Paper:

Development of a Holonomic Omni-Directional Mobile Robot with Step-Climbing Ability

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In this paper, we purpose a new holonomic omnidirectional mobile robot that can pass over steps and rough terrain. A prototype of the omnidirectional mobile robot has seven wheels with free rollers. We adopt a passive suspension for the robot to climb slopes and to pass over steps without actuators and sensors for climbing and analyzed the kinematics of the omnidirectional robot. The performance of the prototype robot is shown through experiments.

1. Introduction

It was expected in recent years to introduce mobile robots into job sites of industrial fields, including factories and nuclear plants, and into ordinary living environments. To accomplish such purposes, the use of a holonomic omnidirectional mobile robot that excels in mobility is advisable. The holonomic omnidirectional mobile robot exhibits locomotion in all directions at any moment. This means that the robot should be useful for operations in narrow space or for cooperative carrying tasks. The robot motion can be planned easily because there are no holonomic constraints of movable direction.

Up to now, most conventional omnidirectional mobile robots have been designed to be applicable to a flat floor, but future robots are required to be applicable to the same environmental conditions as humans. In other words, they should be able to move on rough and flat terrain, so they can get over obstacles. Indoors, there are many irregularities and differences in levels around doors, interior distributing wires, etc. In the open air (e.g., on the premises, streets, etc.), there are differences in level between sideways and roadways, gentle slopes, and other irregularities.

The purpose of our study is to develop a holonomic omnidirectional mobile robot that can get over differences in level and other irregularities.

This paper is organized as follows: Section 2 gives an overview of the robot, Section 3 describes the robot mechanism, Section 4 shows the effectiveness of the mechanism experimentally verified, and Section 5 summarizes conclusions.

2. Schematic Design of Robot

2.1. Specifications Required of Mobile Robot

Our study is intended for developing a robot that can be applied to properly adjusted working conditions. To be specific:

(1)Holonomic omnidirectional mobility

The robot to be developed should be able to generate a specific capacity for locomotion in all directions on flat terrain. This specific capacity is extremely useful for working out operation plans with ease in relation to a cooperative transportation of large objects complicated tasks in narrow space.

(2)Locomotion performance

The robot is required to move quickly and particularly to make a straight advance with precision so it can perform tasks or operations at a high speed. To satisfy these conditions, the robot is to be provided with specifically designed mechanism and control systems.

(3)Travel on rough terrain

The robot should be able to travel indoors, on a plot of land around houses or buildings, and on public roads. On public roads, for example, the irregularity height (the distance between the crest and the trough of irregularities) is approximately several mm, and the degree of inclination of slopes is less than 10deg. At construction job sites, differences in level in most cases for the robot to surmount is up to approximately 20 to 30mm at the most.1) The largest difference in level assumed by our study to exist between sideways and roadways within the range of operations is approximately 100mm.

(4)Travel performance in narrow space

The robot is required to be able to move through doors or within bounds of elevators in buildings. In most cases, the maximum allowable cruising radius of robots in passages or elevators at construction sites is not more than 900mm.[1] Accordingly, the main body of the robot should be designed to be less than 900mm in diameters.

2.2 Previous works and Our Approach

The purpose of our study is to develop a mechanism that can satisfy (1) to (4) above. Let us examine the studies of the conventional mobile robots on referring to these conditions.

Various types of mechanisms that may realize omnidirectional locomotion have been proposed, e.g., legged robots, ball wheel robots,[2,3] crawler robots,[4,5] normal wheeled robots,[6] omnidirectional mobile robot, omnidirectional and holonomic wheeled platforms, and omnidirectional mobile robot.[7-9]

The legged mobile mechanism can realize holonomic omnidirectional locomotion and eminently excels in travel on rough terrain. The mechanism is complicated in structure and control. The maximum speed of the legged robot is much slower than that of the wheeled robot.

The ball wheel robots[2,3] are equipped with omnidirectionally turning ball-wheels, but they are accompanied by slip occurring between the wheels and the floor. Besides, they are complicated in structure and control and not suitable to travel on rough terrain.

The omnidirectional mobile robots[4,5] based on a special crawler mechanism can carry heavy weight and are well fitted for high-speed travel, but they are complicated. There exists a robot that can surmount differences in level to a certain extent[5], but it cannot surmount larger ones.

