The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Motion-planning Method with Active Body-Environment Contact for a Hand-Arm System including Passive Joints

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Abstract— **Human-symbiotic humanoid robots that can perform tasks dexterously using their hands are needed in our homes, welfare facilities, and other places as the average age of the population increases. To improve the task performance of human-symbiotic humanoid robots, a motion-planning method with active body-environment contact was developed. Taking into account the positive and negative effect of mechanical passive elements implemented in joints, this motion-planning method can enables the hand-arm system to establish the active BE contact at the appropriate body-site and to select the joints that perform the movement for executing the given task. Control algorithms for the tool operation, namely, writing with a pen, were also constructed. The motion-planning method was validated through actual experiments on a prototype human-symbiotic humanoid robot.**

I. Introduction

HUMAN-symbiotic humanoid robots are expected to render daily-life support in homes, welfare facilities, and other places, because the issue of the falling birthrate and the aging population is going to have a significant impact on society in the near future. The most basic tasks in daily life are very simple ones such as picking up an object, transferring it to another place, and placing it there. These tasks are often accompanied by other tasks such as opening and closing a room door or a drawer. These tasks are performed very often in daily life, and they are very onerous for elderly or disabled people who have great trouble standing up and sitting down. Hence, research projects to develop a humanoid robot that has human mimetic hands and arms are now proceeding in several countries [1][2]. One of their research purposes is daily-life support using humanoid hands and arms.

Manuscript received March 10, 2010. Part of this work was supported by the Research Institute for Science and Engineering of Waseda University, the GCOE program "Global Robot Academia" from the Ministry of Education, Culture, Sports, Science and Technology of Japan, and fiscal 2007-2010 Grants-in-Aid for scientific Research by the Japan Society for the Promotion of Science (JSPS) No.19206028.

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Dexterity is a very important issue in this research field. That is to say, it is necessary to develop the dexterity to enable robots to achieve high-level performance (such as speed and smoothness of motion during the execution of basic tasks) and to execute more kinds of tasks.

A lot of previous researches have focused on dexterity, but these dealt either the hand or arm. For robust grasping and manipulating corresponding to the uncertainty of [what?] in daily-life environments, many kinds of multi-finger hands and manipulators with a mechanical passive element such as a spring in the joint have been developed by researchers [3][4][5]. It is known that such passivity is very useful from the viewpoint of a humanoid robot aiming to work in response to the uncertainty in daily-life environments. Moreover, a lot of control methods, such as robust grasping [6] and force or trajectory control on a manipulator [7][8][9], have been proposed. However, an important issue still remains; namely, a proper coordination scheme for the hand and arm is needed for dexterous task execution. Few studies have focused on coordinated hand-and-arm motion [10], and the relationship between the hand-arm coordination and the dexterity has not been discussed sufficiently.

In this study, aiming to expand the support abilities of robots, we focused on the dexterity for operating a common utensil. There are a lot of tools used in a every-day life; some examples are kitchen knives and spatulas, pens, screw-drivers, cutters, soldering guns, ear picks, and cotton-tipped swabs. A skill used while operating one of these tools (identified by observing human motion during everyday activities) is referred to as “active body-environment contact “(hereafter, simply “active BE contact”). A person usually puts his (or her) elbow, forearm, or wrist on the table when writing with a pen. Without this skill, the arm would tremble slightly in free space. As a result, it would be impossible to write neatly at the target location and control the contact force at the pen-tip precisely. This skill thus improves a person’s dexterity. In a previous work, we devised a motion-control scheme based on this insight [11]. This scheme provides the basic control structure for the appropriate hand-arm coordinated motion with active BE contact. However, when complicated tasks like tool operation are attempted, some issues regarding the implementation of this motion-control scheme still remain.

Our research purpose is therefore to develop a motion-planning method that allows the hand-arm system to establish active BE contact at the appropriate body site and select the joints that perform the movement for executing the task. In this study, firstly, we devised a motion-planning method in consideration of both the positive and negative effects of a mechanical passive element. Secondly, we derived control algorithms for the operating tools. Finally, we performed experiments using an actual humanoid robot that has passive elements in its joints, in order to validate the motion-planning method.

