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Paper:

Coordinated Transportation of a Single Object by Omni-Directional Mobile Robots with Body Force Sensor

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In this paper, we propose a new mobile robot architecture with a body force sensor. The body force sensor is one force/torque sensor, which is located between the drive mechanism and the body of the mobile robot. The use of the body force sensor almost realizes the collocation of sensor and actuators, and makes the whole body of the mobile robot sensitive to external force/moment. Decentralized motion control algorithm for handling a single object by multiple mobile robots in coordination is implemented in each omni-dirctional mobile robot and multiple mobile robots with the body force sensor realize stable handling of an object. Experimental results illustrate the validity of the proposed architecture.

Keywords: Body force sensor, Force/torque sensor, Collocation, Mobile robot, Coordinated motion control

1. Introduction

The coordination of multiple robots has some advantages similar to the task executed by humans in coordination. Multiple robots in coordination can execute tasks, which could not be done by a single robot. Many control algorithms have been proposed for the handling of a single object by multiple robots in coordination.[1-5]

When multiple robots handle an object in coordination, each robot is usually controlled based on the information from the force/torque sensor attached to it. The force/torque sensor is usually located close to the end effector as shown in **Fig. 1**.

In case of a mobile robot, the force/torque sensor is to be located far from the drive mechanisms of the mobile robot. Therefore, the motion of the mobile robot controlled based on the force/moment information is often destabilized, because the mobile robot body is not completely rigid.

In this paper, we propose a new robot architecture of a mobile robot as shown in **Fig. 2**. The force/torque sensor is located between the drive mechanism and the body of the mobile robot.

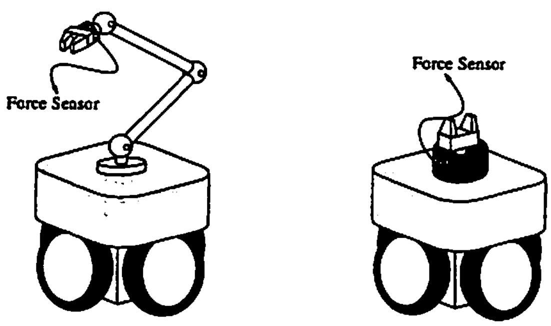


Fig. 1 Conventional System

In the following of this paper, we explain a problem relating to the control algorithm based on the force/moment information and propose a new robot architecture to solve the problem. We then consider some advantages of the proposed robot architecture and develop the force/torque sensor for the proposed robot architecture.

Decentralized control algorithm proposed in reference [4] is experimentally implemented in autonomous omni-directional mobile robots equipped with the developed force/torque sensor. The experimental results illustrate the validity of the proposed mobile robot architecture.

2. Robot Architecture

Let us consider the transportation of a single object by multiple mobile robots in coordination. Most of the conventional control algorithms of multiple robots for handling a single object in coordination are designed based on the force/moment applied to the object. In general, the force/torque sensor is attached to the end efector of each robot as shown in **Fig. 1** to measure the force/moment applied to the object under the assumption that the body of the mobile robot is rigid.

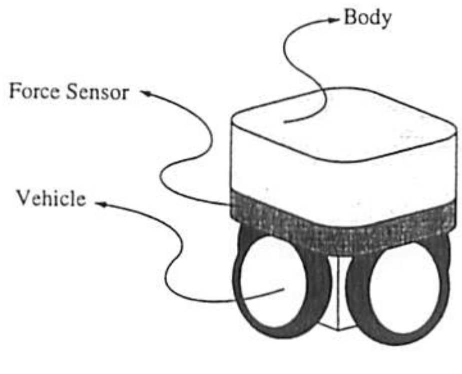


Fig. 2 Proposed System

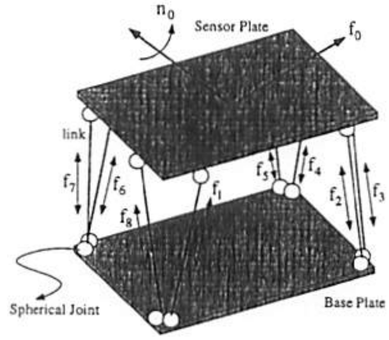


Fig. 3 Structure of Body Force Sensor

In most cases, however, the body of the mobile robot is not completely rigid, because the mobile robot is usually equipped with a suspension mechanism. So, the motion of the mobile robot is easily destabilized when the mobile robot is controlled based on the information from the force/torque sensor attached to the end effector[6]. To realize the handling of a single object by multiple mobile robots, we propose a new robot architecture to solve this problem.

