” so the outer dimension including the tire width needs to be within these values. The developed robot utilizes a system that supports the differences in each vehicle type by providing a margin in the tire on-board position that enables to support the minimum tire inner dimension and maximum tire outer dimension of all target

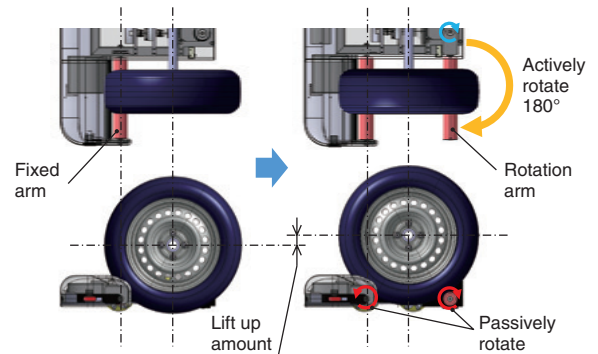


Fig. 5 Sequence of lift up motion

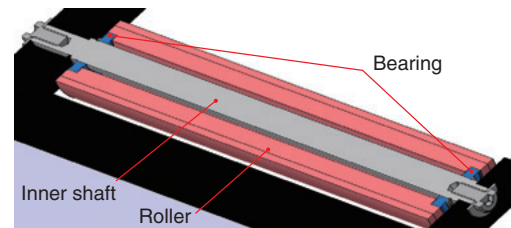


Fig. 6 Sectional view of arm

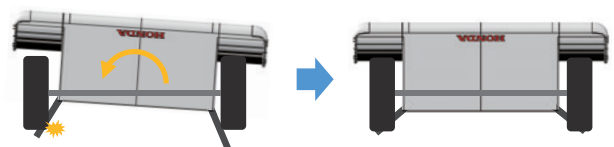


Fig. 7 Self-alignment motion

vehicle types, as shown in Fig. 8(a).

Safety standards stipulate a ground clearance of 90 mm or more in the unladen state, but most general vehicles have a ground clearance of approximately 140 mm. If the thickness of the robot can be kept to 120 mm or less, the system can accommodate around 90% of target vehicle types in Japan.

While no clear safety standards have been established for the wheelbase, the Road Transport Vehicle Law stipulates a total length of 3400 mm or less for Japanese Kei small cars, 4700 mm or less for vehicles with a class code beginning with “5,” and 12000 mm or less for vehicles with a class code beginning with “3,” so the wheelbase does not exceed these values. The developed robot can theoretically transport any full-length vehicle by controlling the distance between the two robots to an arbitrary position in accordance with the wheelbase as shown in Fig. 8(b).

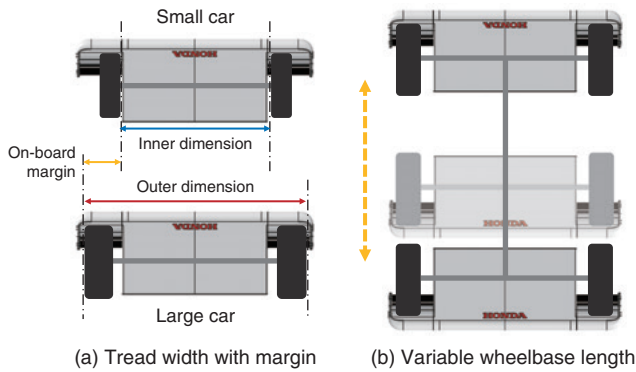


Fig. 8 Supports any size

## 4. Development of Prototype

### 4.1. Verification Items

A prototype was developed for the purpose of verifying transportation operation of a mock-up vehicle in small spaces. The verification items were as follows:

- (1) Robust tire lift up operation using the arm rotation mechanism;
- (2) Synchronization of operation timing and cooperative transport of vehicles by real-time communication between the two robots; and
- (3) Operation in a small space by omni-directional movement such as turning in place and moving sideways.