II. Motion-planning Method with Active BE Contact

The motion-planning method consists of two steps: first, selecting the body-site that establishes the active BE contact and, second, selecting the joints that perform the movement for executing the task prescribed in the task-execution system. We developed the motion-planning method by considering the effect of the passive element. Applying this method, a test robot called "TWENDY-ONE" [13] was given the task of writing with a pen.

A. Effect of Mechanical Passive Element

The positive effect of the mechanical passive is that it allows the passive position of the working point to be adjusted with a small reaction force. A model of a single joint with a mechanical passive element is shown in Fig. 1. When the link-tip of this joint is constrained by the environment (Fig. 1(a)), uncertainties such as model errors in the link length and the position of the object to contact make the joint move in order to adjust the working-point position. The degree of adjustment is determined from the displacement of the mechanical passive element. The reaction torque generated by this displacement is not as large as that generated by the rigid joint because of the flexibility of the passive element. This low reaction torque is the positive effect of the passive element.

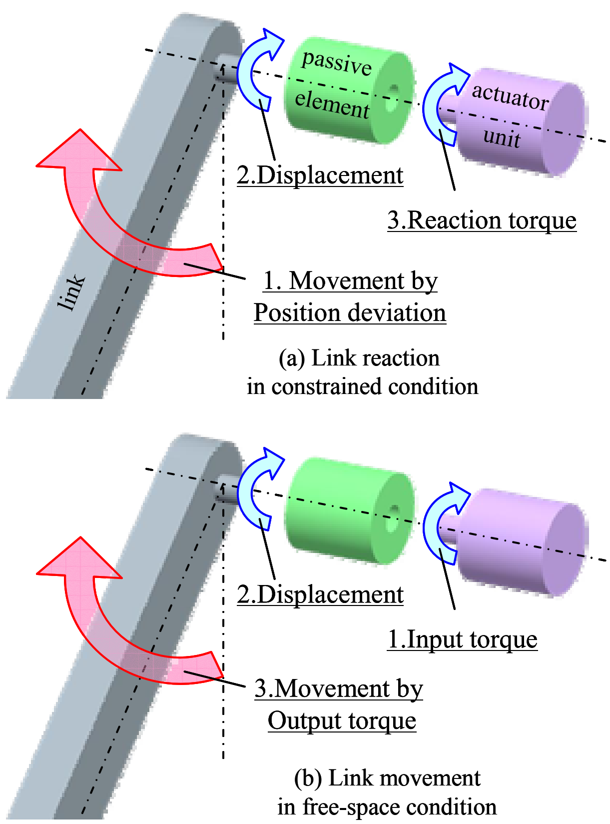


Fig. 1 Torque-transmission mechanism in a joint with a mechanical passive element

The negative effect of the passive element is a time delay when the joint moves rapidly and actively. Fig. 1(b) shows the torque-transmission mechanism when the joint moves actively in free space. The actuator generates the input torque that displaces the passive element. The link movement is generated by the output torque derived from the displacement of the passive element. Owing to this torque-transmission mechanism, the rapid movement of the link needs not only momentarily strong torque but also momentarily large rotation of the actuator corresponding to the displacement of the passive element. Hence, a joint with a mechanical passive element is liable to suffer a time delay when the link makes a rapid movement. This time delay is the negative effect of the passive element.

B. Motion-planning Method with Active BE contact

We devised a motion-planning method suitable for designing a task-execution system in consideration of the effect of the passive element. The uncertainty in everyday life makes the hand-arm movement unstable but the active BE contact can confine this effect to the task-execution system. When the robot establishes active BE contact, one important issue is which body site should be selected for the contact point. The task-execution system executes the task; therefore, the number of joints in the task-execution system has to be sufficient for executing the task.

The other issue is that all joints in the task-execution system should move to execute the task or not all joints should when the system has redundancy. As for selecting the body site for the active BE contact and the joints used for task execution, we should consider exploiting the positive effect and suppressing the negative effect of the passive element. The motion-planning method can be applied to the task-execution system to meet the following requirements in three-step selection (Fig. 2).