To locate the force/torque sensor close to the actuators is known effective for such a problem in the area of the control of flexible structures[7]. This is referred to as the collocation of sensors and actuators[8].

A conventional robot is equipped with the force/torque sensor which is located far from the actuators of the robot as shown in **Fig. 1**, that is, the collocation of the force/torque sensor and the actuators of the mobile robot is not realized. Accordingly, tasks such as handling of a single object in coordination based on the information of this force/torque sensor could not always be done in a stable manner.

Therefore, we propose a new robot architecture, which locates the force/torque sensor close to the actuators of the mobile robot as shown in **Fig. 2**, that is, the force/torque sensor is located between the drive mechanism and the body of the mobile robot. We refer to the force/torque sensor as the body force sensor.

3. Body Force Sensor

3.1. Characteristic

The use of the body force sensor almost realizes the collocation of sensor and actuators. The collocation of sensor and actuators decreases the effect of the body flexibility on the stability of the system when the force feedback is implemented.

The body force sensor also can sense any external force/moment applied to it, that is, the whole body of the mobile robot is sensitive to external force/moment. Therefore, The robot could manipulate a large object using the whole body of the robot. The obstacle avoidance could also be implemented without using additional touch sensors and so on.

3.2. Development of Body Force Sensor

The body force sensor has to bear the weight of the body of the mobile robot because the body force sensor is located between the drive mechanism and the body of the mobile robot. The body force sensor is required rigid. In this paper, we develop a body force sensor using the parallel link mechanism whose rigidity is high.

The body force sensor we designed is shown in **Fig. 3**. In this paper, we refer to the upper plate of the body force sensor as the sensor plate, and refer to the lower plate of the body force sensor as the base plate. The sensor plate is joined with the base plate by eight links, each of which is fitted through spherical joints to both of the plates. Therefore, the moment is not applied to the links, even if any force/moment is applied to the sensor plate.

We can calculate the force applied to the center of the sensor plate using the forces applied to the links, which are measured by the strain gauges attached to the links. The force/moment applied to the sensor plate is calculated as follows;

$$\mathrm{F} = J^T f \quad \dots\dots \quad (1)$$

where $f = (f_1,\dots,f_8)^T \in R^8$ is the forces applied to the links and $F = (f_0, n_0)^T = (f_x, f_y, f_z, n_x, n_y, n_z)^T \in R^6$ is the forces and moments applied to the sensor plate. $J \in R^{8\times 6}$ is the Jacobian matrix of the parallel link mechanism. The Jacobian matrix is defined using the vector of the link length $l = (l_1,\dots,l_8)^T \in R^8$ and the generalized coordinate vector representing the position/orientation of the sensor plate $x = (x, y, z, \alpha, \beta, \gamma)^T \in R^6$ as follows;

$$J = \frac{\partial l}{\partial x} \quad \dots\dots \quad (2)$$

The sensitivity of the body force sensor depends on the Jacobian matrix of the parallel link mechanism. In this paper, the body force sensor has to sense the forces f_x, f_y and the moment n_z as precisely as possible, because the mobile robots are supposed to manipulate an object in a plane. To support a heavy object, the rigidity of the body force sensor should also be high along the vertical direction.

We designed the link parameters of the body force sensor based on the translatability ellipsoid and rotatability ellipsoid discussed in reference[9]. Translatability ellipsoid means the output forces f_0 which the sensor plate can exert without

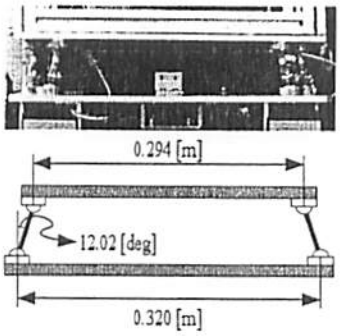
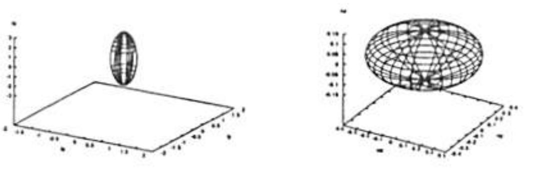


Fig. 4 Developed System



(a)Translatability Ellipsoid (b)Rotatability Ellipsoid

Fig. 5 Analysis of Designed Body Force Sensor

generating any moments and rotatability ellipsoid means the output moment n_0 which the sensor plate can exert without generating any forces based on the assumption that sensitivity of each link is equal.