Many omnidirectional mobile robots with normal wheels are proposed because of the simplicity of the mechanism. But very complicated control is needed when it is applied to realizing holonomic omnidirectional locomotion.[6]

To simplify the wheel mechanism and control system, robots equipped with special wheels equipped with free rollers **(Fig.1)** have been proposed.[7-9]

To the main body of the omnidirectional mobile robot in particular, four special wheels are attached at intervals of 90deg with the view of realizing substantially efficient control and higher locomotion performance.[9] These special wheels, however, are decidedly weak in surmounting differences in level.[10-11] To deal with this,a cooperative method by two robots to surmount steps has been proposed.[12] In actuality, however, there are a large number of relatively small differences in level, and it takes a lot of time for the cooperative mobile robot to surmount such small differences in level. In other words, cooperative technique is unfeasible from the viewpoint of efficiency.

Until now, no proposal has ever been made public as to a robot that is competent enough for both holonomic omnidirectional locomotion performance and rough terrain travel performance.

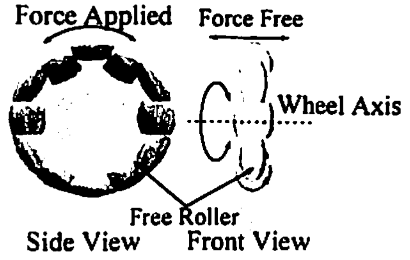


Fig. 1. Wheel with free rollers.

It is difficult to formulate a general definition of the rough terrain travel performance. Accordingly, the rough terrain travel performance is shown with the difference-in-level surmounting performance. To increase the step-climbing performance, the following factors are important:

(a) the torque of each wheel,
(b) the diameter of each wheel,
(c) the coefficient of friction between each wheel and the floor, and the flexibility of each wheel,and
(d) the load of the main robot's body upon each wheel.

The larger the torque and/or the larger the friction coefficient, the better the rough terrain travel performance.

When irregularities are small, a flexible wheel is easily changed to adapt itself to those irregularities one after another, so the movement of the wheel can be facilitated. And the wheel is also changed to adapt itself to differences in level to prevent a slippage. When the wheel is too soft, high-speed locomotion can rarely be attained.[13]

Generally, the surmountable amount of the difference in level increases in proportion to the diameter of the wheel. However, if there is no contrivance on the robot body, it is impossible to climb up the step beyond 1/2,of the wheel diameter even when the driving torque is very large. Surmounting such a great difference in level is comparable to surmounting a vertically rising surface. It is also difficult to surmount a difference in level whose amount is 1/3 the diameter of a wheel. This case is comparable to surmounting a sloping surface of more than 45deg.[14] The reason is that the load of the robot's main body on each wheel decreases in the course of surmounting differences in level. On referring to the conditions (3) and (4) as described in Section 2.1, it is impracticable to make an attempt at surmounting differences in level just by increasing the diameter of wheels since such an attempt will result in making the main body of the robot too large in size. It may therefore be recommendable to introduce specific robots, such as planetary rovers.[15,16] The main bodies of rovers can be deformed so the shapes of the robots agree to differences in level.

With due consideration for the preliminary remarks described above, we intend through our study to develop an omnidirectional mobile robot capable of travel on rough terrain in the following manner.

To satisfy conditions (1) and (2) as described in Section 2.1, it is necessary that the mechanism and the control of a robot are easy and that a robot can move at high speed. Accordingly, the special wheel with free rollers is adopted. The wheels arranged and the main body deformed properly make up for a disadvantage that the wheels with free rollers are weak in surmounting differences in level.

A mechanism designed to deform the robot body using actuators after collecting surrounding information (related to the amount of differences in level, irregularities, etc.) by means of sensors will become too complicated in structure and control and take a lot of time in surmounting differences in level. We therefore intend to develop a new mechanism, by which the posture of the main body is automatically deformed when it comes in touch with a difference in level, so the robot can surmount it.

There are two ways of improving the ability to surmount a difference in level. One is to improve the stop-climbing ability in all the directions equally, and the other is to improve the maximum ability to pass over steps in a fixed direction. The utilization of holonomic omnidirectional mobile performance on a flat floor makes it possible for a robot to freely adjust its posture just before a large difference in level or, in other words, to surmount it after adjusting its posture to a desirable direction. Consequently, the latter way excels the former in expanding the range of travel. The robot we intend to develop is to be the latter one, in which the ability to surmount the largest difference in level possible is preferentially improved. To be specific, small irregularities on the floor are absorbed by a suspension system and large differences in level are surmounted by deforming the main body. In short, the robot we intend to develop through our study is a holonomic omnidirectional mobile robot capable of surmounting large differences in level.