Step 1: Setting DOFs assurance

Firstly, a sufficient number of degrees of freedom (DOF) for the task-execution system is set. We proposed a motion-control scheme based on the concept of OBE loop (Fig. 3) [10]. The new OBE loop produced by the active BE contact divides joints in a hand-arm system into two groups. The bracing-control system controls the contact state at the active BE contact point, and the task-execution system controls the contact at the working point. The task-execution system should have a sufficient number of joints to perform the movement to execute the task. If the number of DOF constraints that the task needs is n, the task-execution system has to include n DOFs in regard to the working point. The joint that is n-th from the working point is called J1.

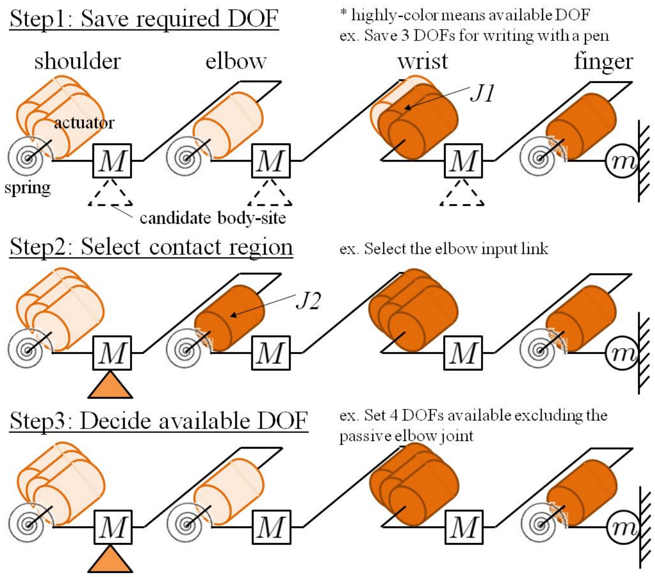


Fig.2 Proposed motion planning with active BE contact

Step 2: Selection of body-site for active BE contact

A mechanical passive element usually has a limit on its the displacement. When the displacement reaches the limit, the positive effect of the mechanical passive element disappears because it is locked by the limit and cannot be displaced further. On the other hand, upper human joints like the shoulder generically tend to produce a larger position error at the working point than lower joints like fingers because the distance between the shoulder joints and the working point is greater. For the same reason, an upper passive element can adjust the working-point position more widely without being constrained by the limit. This means that a passive element on the lower joints cannot compensate all the position error produced by the movement of the upper joints. For this reason, to be sure to exploit the positive effect of a passive element, the uppermost joint in the task-execution system should have a passive element. At the same time, the link with joints above J1 has to be selected as the body site for the active BE contact. The body site for the active BE contact is the input link of joint J2, which is the lowest joint with a passive element within joints above J1.

Step 3: Suppression of redundancy

When J2 is identical with J1, the task-execution system has a sufficient and requisite number of joints. When J2 is the upper joint in relation to J1, the task-execution system has redundancy, which is desirable from the viewpoint of reducing the required movement of each joint. The joint with the passive element should not actively move for the task execution in the redundant task-execution system because of the negative effect of the passive element. However, the negative effect gets smaller when the link mass is small. In particular, the finger joint has a very small-mass link and can move quickly. Only the joints with the passive element on the arm system should therefore be excluded from the task-execution system when the system has redundancy.

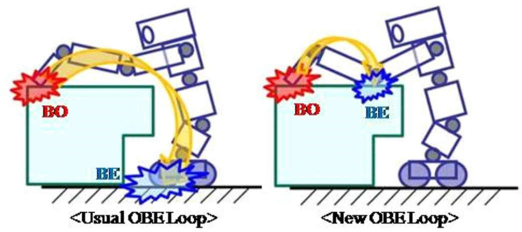


Fig. 3 OBE loop produced by active BE contact

C. Example of Applying Proposed Motion-planning Method

The motion-planning method was applied to the task described below; that is, a robot named "TWENDY-ONE" was assigned the task of writing with a pen like a human (Fig. 4).