### 4.2. Mock-up Vehicle

Figure 9 shows the mock-up vehicle for transport that was used in verification. This mock-up was made based on the widely used Honda FIT (2013 model year), which is a standard-sized vehicle positioned midway between a Japanese Kei small car and a full-sized vehicle. The mock-up consisted of an aluminum base frame combined with

Table 1 Specifications

|                     |                 |                    |
|---------------------|-----------------|--------------------|
| Weight [kg]         |                 | 80 / 1 unit        |
| Forward speed [m/s] |                 | Max. 1.9           |
| Withstand load [kg] |                 | 800 / 2 units      |
| Actuator            |                 | Wheel x 4, Arm x 2 |
| Motor               | Type            | Brushless DC motor |
|                     | Performance [W] | 260                |
| Battery             | Type            | Li-Fe              |
|                     | Capacity        | 24 V x 36 Ah       |
| CPU                 |                 | Renesas RX62G      |
| Control period [ms] |                 | 10                 |

a brass wire frame in the shape of the body outlines and actual vehicle tires to enable the robot operation during transportation to be easily understood. The mock-up had outside dimensions of total length of 4000 mm, total width of 1700 mm, total height of 1500 mm, ground clearance of 210 mm, and total weight of approximately 200 kg.

### 4.3. Mechanical Design

The prototype was based on the requirements set forth in Chapter 3, and had specifications sufficient for confirming the verification items presented in Section 4.1. using the mock-up vehicle shown in Fig. 9. Figure 10 shows the hardware of the prototype, and Table 1 shows the specifications.

#### 4.3.1. Movement mechanism

Mecanum wheels<sup>(9)</sup> were adopted for the wheels, and Fig. 11 shows their appearance. Mecanum wheels enable free omni-directional movement by independently controlling each of the four wheels. Figure 12 shows a

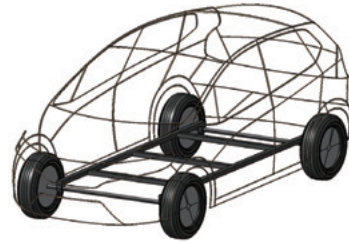


Fig. 9 Wire frame model for experiment

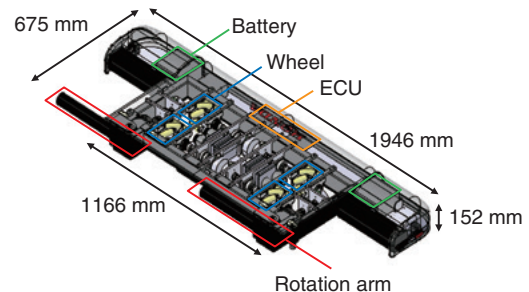


Fig. 10 Appearance of robot prototype hardware

diagram expressing the direction of main body movement produced by the direction of rotation of the wheels. Mecanum wheels are increasingly used not only in research but also for unmanned vehicles used to transport heavy objects<sup>(10)</sup>. The use of mecanum wheels to perform operations such as moving sideways and turning in place, which are challenging to achieve by a car, reduces the space needed for switchbacks and achieves high-density transportation.

#### 4.3.2. Arm mechanism

The drive mechanism of the arm uses a bevel gearbox that amplifies the motor torque and translates the rotation axis by 90 degrees in a different direction. In addition, the distance between the fixed arm and the rotation arm was set so that the lift up amount for a tire size of 185/55R16 is 30 mm from the bottom of the tire to the road surface.

#### 4.4. Control Design

This section describes the motion control for the robot unit and synchronous control between two robots needed to realize vehicle transportation operation.