3. Design of Robot Mechanism

3.1. Mechanism of Wheel

To realize high-speed holonomic omnidirectional locomotion, special wheels with free rollers (**Fig.1**) have been adopted.

The wheel of this type can freely rotate in the direction perpendicular to the direction of drive. By attaching more than two wheels of this type to the main body without arranging them parallel to each other, omnidirectional locomotion can be realized. The use of round wheels formed by combining small and large cylindrical free rollers has resulted in realizing smooth travel.

To improve the ability to surmount differences in level, each wheel should have drive. Accordingly, each wheel is equipped with an actuator and, in addition, with suspensions to form a wheel unit. As a result, small irregularities of approximately several mm in height can be absorbed by the up-and-down movement of the wheel unit itself (**Fig.2**).

To increase gripping power, each wheel is made of rubber. To improve the ability to surmount differences in level, the surface of each free roller is studded.

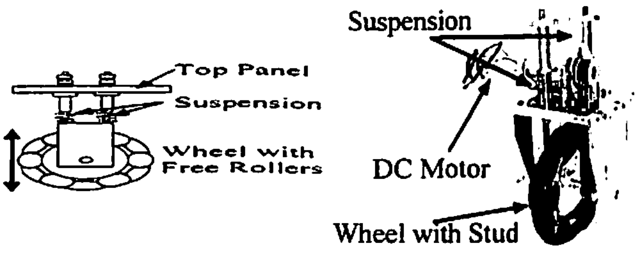


Fig.2. Wheel unit

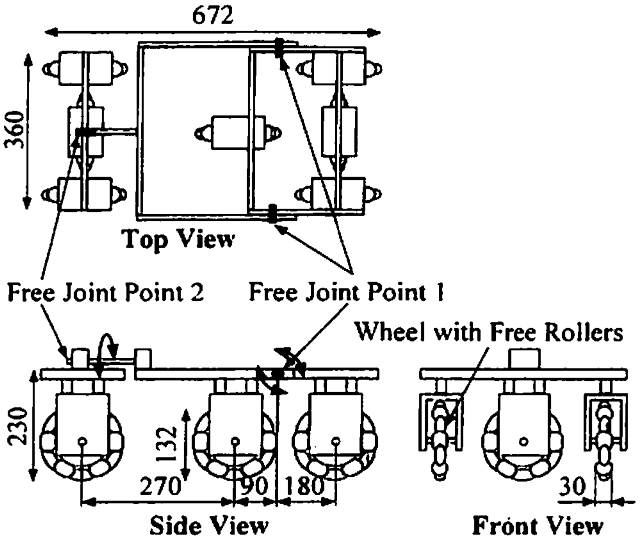


Fig. 3. Mobile robot with seven wheels.

3.2. Mechanism of Main Body

The wheel unit thus attached to the main body is useful for realizing holonomic omnidirectional locomotion and increasing the ability to surmount differences in level.

For realization of holonomic omnidirectional locomotion, it is necessary to adjust the direction of the wheels with the free rollers and attach them to the main body of the robot.

The most important factor in improving the ability to surmount differences in level is that each wheel has drive while surmounting differences in level. The conventional omnidirectional robot equipped with the conventional wheels having free rollers takes no notice of the ability to surmount differences in level, so a wheel is arranged every 120deg[7,8] or every 90deg.[9]

By such an arrangement as this, however, the free rollers come in contact perpendicularly with a difference in level while surmounting it and no driving force can be convey to the ground. Consequently, the ability to surmount differences in level inevitably declines to a great extent. Even when one of the wheels has succeeded in surmounting a difference in level after reaching it first, the remaining wheels are caused to float off the floor. As a result, no driving power can be conveyed to the ground. Such problems as described above cannot be solved only by making the wheels larger in diameter.

