Environment Estimation Using Serial-type Dual Actuator Unit Capable of Force Estimation

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Abstract − Control of a robot manipulator in contact with the environment is usually conducted by a direct feedback control system using a force-torque sensor or an indirect impedance control scheme. Although these methods have been successfully applied to many applications, some problems such as the cost have to be solved to make the practical use. To cope with such problems, redundant actuation was used to enhance the performance of position/force controllers. This paper proposes a novel design of a dual actuator unit (DAU) composed of two actuators connected in series to provide the capability of force estimation, as well as the environment estimation. The torque exerted on the joint, the stiffness and surface of the environment in contact with the manipulator can be estimated without an expensive force sensor by using encoder information. Various experiments demonstrate that the DAU can provide good performance for the force and the environment estimation.

Keywords − Redundant actuation, Serial actuation, Environment estimation, Stiffness estimation, Surface estimation.

1. Introduction

A robot manipulator operating in free space can be controlled by a conventional position control scheme. In this case, a manipulator usually has high stiffness for improved positioning accuracy. When the manipulator contacts or collides with the external environment, such high stiffness might cause damage to both the manipulator and the environment. In this situation, therefore, accurate force control is required to ensure safe and smooth movement.

Force control of a manipulator is usually executed directly by the feedback control system using a force sensor [1]. This approach shows good experimental results for the force control, but it requires the use of an expensive force/torque sensor. On the other hand, force control can be implemented indirectly by the stiffness control method in which the contact force is indirectly controlled by adjusting the desired position of the end-effector [2]. The problem with indirect force control strategies is that forces cannot be regulated unless the exact environment model is known [3]. To cope with these problems, the model based force estimation methods have been suggested [4, 5] to implement the force control without expensive force/torque sensor. Also, several research efforts related to the environment estimation have been conducted [6, 7] to improve the performance of the impedance control.

This paper proposes a novel design of a dual actuator unit (DAU) capable of force and environment estimation for direct/indirect force control. Force estimation is related to direct force control, whereas environment estimation is linked to indirect force control. The DAU is composed of two actuators connected in series via a planetary gear trains and each actuator is responsible for positioning and variable stiffness independently. Since one actuator (called a positioning actuator) controls position and the other actuator (called a stiffness modulator) modulates stiffness, the DAU can control position and stiffness simultaneously at the same joint. Such a unit can implement force control of a manipulator more easily. Also, the DAU can provide good performance for position tracking, force estimation and collision safety [8].

To estimate both the force and environment, the position information provided by the two encoders installed at each actuator is used. The force measurement can be realized by using an explicit force sensor, but high cost often precludes the use of such devices in practical applications. Although a DAU has a slightly lower resolution than a force sensor, it can be a practical solution to the implementation of force control in real applications.

To verify the performance of the force and environment estimation, a series of experiments were conducted and the results show that the DAU is proper to apply both direct and indirect force controls.

The remainder of this paper is organized as follows. Section 2 presents the serial-type dual actuator unit. Section 3 deals with force and environment estimation and section 4 shows the experimental result. Finally, section 5 presents conclusions.

2. Serial-type Dual Actuator Unit

The DAU shown conceptually in Fig. 1 is based on redundant actuation. The DAU is composed of two actuators; one for position control, called a positioning actuator (PA), and the other for stiffness control, called a stiffness modulator (SM). In this unit, the output shaft of SM rotates relative to the body of PA since the body of SM is connected together to the output shaft of PA. Consequently, the position and the joint stiffness are decided by only the PA and SM, respectively. A 2 DOF planetary gear train was adopted in this DAU for the power transmission system to connect two actuators in series and it makes the system more compact [8].

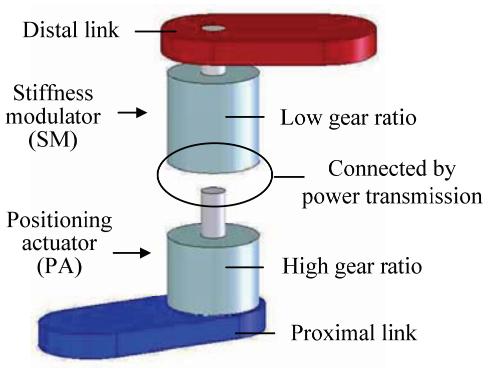

Fig. 1 Conceptual diagram of DAU.

2.2 Prototype of Serial-type Dual Actuator Unit

The prototype of the DAU based on a planetary gear train, shown in Fig. 2, was constructed for various experiments related to the performance of the DAU. The DAU uses two 20 W brushless DC motors. The gear ratio of the position control part of the DAU is 690:1, while that of the stiffness control part is 56:1. The total size is 29 x 61 x 115 mm, and the weight of the unit is about 500 g.