That is, two ellipsoid mean the force/moment applied to the sensor plate when the output force f of each link is expressed as follows;

$$|f| \leq 1 \quad \text{(3)}$$

The shorter the axis of the ellipsoid is, the higher the relative sensitivity along the axis direction is.

Fig. 4 shows the body force sensor developed in this research, and Jacobian matrix of the parallel link mechanism expressed as follows;

$$J^T = \begin{bmatrix} 0.00 & -0.21 & 0.98 & 0.14 & -0.20 & -0.04 \\ -0.21 & 0.00 & 0.98 & 0.20 & -0.14 & 0.04 \\ 0.21 & 0.00 & 0.98 & 0.20 & 0.14 & -0.04 \\ 0.00 & -0.21 & 0.98 & 0.14 & 0.20 & 0.04 \\ 0.00 & 0.21 & 0.98 & -0.14 & 0.20 & -0.04 \\ 0.21 & 0.00 & 0.98 & -0.20 & 0.14 & 0.04 \\ -0.21 & 0.00 & 0.98 & -0.20 & -0.14 & -0.04 \\ 0.00 & 0.21 & 0.98 & -0.14 & -0.20 & 0.04 \end{bmatrix} \quad (4)$$

The translatability ellipsoid and the rotatability ellipsoid of the body force sensor developed in this research are shown in **Fig. 5**. These ellipsoids show that the relative sensitivity of the body force sensor is high with respect to the forces f_x, f_y and the moment n_z.

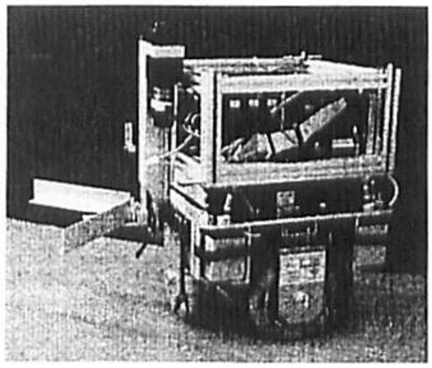


Fig. 6 Experimental System

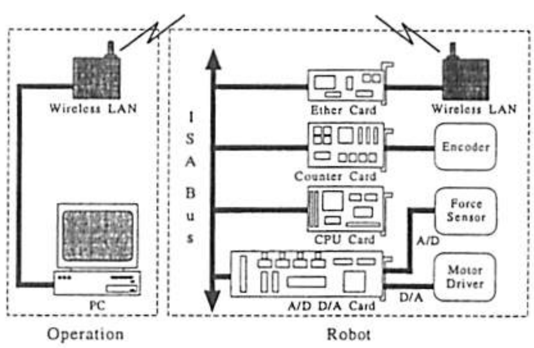


Fig. 7 System Structure

4. Experiments

We did two types of experiments for handling a single object using multiple omni-directional mobile robots in coordination to indicate the validity of the body force sensor. One is the experiment without body force sensor, and the other is the experiment using the body force sensor.

4.1. Experimental System

The mobile robot we used in these experiments is shown in **Fig. 6**. The mobile robot consists of an omni-directional mobile base, body force sensor, and a fork lift system. The omni-directional mobile base has the ZEN mechanism proposed by Asama et al.[10]. The system is controlled by an onboard PC-based controller as shown in **Fig. 7**, powered by onboard rechargeable battery and connected to the network system of our laboratory through the wireless Ethernet.

To realize the handling a single objet by multiple mobile robots in coordination, we used the decentralized motion control algorithm proposed in reference[4]. In this algorithm, the desired trajectory of the object is given to one of the robots referred to as the leader, and the other robots referred to as the follower estimate the desired motion of the object commanded to the leader to transport the object in coordination with the leader. The control algorithm was implemented using VxWorks. The sampling rate was 1024Hz.