The use of a suspension system designed to deform the main body of the robot makes it possible for relatively

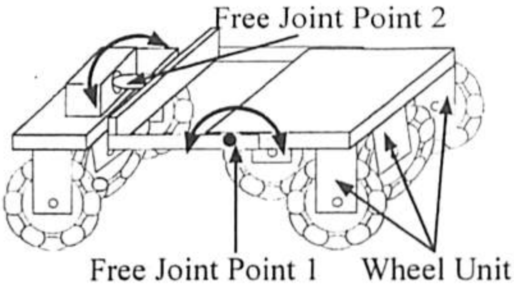
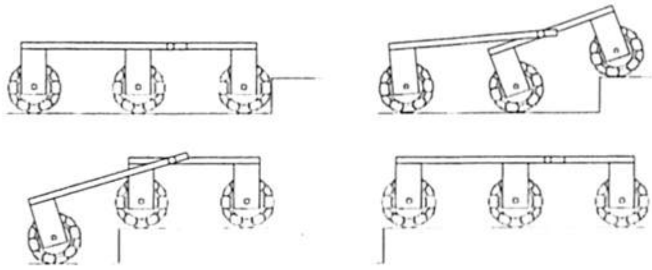


Fig. 4. Suspension system.



Fi g. 5. Step-process of climbing.

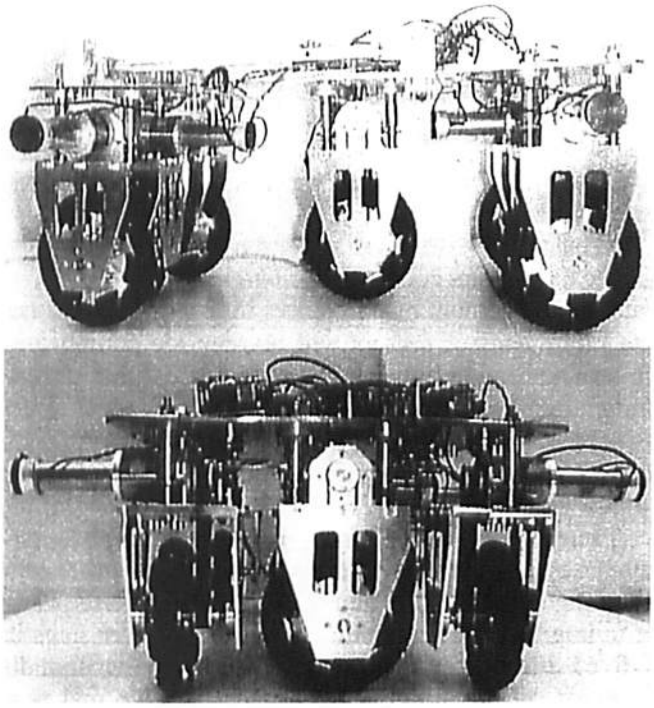


Fig. 6. Overview of prototype robot.

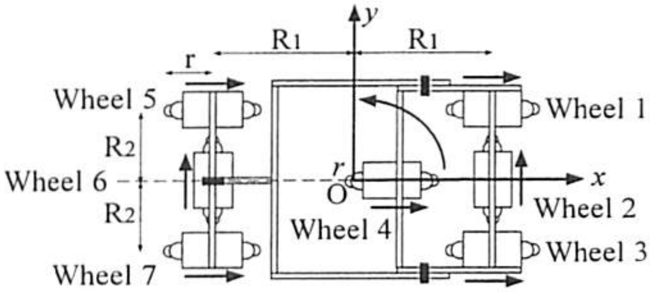


Fig. 7. Coordinates of robot.

small wheels to surmount relatively large differences in level. That is, seven wheel units (**Fig.2**) equipped with suspensions, which are designed to cope with irregularities of approximately several mm, have been attached to the main body of the robot with the view of improving holonomic omnidirectional locomotion and rough terrain travel performance (**Fig.3**).

As for the size of the main body of the robot and the diameter of wheels, the main body has been designed in such a way that it can be placed in a circle of 900mm in diameter. This makes it possible for the robot to travel in narrow space.

As for holonomic omnidirectional mobile locomotion, wheels have been arranged perpendicularly or in parallel with each other so as to realize straightly advancing performance.

It is assumed that the mobile robot turns around the central point in the figure of the robot (the midpoint "O" in **Fig.7**, i.e., the intermediate point between the front wheels and the rear wheels). When a wheel passes on the midpoint "O", the friction coefficient between the wheel and the midpoint "O" increases. Advance arrangements have been taken, therefore, for preventing the wheel from passing on the midpoint "O".

To facilitate the rough terrain travel performance, two sections of the robot body are connected by two links in such a way that all the wheels come constantly in contact with the floor (**Fig.4**).

