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Improved Manipulation Efficiency Using a Serial-type Dual Actuator Unit

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Abstract: Service robots are often required to be able to perform both the position control and force control for various tasks. In addition, service robots should cope with collision safety to prevent possible damage to humans and environments during unintended collision. To this end, several redundant actuation systems have been proposed. In this research, the Dual Actuator Unit (DAU) was developed to improve the manipulation efficiency by maximizing the velocity or payload depending on various situations. The DAU is composed of two actuators connected in series through a planetary gear train and a cam-based clutch system. In this paper, the characteristics of the DAU having three operating modes – dual actuation mode, high speed mode and high torque mode - are discussed. Various experiments show that the DAU can carry out the given task flexibly and it can improve the manipulation efficiency.

Keywords: Dual Actuator Unit (DAU), Redundant actuation, Position/force control, Planetary gear train

1. INTRODUCTION

Service robots are often required to be able to perform both position control and force control for various tasks. Furthermore, collision safety has to be guaranteed for unintended collision because service robots often undergo physical interaction with humans and environments. If spring elements are inserted into a manipulator with high stiffness, force control can be implemented indirectly by adjusting the displacement of a spring in proportion to the external force [1][2], or unintended collision can be handled by absorbing a collision force. However, there are some limitations to improving the performance of a force/position controller using the passive elements with constant stiffness because the system performance depends heavily on the mechanical characteristics of such passive elements.

To cope with this problem, several types of redundant actuation systems have been proposed for simultaneous position and force control. They utilize more actuators than the number of degrees of freedom required for the system. Redundant actuation can be achieved by either parallel or serial connection of actuators. Bicchi developed the variable stiffness unit (VSU) which could control the joint stiffness by changing the mechanical impedance [3]. The VSU, which was composed of double actuators, controlled the position and stiffness simultaneously by controlling the position and torque generated by two actuators. Khatib improved the response performance of a force/position controller by using the distributed actuation approach [4]. This approach used two actuators connected in parallel; one is the high torque-low frequency actuator placed at the base and the other is the low torque-high frequency actuator at the joints of the manipulator. Ham developed the MACCEPA (mechanically adjustable compliance and controllable equilibrium position actuation) which could control the force and torque independently by using two motors with a spring [5]. One motor controls the equilibrium position and the other motor controls the stiffness of the joint by adjusting the pre-tension of the spring. Mukaibo developed the double actuator joint mechanism which could simply control the position and force at the same time by adopting the equilibrium point control [6].

Among them, the parallel actuation system suffers from a large size and heavy weight because the complex structures and algorithms are needed for position and force control. On the other hand, a serial actuation system has some drawbacks of a low payload and the large accumulated gear backlash.

In this research, a *dual actuator unit* (DAU) was developed to solve a payload problem caused by the serial connection and to improve the manipulation efficiency. 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). The PA and SM are connected in series through a planetary gear train to transmit the power to a single output shaft. The torque exerted on the joint of DAU can be estimated by the encoder information without an expensive force/torque sensor [7]. Based on the torque-velocity characteristics, the DAU has three operation modes; *high-speed mode*, *dual-actuation mode* and *high-torque mode*. For the high torque mode, a cam-based clutch system is installed at the DAU to lock the SM. The DAU can improve the manipulation efficiency by maximizing the velocity or generated torque according to various situations.

In this paper, the characteristics of the three operation modes are discussed. To improve the performance of the position control, the compensation method for PA using the SM's encoder information was proposed. Various experiments show that the DAU can carry out the given task in a flexible manner and it can improve the manipulation efficiency.

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2. DUAL ACTUATOR UNIT

2.1 Dual Actuator Unit

To improve the performance of the position/force control, the DAU (dual actuator unit) adopts redundant actuation that utilizes more actuators than the number of DOFs required by the system. The DAU is composed of two actuators and a power transmission system, as shown in Fig. 1(a). The positioning actuator (PA) of the DAU controls the position of a manipulator, whereas the stiffness modulator (SM) controls the joint stiffness. Figure 1(b) illustrates the torque-angular velocity characteristics of two actuators. A high torque-low speed PA with a high gear ratio is beneficial to positioning accuracy, whereas a low torque-high speed SM with a low gear ratio is advantageous to soft manipulation. The power transmission system is used to combine the two powers generated by two actuators.