##### 4.4.1. Motion control

Figure 13 shows a kinematic model of the robot. Here,

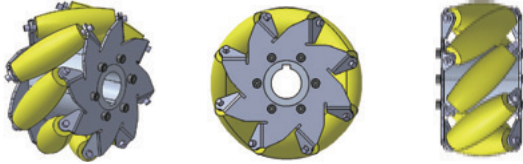


Fig. 11 Appearance of mecanum wheel hardware

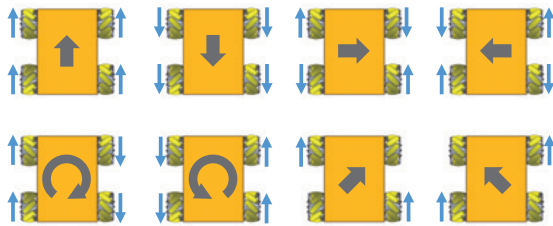


Fig. 12 Moving direction by mecanum wheel

$\phi$  is the rotation angle of the robot body as viewed from the absolute coordinate system  $\Sigma_w$ ,  $x$  and  $y$  are the origin of the robot coordinate system  $\Sigma_{RB}$ , and  $v_1$  to  $v_4$  are the respective tangential velocities of the wheels. Equation (1) shows the inverse kinetics of the robot.  $v_1$  to  $v_4$  are derived by giving the target velocities  $\dot{x}$ ,  $\dot{y}$ , and  $\dot{\phi}$  and performing matrix operations.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} -1 & 1 & W+L \\ 1 & 1 & -(W+L) \\ -1 & 1 & -(W+L) \\ 1 & 1 & W+L \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} \quad (1)$$

In addition, Eq. (2) is used to convert the tangential velocity  $v$  of the wheels to angular velocity  $\dot{\theta}$ . Here,  $r$  is the wheel radius.

$$\dot{\theta} = \frac{v}{r} \quad (2)$$

Figure 14 shows the block diagram of the control system. PI controller is applied to reduce the cumulative position deviation, using the robot velocities  $\dot{x}$ ,  $\dot{y}$ , and  $\dot{\phi}$  as outputs and the wheel motor torques  $\tau_{1...4}$  as inputs. By applying arbitrary target velocities to  $\dot{x}_d$ ,  $\dot{y}_d$ , and  $\dot{\phi}_d$ , control is performed to track those velocities. Note that the wheel rotation angles were measured using encoders, and the angular velocities used the values estimated using a state observer.

##### 4.4.2. Synchronous control

In order to transport vehicles using two independent robots, it is necessary for the robots to operate

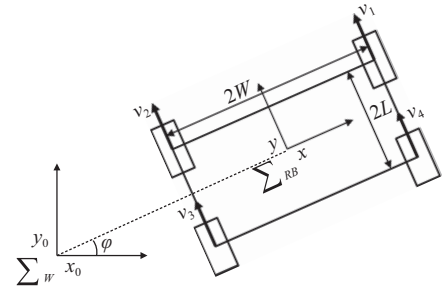


Fig. 13 Kinematic model of robot

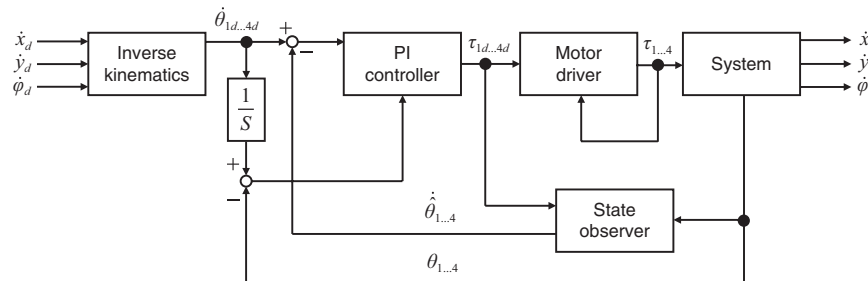


Fig. 14 Block diagram of control system

cooperatively. In this system, one robot is defined as the parent unit and the other as the child unit, and the robots perform vehicle transportation operation while confirming each other's operational status by wireless communication. Specifically, cooperative transport is performed by dividing the operation tasks during vehicle transportation into multiple steps, mutually confirming the situation and deviation state in the current step before the initiation of each step, and synchronizing the start time of the next step as shown in Fig. 15. In this system, operation was modeled using a finite state machine<sup>(11)</sup>. Note that the transition of each step occurs when all of the conditions (1) to (3) below are met:

- (1) When a task in the current step is completed;
- (2) When both robots are in the same state; and
- (3) When a task completion command for the current step is received from one robot.

As a failsafe specification, the robots were designed to halt each other's operation in the event of inoperability or communication loss due to some factor.