Figure 5 shows the movement of the links when the robot surmounts a large difference in level. The free joint point 1 is deformed as soon as it comes in contact with a difference in level, so the robot can smoothly surmount it as shown in **Fig.5**. The free joint point 2 is used to cope with the difference of elevation between the left and right wheels.

Thus the omnidirectional mobile robot capable of surmounting considerably large differences in level has been developed with the wheel units and the links connected to its main body (**Fig.6**).

3.3. Robot Kinematics

A description of robot kinematics is given as follows. Each variable when the robot is on a flat floor is shown in **Fig.7**.

Here, we assume that the rotational speed of the wheel i is $\omega_i$rad/s, the radius of the wheel is $r$mm, the gear ratio between the actuator and the wheel is k, and the rotational speed of the actuator i is $V_i$rad/s. Then the following equation is obtained.

$$\omega_i = kV_i \quad \cdots\cdots\cdots\cdots \quad (1)$$

It is assumed that $[{}^r\dot{x}\ {}^r\dot{y}\ {}^r\dot{\theta}]^T$ is taken as the robot travel speed in basic coordinates.

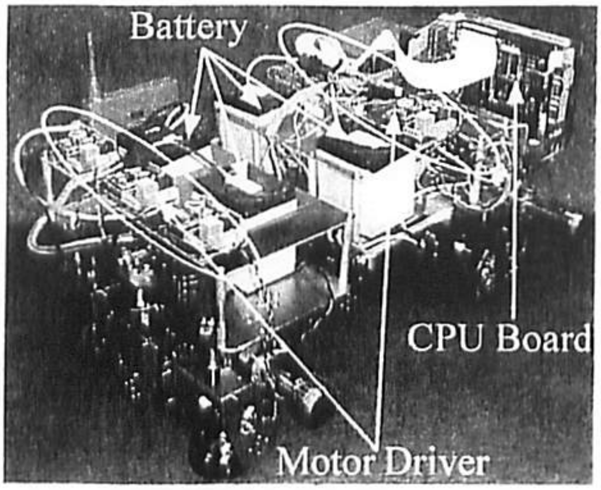


Fig. 8. Prototype robot.

The wheels Nos.1 and 5 and the wheels Nos.3 and 7 are on the same straight lines, respectively. Consequently, the relationship between the travel speed of the main body of the robot and the rotational frequency of each wheel is as follows:

$$\omega_1 = \omega_5 \text{ and } \omega_3 = \omega_7 \quad \ldots\ldots (2)$$

$${}^r\dot{x} = \frac{1}{5}(r\omega_1 + r\omega_3 + r\omega_4 + r\omega_5 + r\omega_7) \quad \ldots\ldots (3)$$

$${}^r\dot{y} = \frac{1}{2}(r\omega_2 + r\omega_6) \quad \ldots\ldots (4)$$

$${}^r\dot{\theta} = \frac{1}{6}\left(-\frac{r\omega_1}{R_2} + \frac{r\omega_2}{R_1} + \frac{r\omega_3}{R_2} - \frac{r\omega_5}{R_2} - \frac{r\omega_6}{R_1} + \frac{r\omega_7}{R_2}\right) \quad \ldots\ldots (5)$$

The relationship calculated between the travel speed and the rotational frequency of the actuator by substituting eq. (1) into Eqs.(2) to (5) can be expressed by Eq.(6)

$$\begin{bmatrix} {}^r\dot{x} \\ {}^r\dot{y} \\ {}^r\dot{\theta} \end{bmatrix} = J \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_7 \end{bmatrix} \quad \ldots\ldots (6)$$

where

$$J = \begin{bmatrix} \frac{kr}{5} & \frac{0}{kr} & \frac{kr}{5} & \frac{kr}{5} & \frac{kr}{5} & 0 & \frac{kr}{5} \\ 0 & 2 & 0 & 0 & 0 & \frac{kr}{2} & 0 \\ -\frac{kr}{6R_2} & \frac{kr}{6R_1} & \frac{kr}{6R_2} & 0 & -\frac{kr}{6R_2} & -\frac{kr}{6R_1} & \frac{kr}{6R_2} \end{bmatrix}$$

Therefore, the command value to each actuator for realization of a target speed can be obtained according to the following equations.