4.2. Experimental Results without Body Force Sensor

In this experiment, we used two mobile robots as shown in **Fig. 8**. A six-axis force/torque sensor (JR3 QFS-2012A15) is attached to the top of the robot body, which is located

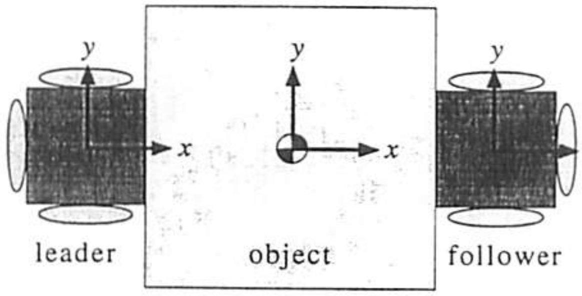
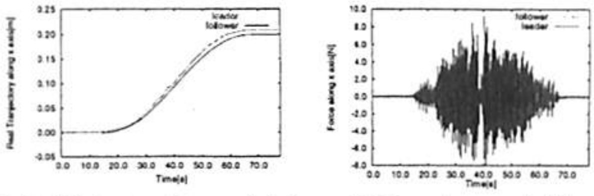
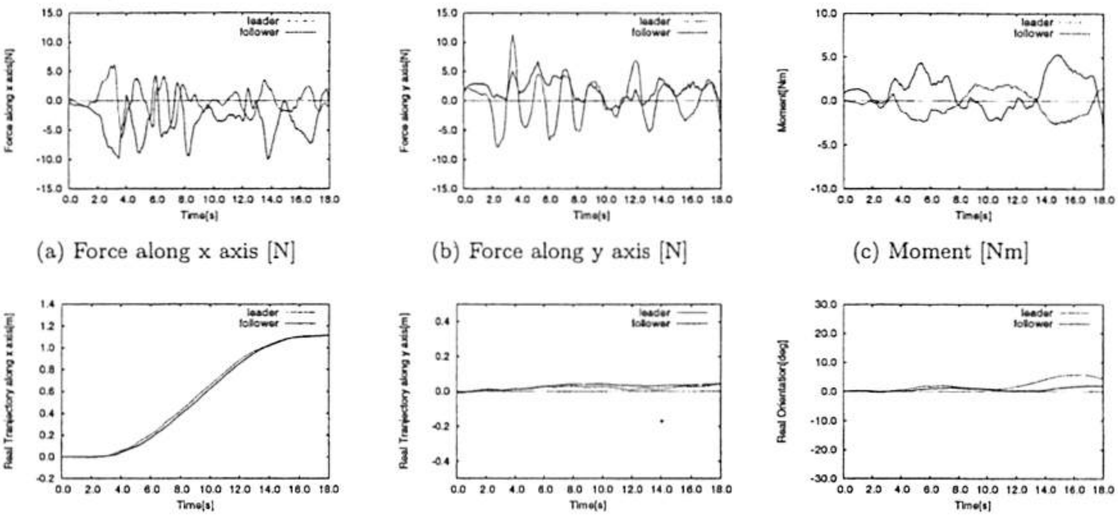


Fig. 8 Coordinate System



(a) Real Trajectory along x axis [m] (b) Force along x axis [N]

Fig. 9 Experimental Results without Body Force Sensor



(a) Force along x axis [N] (b) Force along y axis [N] (c) Moment [Nm]

(d) Real Trajectory along x axis [m] (e) Real Trajectory along y axis [m] (f) Real Orientation [deg]

Fig. 10 Experimental Results using Body Force Sensor

45cm above the body force sensor. The mobile robots hold the object by the gripper attached to the force/torque sensor.

In this case, it was difficult to transport a single object by those mobile robots without any vibration. We successfully executed experiments by restricting the motion of the robots along an axis (x-axis as shown in **Fig. 8**). The transportation of the object could be executed by slow velocity only. **Fig. 9** shows an example of the experimental results. **Fig. 9(a)** shows the motion of the robot along the x-axis and **Fig. 9(b)** shows the force along x-axis. You can see the oscillatory results in these figures.

4.3. Experimental Results using Body Force Sensor

In this experiment, the body force sensor is attached between the actuator and the body of the mobile robot. Two mobile robots hold the object as shown in **Fig. 8** by the gripper, which is located 45cm above the body force sensor and we used the same parameter as the previous experiment to compare with the experiment without body force sensor.