Fig. 2. Prototype of DAU; (a) DAU, and (b) internal view of DAU with planetary gear train.

3. Force and Environment Estimation

Information on the environment, such as its location, shape and stiffness, is sometimes required for successful execution of tasks. Such information can be obtained by a range sensor that measures the distance to the environment or a camera that recognizes the shape of an object. However, the range sensor usually provides the distance to a single point and the camera image is often corrupted by lighting conditions. Furthermore, it is very difficult to know the stiffness of the environment without contacting it. During contact with the environment, the manipulator needs to maintain constant contact force, which requires an expensive F/T sensor at its end-effector. However, since the DAU has force sensing capability, the manipulator equipped with DAUs can estimate the position, shape, and stiffness of the environment without any damage to the environment.

3.1 Force Estimation

The ability of the force estimation is the key feature of the serial-type DAU. Fig. 3 represents the frames related to the shafts of PA and SM for the DAU-based system. The two frames are coincident with each other if there is no contact force, as illustrated in Fig. 3(a).

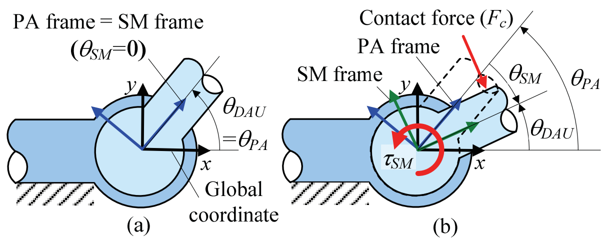

Fig. 3. Frames of PA and SM; (a) without contact force, and (b) with contact force.

When the force applied on the link, however, the SM frame rotates relative to the PA frame and thus the difference θ_{SM} between the two frames occurs.

$$\theta_{SM} = \theta_{DAU} - \theta_{PA} \tag{1}$$

where θ_{PA} and θ_{DAU} are the rotational angle of the output shafts of PA and DAU measured from the global coordinate. Then, the output torque τ_{SM} of DAU is given by

$$\tau_{SM} = k_{SM} \cdot \theta_{SM} \tag{2}$$

where k_{SM} is the joint stiffness which can be set by the user and θ_{SM} is the measured encoder value. As a result, the joint torque τ_{SM} can be obtained. Therefore, if DAUs are used for joint actuators of a multi-DOF manipulator, then the end-effector force F_c can be estimated from the joint torques τ_{SM} by the following Jacobian relation

$$\tau_{SM} = J^T F_c \tag{3}$$

3.2 Stiffness Estimation

The method for estimating environmental stiffness is illustrated in Fig. 4. Because the stiffness is defined as the ratio of applied force to the corresponding displacement, it can be obtained by simultaneously measuring both quantities. The contact of the manipulator with the environment can be detected by observing whether or not the error between the desired and the actual end-effector position is larger than the user-specified threshold during the motion. At the moment of contact, the position is set as the contact position x_c. In order for the end-effector to reach the desired position x_d, the manipulator applies the force to the environment. Finally, it reaches the equilibrium position x_{eq} since force balance is achieved. Note that the position of PA actually reaches x_d, but the position of DAU is x_{eq} because of the compliance of SM, as shown in Fig. 4. To simplify the analysis, the damping effect is neglected.

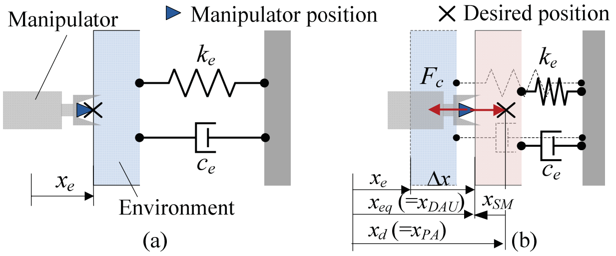

Fig. 4. Stiffness estimation using DAU.

By applying the force balance equation at the equilibrium state, the contact force F_c is given by

$$F_c = k_e(x_{eq} - x_e) = k_m(x_d - x_{eq}) \tag{4}$$

where F_c is the contact force that can be estimated as explained in Section 3.1, and k_e and k_m are the stiffness of the environment and the manipulator, respectively. Provided that the DAUs are used for a manipulator, the desired position x_d can be replaced by the position of PA (x_{PA}) because PA always follows x_d. Now, the position of the end-effector (i.e., x_{DAU}) is x_{eq}, which corresponds to the sum of x_{PA} and x_{SM}, where x_{SM} is the relative displacement of SM. Because k_m is equal to the stiffness of SM k_{SM}, the environmental stiffness k_e can be written as

$$k_e = \frac{(x_d - x_{eq})}{(x_{eq} - x_e)} k_m = \frac{k_{SM} x_{SM}}{(x_{PA} + x_{SM} - x_e)} \tag{5}$$