Each arm of TWENDY-ONE has a seven-DOF redundant manipulator. The layout of the joints and the movable range of each joint are similar to those of a human. The total length of the arm is 627 mm. A six-axis force/torque sensor is equipped in the wrist. An original passive mechanism using viscous and elastic mechanical elements was implemented in the shoulder (three DOFs) and elbow (one DOF) of TWENDY-ONE's arm [12]. The displacement of the mechanical spring can be measured by an angle sensor (encoder) fitted in this mechanism.

A human-mimetic hand with three fingers and a thumb

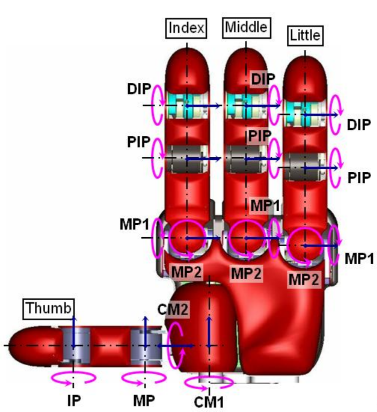


Fig. 5 DOF layout of TWENDY-ONE hand

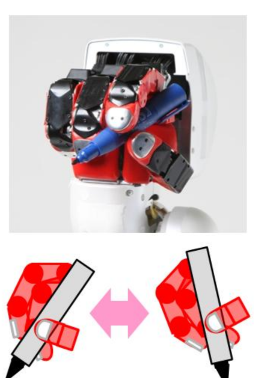


Fig. 6 Grasping and handling a pen by the tri-digital grip

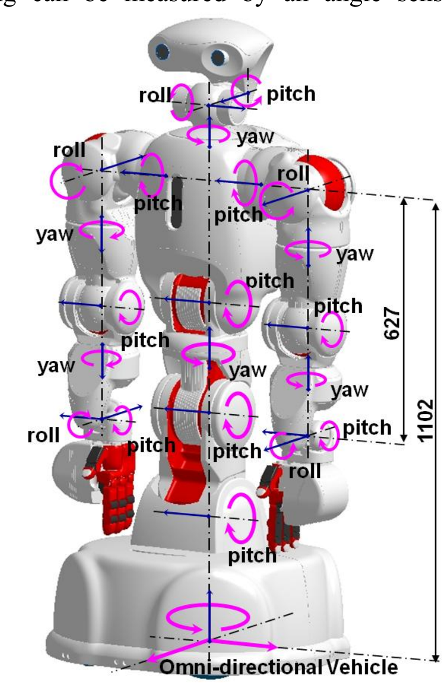


Fig. 4 DOF layout of whole body of TWENDY-ONE

(with thirteen DOF) -which can execute nineteen kinds of grasping motions like a human- was designed (Fig. 5) [13]. Every fingertip has a small six-axis force/torque sensor and a human-like gentle curved surface with a nail. The length of the links and the layout of DOF are similar to those of human fingers. The metacarpophalangeal (MP) and distal interphalangeal (DIP) joints of the index, middle, and little fingers have mechanical springs whose displacement can be measured by the angle sensor (potentiometer). The sides and tops of the fingers as well as the palm are covered with soft material (silicone).

According to step 1, joint J1 is selected from the task requirement. For writing with a pen, the position of the pen tip is constrained according to the shape of the line to be written. Three DOF are therefore needed for the task execution. The hand can grasp like a human hand with contacts at the side of index MP2 joint index-finger joint MP2 and the fingertip of the thumb, index, and middle finger. We call this grasping posture the "tri-digital grip". It can also manipulate the pen in the rotation direction of index joint MP1 while holding the same grasping state (Fig. 6). While maintaining this grip, the hand has one DOF. The roll joint of the wrist is therefore selected as J1.

In step 2, the body site for active BE contact is selected. Joint J2 has to be above J1 and have a passive element. The roll and yaw joints of TWENDY-ONE's wrist do not have passive elements. Accordingly, the elbow joint is selected as J2, and the input link of the elbow joint is selected as the body site for the active BE contact.