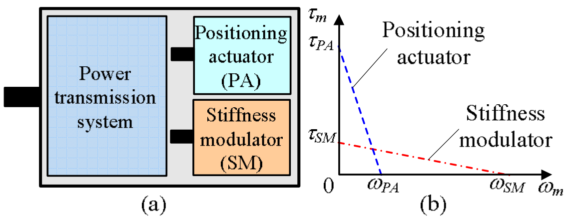

Fig. 1 DAU; (a) conceptual diagram of DAU, and (b) T_m-ω_m curve for each motor

2.2 Serial type of DAU

In redundant actuation, the characteristics of a system depend on how the actuators are connected. According to the connection type, two different ways can be considered to realize a redundant actuation system; one is the serial actuation, which is adopted in the DAU, and the other is the parallel actuation. In serial actuation, one actuator is fixed at the other actuator's output shaft, as shown in Fig. 2, so one actuator rotates relative to the other. The position and force control can be separated in the serial actuation, so the contact force can be easily controlled. Moreover, the serial actuation can estimate the contact force or can detect collision by using the encoders installed at each actuator.

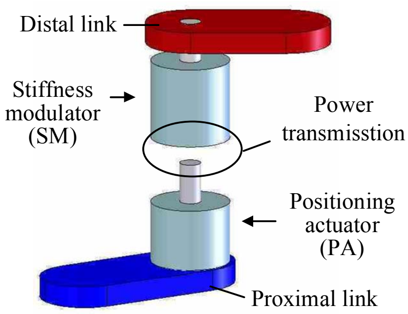

Fig. 2 Two actuators connected in series

A serial actuation system, however, has some drawbacks. If the actuators with different output torques are connected in series, the maximum payload is determined by the actuator that has the lowest output torque. Hence it is difficult to obtain a high payload using the serial actuation. In addition, the accumulated gear backlash caused by the gear reducers can cause the vibration of a manipulator during its movement.

2.3 Power Transmission System

A power transmission system is required to combine the powers from two actuators used in the DAU. For this purpose, a planetary gear train is used in this research. It can leads to a small-sized and light-weighted system. A planetary gear train is composed of a sun gear, a carrier and a ring gear. If any two gears are connected to the input part, the remaining gear serves as an output part. For example, if two actuators are connected to the sun gear and ring gear, respectively, the carrier functions as an output shaft.

3. THREE MODES OF DAU

The three modes of DAU can be provided by controlling the PA (high torque-low velocity) and the SM (low torque-high velocity). The high speed mode, dual actuation mode and high torque mode are illustrated in Fig. 3, and the torque-velocity characteristics of each mode are shown in Fig. 4. Unlike the high speed mode and dual actuation mode, the high torque mode needs an additional clutch system. The clutch system installed in the DAU will be discussed in the high-torque mode section.

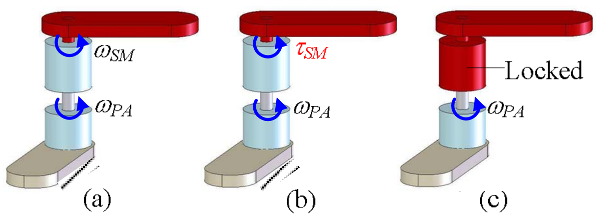

Fig. 3 Schematics of three modes of DAU; (a) high speed mode, (b) dual actuation mode, and (c) high torque mode.

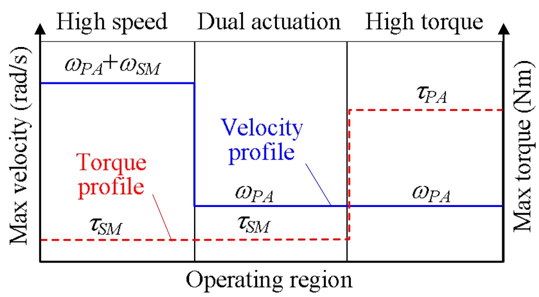

Fig. 4 Velocity and torque profiles for each mode

3.1 High Speed Mode

In the high speed mode shown in Fig. 3(a), the manipulator can control the position rapidly when no or a small external force is applied. In this mode, two actuators used in the DAU play a role of position control. Since two actuators are connected in series, the maximum rotational velocity corresponds to the sum of two actuator's velocities while the maximum torque is limited by the maximum torque of the SM. Although the manipulator cannot control the position and stiffness simultaneously in this mode, the manipulator can reach quickly to the desired position, which results in the reduced task time.

3.2 Dual Actuation Mode

The dual actuation mode represented in Fig. 3 (b) can realize the unique feature of the DAU. In this mode, one actuator controls the position of a manipulator while the other adjusts the joint stiffness. As shown in Fig. 4, the rotational speed of the DAU is determined by the PA with a high gear ratio whereas the output torque is determined by the SM with a low gear ratio.