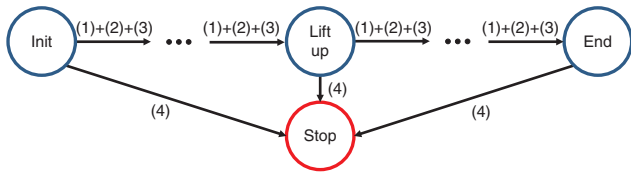


Fig. 15 Example of state flow diagram

## 5. Operation Verification Experiments

Verification experiments were conducted using the developed prototype to confirm mock-up vehicle lift up operation and vehicle transportation operation. This chapter describes the contents and results of each experiment.

### 5.1. Vehicle Lift Up Operation

This experiment verified the basic lift up operation and the lift up operation when control deviation occurred during robot unit movement, as indicated in Section 4.1. (1). Figure 16 shows the conditions of the lift up operation experiment. After the robot entered underneath the vehicle [(1) in the figure], the two arms were rotated 180 degrees on a horizontal plane [(2) and (3) in the figure], and the target lift up operation of 30 mm was achieved by clasp the tires between the arms and lifting up the vehicle [(4) in the figure]. In addition, even when deviation of around 120 mm occurred on one side when entering underneath the vehicle, the robot posture was aligned by the rotational force of the arm to realize robust lift up operation as shown in Fig. 17.

### 5.2. Vehicle Transportation Operation

#### 5.2.1. Motion planning

In this experiment, operation assuming parallel parking

was performed in a small indoor space just  $4.3 \text{ m} \times 7 \text{ m}$ , where parking only by steering the car would be challenging. Figure 18 shows the operation order and paths of the robots. As shown in (1) in the figure, the mock-up vehicle is positioned 4 m away and rotated by 90 degrees relative to the target grid in which a single vehicle will fit, and the robots initiate operation at positions 2 m directly to the side of the mock-up vehicle. Note that PTP control<sup>(12)</sup> was applied to the movement trajectories of the robots. The waypoints through which the robots pass are set in advance (green dots in the figure), and the paths between each of the set multiple waypoints are interpolated using a 5th-order polynomial<sup>(13)</sup>.

#### 5.2.2. Experimental results

Figure 19 shows the conditions of the transportation operation experiment.