3.3 Surface Estimation

By using the estimated stiffness of the environment stated previously, the surface of the environment can be obtained. Of course, the manipulator can estimate the surface by detecting x_e for the whole surface, which is very inefficient. To obtain the surface information in this research, the end-effector moved while the position of the surface was stored, as shown in Fig. 5. While the manipulator follows path 1, the end-effector contacts the wall, and then it applies force to the wall. The position information of PA and SM are saved in every sampling time, while the manipulator follows path 2 (which can be a curved surface). At some point, the manipulator departs from the environment (i.e., path 3). By applying the equation of force balance at the contact point, the surface information x_e can be obtained as follows:

$$x_e = x_{eq} - \frac{k_m}{k_e}(x_d - x_{eq}) = (x_{PA} + x_{SM}) - F_c / k_e \tag{6}$$

If the force F_c is too small, or the stiffness of the environment k_e is much larger than k_{SM}, the last term on the right side of Eq. (6) can be neglected. As a result, x_e can only be represented by x_{PA} and x_{SM}.

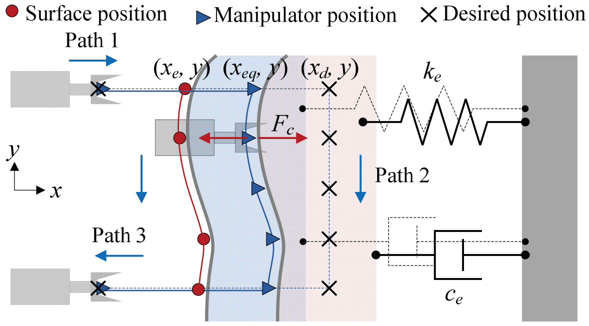

Fig. 5. Surface estimation by using DAU.

4. Experiment on Environment Estimation

To verify the performance of environment estimation, the five-bar parallel manipulator equipped with two DAUs was developed, as shown in Fig. 6. To give a better understanding, the intermediate length whose length is zero is introduced in the enlarged view. Therefore, joint 1 consists of link 1, link 2, and the zero-length intermediate link. PA controlling the position of the intermediate link connects the intermediate link with link 1 fixed to the ground, whereas SM adjusting the joint stiffness of the intermediate joint connects link 2 with the intermediate link. The length of link 1 is 0 cm, and the lengths of the other links are all 20 cm. The operating range of joint 1 and joint 2 are 35±75° and 145±75°, respectively.

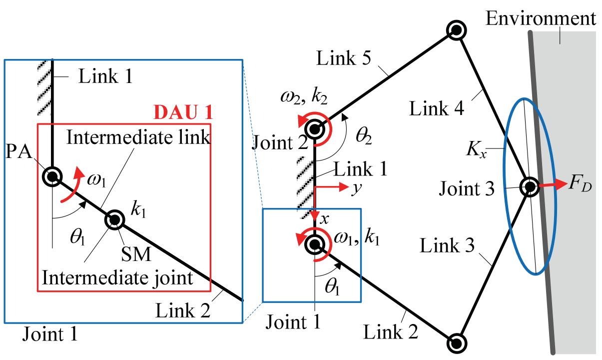

Fig. 6. Kinematic diagram of five-bar parallel manipulator with two DAUs

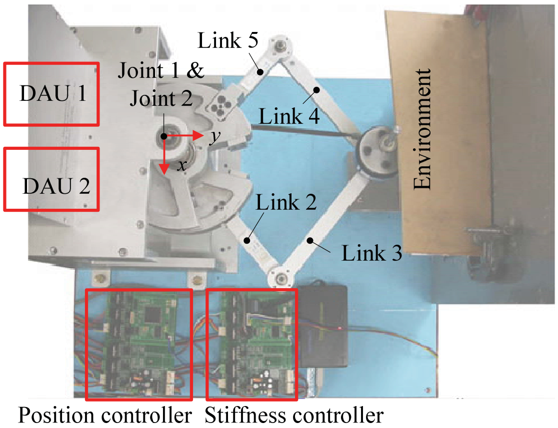

Fig. 7. Five-bar parallel manipulator with two DAUs

4.1 Stiffness Estimation

At first, the manipulator approaches the environment to estimate the environmental stiffness. After the manipulator contacts with a force of 3 N, the contact force was increased up to 10 N by increasing the stiffness of the DAU about three times, and the position of the end-effector was measured at the same time. As shown in Fig. 8(a), the end-effector is initially placed at y = 268.3 mm from the origin and the displacement of 2.0 mm occurs when the force was increased. The environmental stiffness was estimated at 3.5 kN/m while the actual stiffness was measured as 3.75 kN/m using the F/T sensor. Although an error of about 7% occurs, it is reasonable to use the estimated environmental stiffness in practical applications.