According to the tasks, the control scheme can be divided into position control, force control and the hybrid position/force control. For example, to apply a force to the fixed wall, the manipulator has to moves toward the wall by means of position control. Then the manipulator applies the force to the wall by using the force control scheme. In contrast with the previous example, to move an object to the specified position with a certain force requires the hybrid position/ force control that can be implemented by the dual actuation mode.

Figure 5 shows that the task requiring the hybrid position/force control. Suppose the link is supposed to rotate 90° counterclockwise from the initial position. If the link is allowed to rotate freely, the link can reach the desired position by the position control of PA. During the motion, however, suppose the link encounters an object lying on the friction surface. In this case, even if the PA rotates 90°, the link cannot reach the desired position because the reaction force from the object causes the SM to rotate opposite to the direction of the PA rotation, as shown in Fig. 5(a). The link position θ_{Link} is given by

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

where θ_{PA} and θ_{SM} are the angular positions of PA and SM, respectively. The error between the desired and the actual link position happens to be θ_{SM} that is determined by the magnitude of the reaction force and the user-specified stiffness of the SM. To cope with this problem, the desired position of PA is compensated by measuring θ_{SM} with the encoder installed at the SM as follows:

$$\theta'_{PA,d} = \theta_{PA,d} + \theta_{SM} \tag{2}$$

where $\theta_{PA,d}$ is the desired position of PA, $\theta'_{PA,d}$ is the compensated desired position of PA by taking θ_{SM} into account. As shown in Fig. 5(b), the link can reach the desired position by considering this compensation of PA.

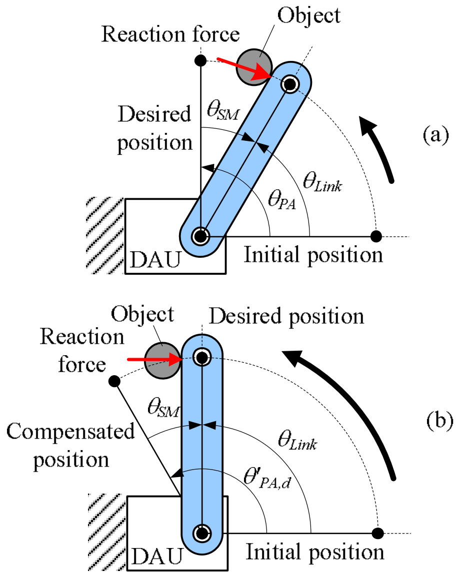

Fig. 5 Compensation for PA position in dual actuation mode; (a) before compensation, and (b) after compensation.

While PA compensates for the desired position of PA, the desired force is controlled by using θ_{SM}. When the angular position θ_{SM} occurs due to the external force, the relation between the desired joint stiffness K_{SM} and the current i_{SM} supplied to SM can be described by

$$i_{SM} = \frac{K_{SM} \cdot \theta_{SM}}{K_{T,SM}} \tag{3}$$

where $K_{T,SM}$ is the torque constant of SM. That is, the current proportional to θ_{SM} is supplied to the motor to implement the desired joint stiffness. In this system, the θ_{SM} is measured every 1msec by the encoder. Since no current is supplied to the SM when no external force is applied, the SM cannot implement the desired stiffness at the very beginning of the application of the external force. Therefore, the DAU is not suitable to deal with fast dynamic force.

3.3 High Torque Mode

The high torque mode shown in Fig. 3(c) can be used to perform such tasks as lifting up a heavy object. To obtain a high torque, SM is locked by a mechanical clutch and only PA is activated. Therefore, the output speed and torque are determined by the PA. Although the manipulator can conduct only position control in the high torque mode, it is able to carry out various tasks requiring a high torque.

As mentioned above, the high torque mode requires a clutch mechanism to lock the SM. It is desirable for this mechanism to be compact and simple but strong enough to firmly lock the SM. A cam-based clutch system was designed in this research, as shown in Fig. 6. It is composed of a cam, a locking gear and a leaf spring. In the cam mechanism, the pressure angle varies with the cam-profile. The clutch system based on the cam-mechanism can obtain the high output force from the low input torque. The gear teeth generated on the one side of a locking gear mesh with the SM gear and the tip of the locking gear remains in contact with the cam. Therefore, the SM is locked or released by controlling the rotation of the cam and the link. The leaf spring was used to recover the initial position of a locking gear when the clutch system is released.