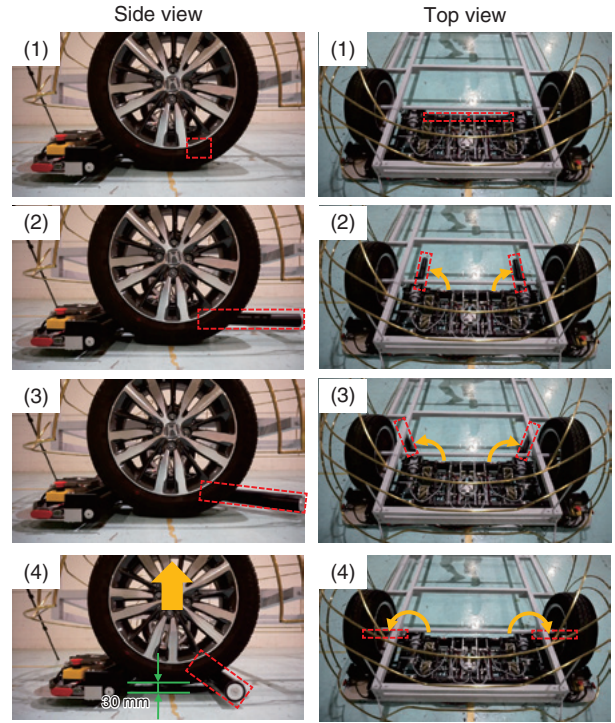


Fig. 16 Lift up motion by prototype

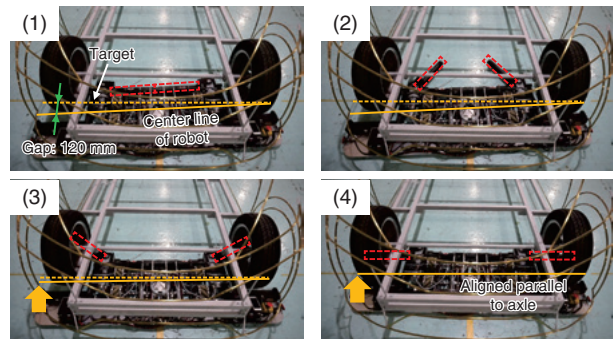


Fig. 17 Self-alignment motion by prototype

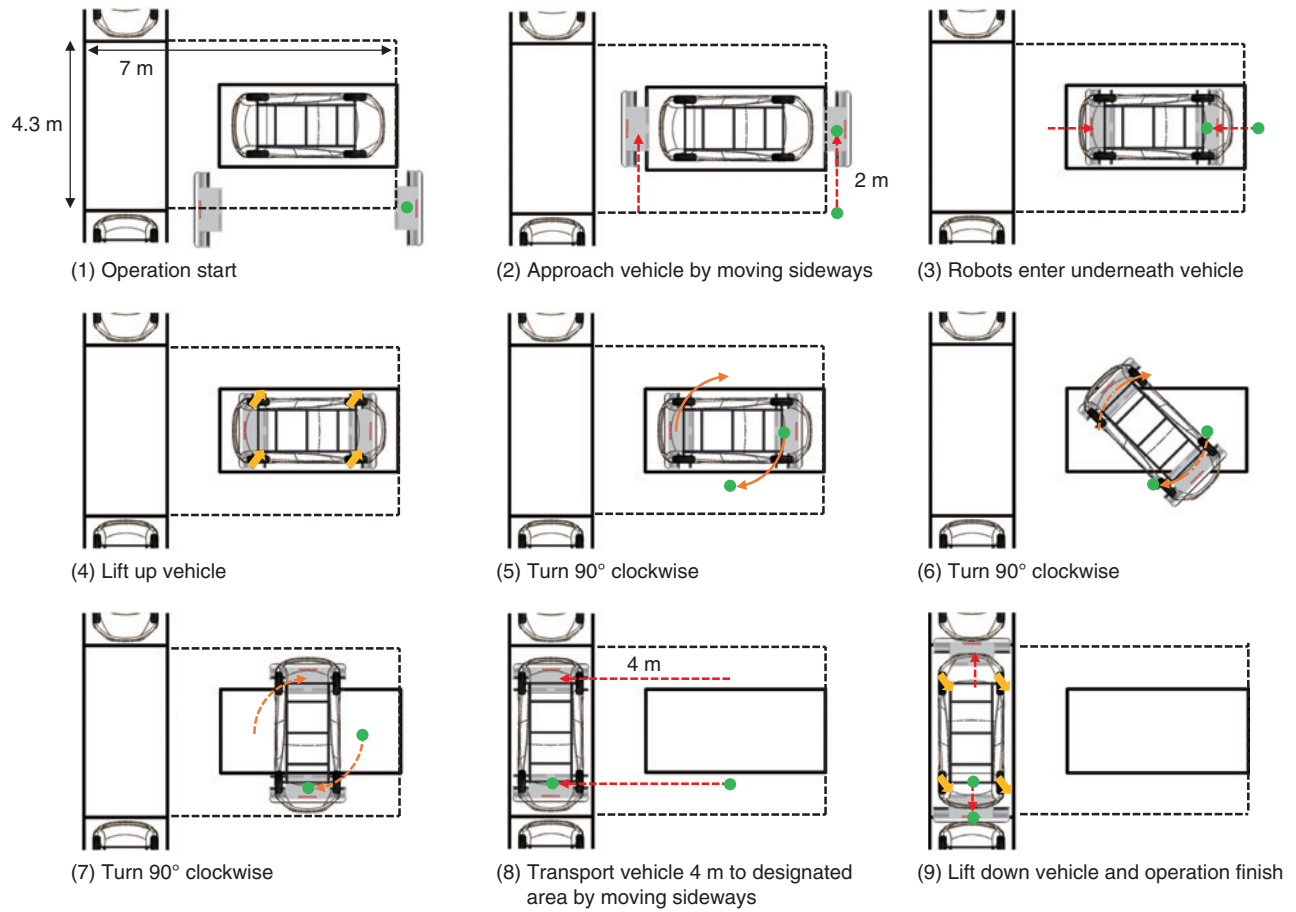


Fig. 18 Motion planning for experiments

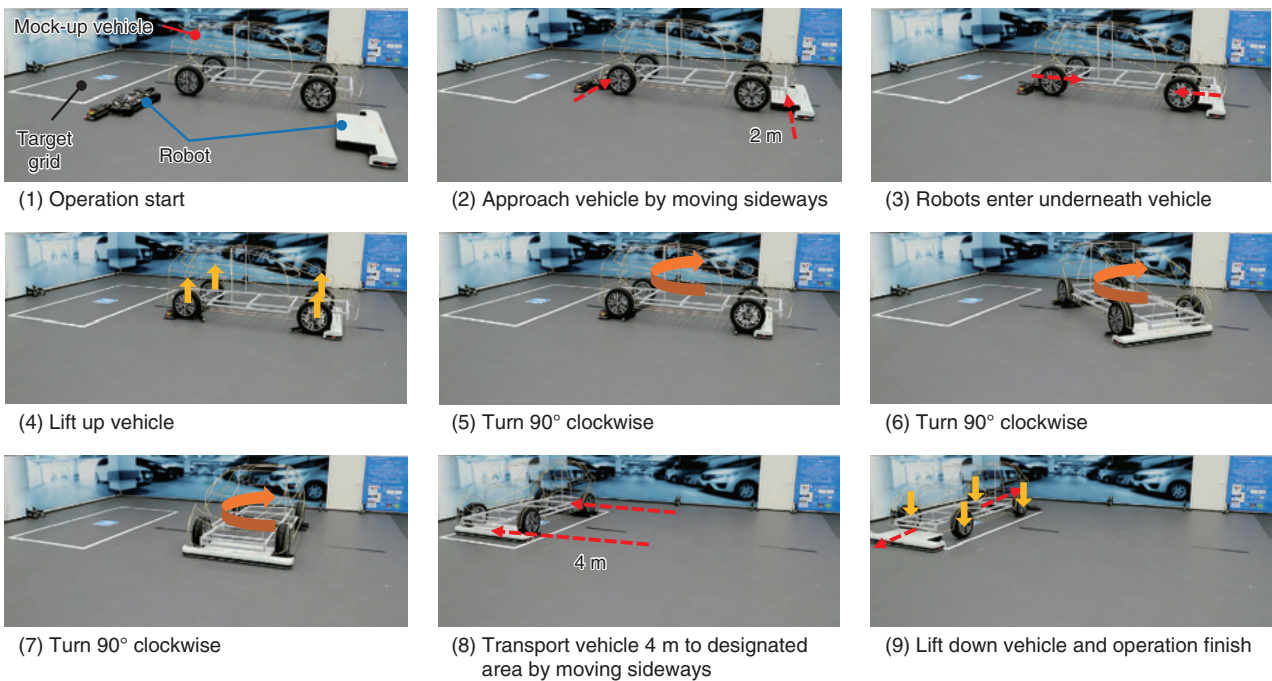


Fig. 19 Cooperative transportation by prototype

(2) and (3) in the figure show that the two robots were able to synchronously enter underneath the vehicle by combining sideways and longitudinal movements.

(4) in the figure shows that after detecting contact between the mock-up vehicle tires and the fixed arms of the robots, the rotation arms were synchronously rotated 180 degrees, enabling lift up while maintaining the level state of the mock-up vehicle.

(5) through (7) in the figure show that the two robots were able to turn the mock-up vehicle 90 degrees in place by tracing circular trajectories while cooperatively transporting the vehicle.

(8) in the figure shows that the robots cooperatively transported the vehicle by moving sideways while maintaining the vehicle rotation angle of 90 degrees, enabling accurate parallel parking within the target grid.

These results confirmed that operation using robots for cooperative transport and omni-directional movement of a vehicle can be realized. This verified that both vehicle switchback and the space needed for switchback can be reduced, and that vehicles can be efficiently transported within a small space.

## 6. Conclusion

The concept of an unmanned vehicle transportation system was presented, vehicle transport robots that play a central role in that system were devised, and a prototype was developed to verify the principles of operation. Operation verification experiments using the prototype confirmed the effectiveness of the following functions and demonstrated the validity of the concept of “a system that can be operated within a small space”:

- (1) Cooperative vehicle lift up and transport operation using a pair of thin robots; and
- (2) Vehicle transportation operation in a small space by omni-directional movement operation such as turning in place and moving sideways.

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