$$V_1 = V_5 = \frac{1}{kr}({}^r\dot{x} - R_2\,{}^r\dot{\theta}) \quad \ldots\ldots (7)$$

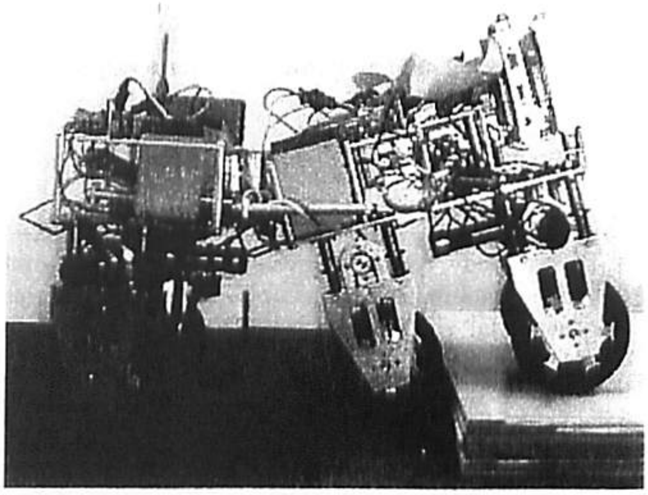


Fig. 9. Experimental view of step climbing.

$$V_2 = \frac{1}{kr}({}^r\dot{y} + R_1\,{}^r\dot{\theta}) \quad \ldots\ldots (8)$$

$$V_3 = V_7 = \frac{1}{kr}({}^r\dot{x} + R_2\,{}^r\dot{\theta}) \quad \ldots\ldots (9)$$

$$V_4 = \frac{1}{kr}\,{}^r\dot{x} \quad \ldots\ldots (10)$$

$$V_6 = \frac{1}{kr}({}^r\dot{y} - R_1\,{}^r\dot{\theta}) \quad \ldots\ldots (11)$$

The use of the command described above make it possible for the robot to respond to any speed command.

3.4. Design of Electric Apparatus

A control unit with a power source is mounted on the main body of the robot to realize completely automatic locomotion. A PC-AT compatibility system mounted on the robot is used to exercise control over all actions. Each of seven small motor drivers (Titech Driver version 2) provides control to the motor of each wheel. The command to each motor driver is given through a multifunctional input/output board (half-sized Titech Interface Board) that is connected to the ISA bus of the PC-AT compatibility system. As a power source, four 12V batteries (two for the electric apparatus and two for the driving system) are used.

4. Experiments

An experiment in travel has been conducted to verify the performance of the holonomic omnidirectional mobile robot. The results of the experiment show that it is possible to perform holonomic omnidirectional locomotion on the flat floor.

To testify the rough terrain travel performance, an experiment has been conducted in surmounting differences in level (**Fig.9**). The results of the experiment show that it is possible to climb or descend considerably smooth differences in level, and also possible to surmount a difference in level to the utmost extent of 100mm.

This satisfies the requirements of our specifications.

5. Conclusion

By our study, we have developed a holonomic omni-directional mobile robot capable of travel in unfavorable environmental conditions where there are a number of irregularities and differences in level. To produce a robot that can satisfy the requirements of the specifications, we have introduced special wheels having free rollers and a link mechanism designed to connect two sections of the main body of the robot into one.

According to a travel performance experiment, the requirements of the design guide have been fully satisfied. This proves that the newly developed holonomic omni-directional mobile robot can surmount differences in level of 100mm.

In the future, we intends to develop a new sensor system for discovering the presence of a particular quality in surroundings and to formulate a locomotion program based on the information collected by the sensor system.

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- "Human Genome Analysis System", nature, pp.352 (1991)
- "A Database System and an Expert System for Realizing Factory Automation", Bioproducts and Bioprocess (1989)
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1987-Full Professor of the University of Tokyo

Main Works:
- Automatic Assembly, Multiple mobile robot systems, Robot language in manufacturing, and Environmental design for robot systems

Membership in Learned Societies:
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1962-Joined the Chemical Engineering Laboratory of The Institute of Physical and Chemical Research (RIKEN)
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- Masafumi Mochizuki and Kazumi Sato "Gas-Liquid Mixing by Multiple Stirrers", Kagaku-Kogaku no Shinpo 34, Makishoten, pp.102-122 (2000)

Membership in Learned Societies:
- The Society of Chemical Engineering, Japan (SCEJ)