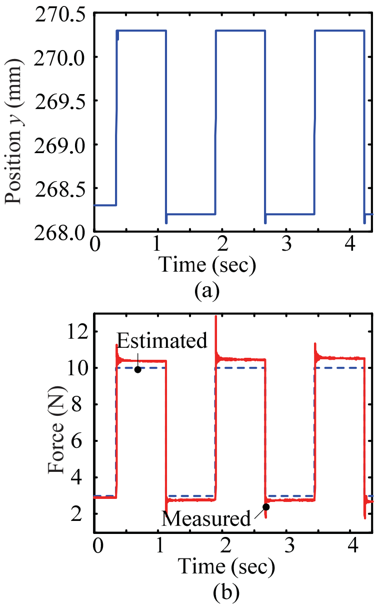

Fig. 8. Experimental results for stiffness estimation; (a) position of end-effector in the y direction, and (b) estimated and measured contact forces.

4.2 Surface Estimation

Figure 9 shows the experiment on the estimation of the environmental surface. The contact force was initially set to 3N, which makes the last term associated with the force in Eq. (6) negligible. Consequently, the environmental surface can be estimated by using the position information. As shown in Fig. 9, the desired trajectory of the manipulator equipped with DAUs was given by the rectangular shape, and the initial position was set to (0, 20). As the manipulator follows the desired trajectory, the endpoint passes through the points of (7, 20), (7, 30), (0, 30), and (0, 20) in sequence. If there were no environment, the manipulator would follow the desired trajectory (I→II→III→V). However, the real trajectory was changed to (I→II→IV→V) due to the existence of the environment. The environment was inclined at an angle of 10 deg. The experimental results represented in Fig. 9 and the trajectories of the environments can be obtained accurately by using the position information only.

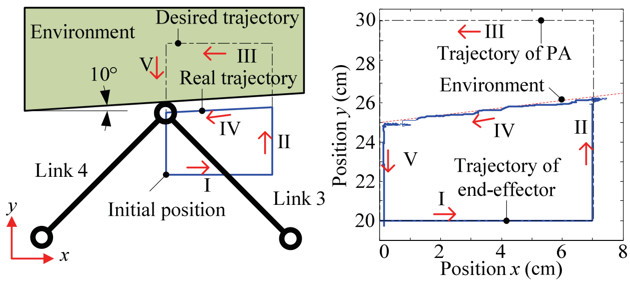

Fig. 9. Experimental results for surface estimation.

5. Conclusions

A serial-type dual actuator unit (DAU) capable of force estimation was proposed in this research. The performance of environment estimation was investigated through a series of experiments. Form this research, the following conclusions are drawn

(1) The torque exerted on the joint of a DAU can be estimated by the encoder information without an expensive force/torque sensor. Direct force control can be conducted by using the estimated force and torque information.

(2) Indirect force control, such as stiffness control and impedance control can be implemented by using the DAU which can estimate the stiffness and surface of the environment.

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References

[1] L. Villani, B. Siciliano, “Robot Force Control,” Boston, Kluwer Academic Publishers, 1999.
[2] J. J. E. Slotine and H. Asada, “Robot Analysis and Control,” New York, John Wiley and Sons, 1986.
[3] V. Assuncao, W. Schumacher, “Hybrid Force Control for Parallel Manipulators,” The 11th Mediterranean Conference on Control and Automation (MED’03), 2003.
[4] P. J. Hacksel and S. E. Salcudean, “Estimation of Environment Forces and Rigid-Body Velocities using Observers,” IEEE International Conference on Robotics and Automation, pp. 931-936, 1994.
[5] K. S. Eom, I. H. Suh, W. K. Chung and S. R. Oh, “Disturbance Observer Based Force Control of Robot Manipulator without Force Sensor,” IEEE International Conference on Robotics and Automation, pp. 3012-3017, 1998.
[6] L. J. Love and W. J. Book, “Environment Estimation for Enhanced Impedance Control,” IEEE International Conference on Robotics and Automation, pp. 1854-1859, 1995.
[7] D. Erickson, M. Weber and I. Sharf, “Contact Stiffness and Damping Estimation for Robotic System,” The International Journal of Robotics Research, Vol. 22, No. 1, pp. 41-57, 2003.
[8] B. S. Kim, J. J. Park and J. B. Song, "Improved Manipulation Efficiency Using a Serial-type Dual Actuator Unit," International Conference on Control, Automation and Systems, pp. 30-35, 2007.