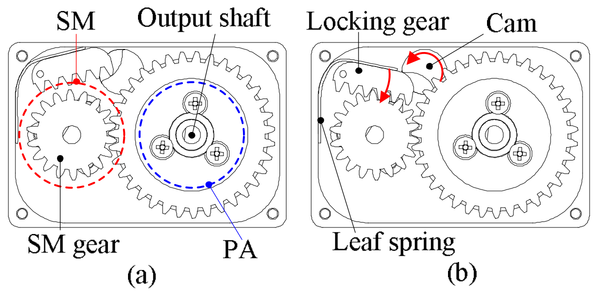

Fig. 6 Clutch mechanism for high torque mode; (a) before clutching, and (b) after clutching.

By conducting these three modes of a DAU, the manipulator can minimize the time to do a certain task. For example, when the manipulator is commanded to move an object to another place, it can approach the object rapidly in the high speed mode, and then it carefully grasps the object in the dual actuation mode. Finally, the manipulator moves the object to the desired place accurately after switching to the high torque mode.

4. EXPERIMENTS

4.1 Prototype

The DAU prototype equipped with the cam-based clutch mechanism was constructed, as shown in Fig. 7. The DAU uses two 20W brushless DC motors. The gear ratio of the position control part (including the motor and planetary gear train) is 690:1, while that of the stiffness control part is 163:1. The maximum torque and rotational velocity for three modes are listed in Table 1. The speed at the high speed mode is 5 times faster than that at the high torque mode, whereas the payload at the high torque mode is 4 times higher than that of the other modes.

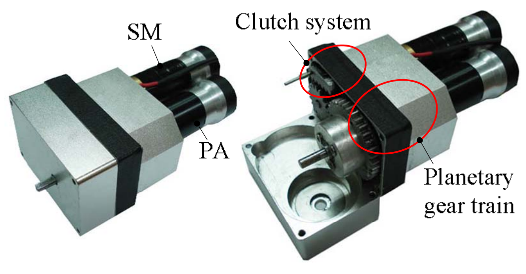

Fig. 7 Prototype of DAU with cam-based clutch system

Fig. 8 shows that the cam-based clutch mechanism. The SM can be locked by a small force transmitted from the clutch system. In the dual actuation mode or the high speed mode the clutch is released (Fig. 8(a)) while in the high torque mode the clutch is locked (Fig. 8(b)).

Table 1 Maximum velocity and torque for three modes.

Operating Mode	Max. velocity (rpm)	Max. torque (N·m)
High speed	72.1	3.1
Dual actuation	58.3	3.1
High torque	13.8	13.0

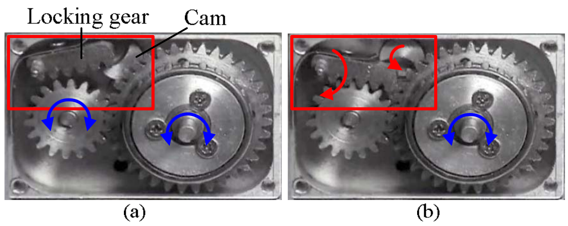

Fig. 8 Clutch mechanism; (a) released, and (b) locked.

4.2 Step Responses for Three Modes

Step responses were observed for three modes of the DAU with and without a load. A load of 1kg was attached to the end of the 20cm link, as shown in Fig. 9(a). The DAU without a load can track the desired position accurately for all three modes, as shown in Fig. 9(b). The high speed mode shows the smallest settling time in reaching the target position. However, when the load was applied to the DAU, the error between the target and the actual position occurs in the dual actuation and high speed modes, as shown in Fig. 9(c). This error caused by the external force can be reduced by adjusting the PID gains of the SM controller when the external force (i.e., the mass in this case) is smaller than the motor's maximum capacity. However, when the external force is comparable to the motor's maximum capacity, the error can be reduced only by locking the SM (i.e., high torque mode).

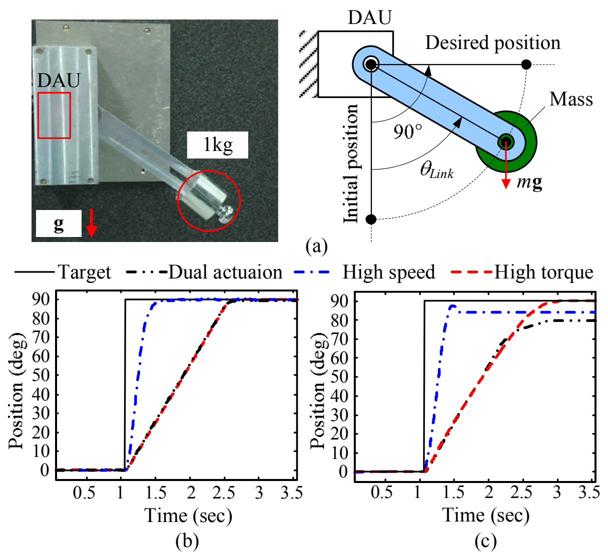

Fig. 9 Step responses for three modes: (a) experimental setup, (b) with no-load, and (c) with load.