In this case, the leader is given a desired trajectory along x-axis as shown in **Fig. 8**. The orientations of all of the robots are kept constant during the transportation of the object. The results are shown in **Fig. 10**. The solid lines show the results relating to the leader. The dotted lines show the results relating to the follower. You can see that the transportation of a single object has been successfully achieved.

Fig. 11 shows an example of the experiments using the three omni-directional mobile robots with body force sensor. In this experiment, two followers can estimate the desired trajectory of the object using the concept of the virtual leader proposed in reference [4] and three omni-directional mobile robots with body force sensor can handle a single object in coordination successfully.

5. Conclusions

In this paper, we proposed new robot architecture for handling of a single object by multiple mobile robots in coordination. The advantages of the proposed architecture over the conventional one were that the collocation of sensor and actuators was almost realized and the whole body of the mobile robot was sensitive to external force/moment. Accordingly, tasks such as handling of a single object in coordination based on the information of the force/torque sensor could be done in a stable manner. The decentralized control

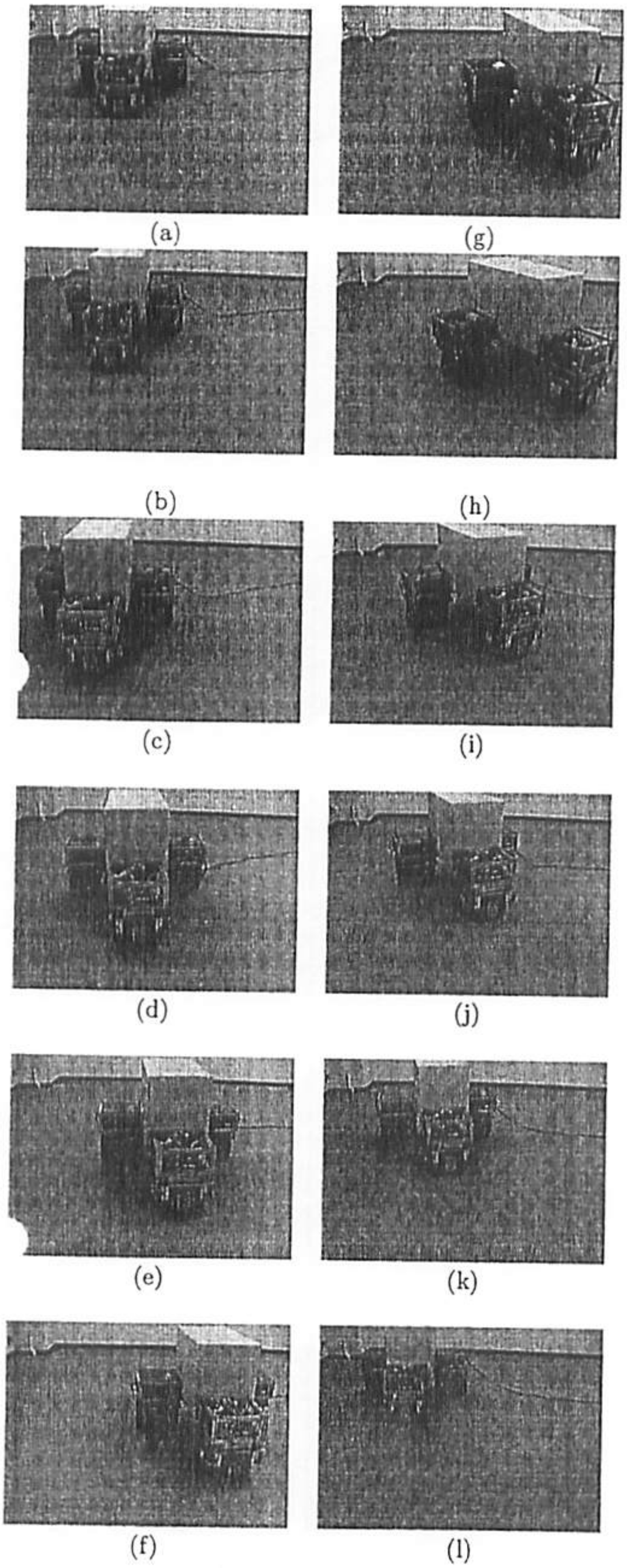


Fig. 11. Example of Experiments

algorithm proposed in reference [4] was experimentally implemented in multiple autonomous omni-directional mobile robots equipped with the body force sensor, and the experimental results illustrated the validity of the proposed architecture.

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