4.3 Position Accuracy with Compensation

To improve the accuracy of the position control in dual actuation mode, the desired position of PA was compensated. The experiments were carried out for the dual actuation mode with and without compensation of the position of PA. As in the previous experiment, a mass of 1kg was attached to the end of the 20cm link, as shown in Fig. 9(a) and the desired position was set at 90º. As shown in Fig. 10(a), without compensation of PA some error between the desired and the actual position occurred even though the PA reaches the desired position. This error caused by SM can be reduced by compensating the desired position of PA, as shown in Fig. 10(b).

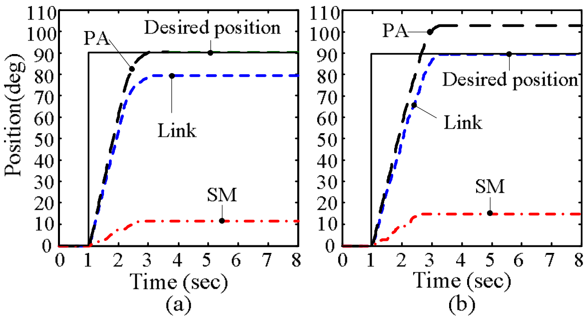

Fig. 10 Experimental results for compensation of PA; (a) without compensation, and (b) with compensation.

4.3 Manipulation Efficiency with Mode Switch

To verify the improvement of the manipulation efficiency, the task time was measured with and without mode switch. As shown in Fig. 11(a), the link attached to the output shaft of the DAU approaches the object placed 100º away from the initial position (I). Then the link applies a force to the object for 2 seconds (II) and returns back to the initial position (III). The time to complete this task was measured by the encoder information and the contact force was measured using a force/torque sensor installed at the object.

The experiments were carried out for two cases; one for the dual actuation mode and the other for the mode mixed of the high speed mode and the dual actuation mode. In the mixed mode, the link approaches the object quickly at the high speed mode and then applies a force at the dual actuation mode. To return to the initial position, the DAU switches to the high speed mode again. The link position and the measured force at the object were illustrated in Fig. 11(b) and 11(c). The experimental results show that the mixed mode is more efficient than the single mode such as the dual actuation mode. In this experiment, the mixed mode reduced the task time more than 30% (2 second) for one cycle.

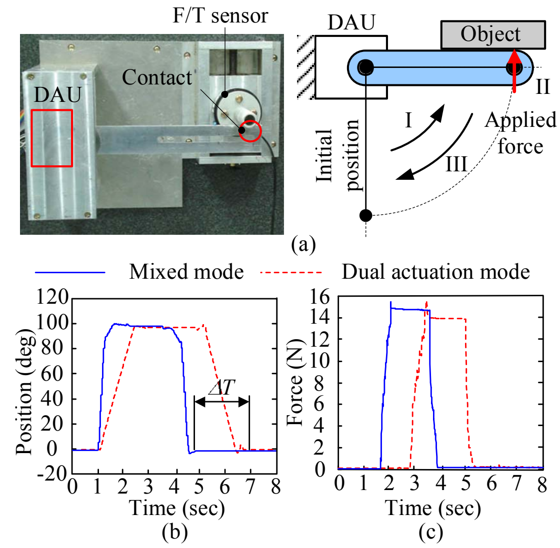

Fig. 11 Step responses for three modes: (a) position of link and (b) measured force at object

5. CONCLUSIONS

In this research, the dual actuator unit (DAU) using a clutch system was proposed to improve the manipulation efficiency. From the analysis and experiments, the following conclusions have been drawn.

1. DAU is capable of three modes and the manipulation efficiency can be improved by appropriately selecting the mode according to various situations.

2. Since the clutch in action locks the stiffness modulator, the payload of a DAU can be maximized and the positioning accuracy can be improved.

3. By compensating the position of PA from the SM's encoder information, the position accuracy can be improved.

The proposed DAU in this research can be used for a variety of applications requiring position and force control simultaneously, such as arms or legs of a humanoid robot. With the mode switch, DAU can also be used for other fields requiring the fast speed as well as the high payload.

ACKNOWLEDGEMENT

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