The task-execution system has five DOFs and is redundant. Only four joints, excluding the elbow joint, should move for suppressing the negative effect of the passive element. This is step 3.

III. Control Algorithms for Tool Operation

Control algorithms using the positive effect of the mechanical passive element for tool operations like writing with a pen were developed. The control algorithms of the task-execution system must control grasping and handling, the force at the working point, and the trajectory of the working point.

The force exerted at the working point is regulated by spring-displacement control at the elbow joint. After grasping the pen and establishing the active BE contact at the input link of the elbow joint, the task-execution system should apply a certain constant level of force at the working point. The reference angle of the elbow actuator is calculated from the initial joint angle when the contact is established by the slight force, the displacement due to the self-weight, and the displacement corresponding to the reference force at the working point. This algorithm doesn't use the information of the force sensor and is based on the position control of the actuator angle. Consequently, this algorithm is very simple but can control the exerted force at high accuracy.

We have developed the very simple control method for grasping depending on the positive effect of the passive element. TWENDY-ONE hand has the coil springs and soft material covering as the mechanical passive element and can roughly grasp the object using only the information about the shape and size of the object [14]. We arrange this method for the grasping and handling control of writing with a pen. Determining the initial posture and end posture manually, our algorithm interpolates the angle of each joint between these two postures. However, the pen handling is very complicated because each contact point moves on the surface of the fingertip, and the grasping force changes during handling. The adjusting movement of the thumb and middle finger is implemented by a simple force control to hold the exerted grasping force at the certain level. Joint MP of the index finger contains a passive element, and the positive effect of this element is expected to stabilize the grasping state. The thumb and middle finger are rigid and are expected to control the rapid adjustment movement by the grasping force without incurring the negative effect of the passive element. The alternation of the grasping force is measured by the force sensors implemented in the fingertips. The progress of the pen handling is represented by the index-finger angle.

The motion-planning method stipulated that one DOF of the index finger and three DOFs of the wrist execute the writing task. Using these four DOFs, the resolved motion rate control makes the trajectory for writing the line. To maintain the level of the contact force at the working point during writing, this trajectory controller adjusts the position of the working point according to the alternation of the displacement of the mechanical spring at the elbow joint. A control diagram including these three control algorithms is shown in Fig. 7.

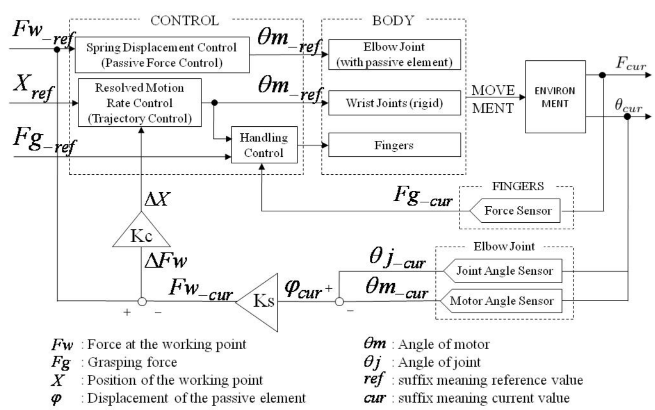


Fig.7 Control block diagram for the tool operation using passive element

IV. Physical Experiment

To validate the motion-planning method, we conducted a physical test using TWENDY-ONE. The parameters of the experiment were as follows: presence or absence of active BE contact; either TWENDY-ONE pinched the pen with its tri-digital grip like a human or grasped it with cylindrical palmer prehension; presence or absence of active elbow joint movement for executing the task execution. The test was conducted under the four conditions (with combinations of the three parameters) described below. The condition chosen by the motion-planning method was (a).

(a) With active BE contact, with tri-digital grip, and without elbow-joint movement

(b) Without active BE contact, with tri-digital grip, and without elbow-joint movement

(c) With active BE contact, with tri-digital grip, and with elbow-joint movement

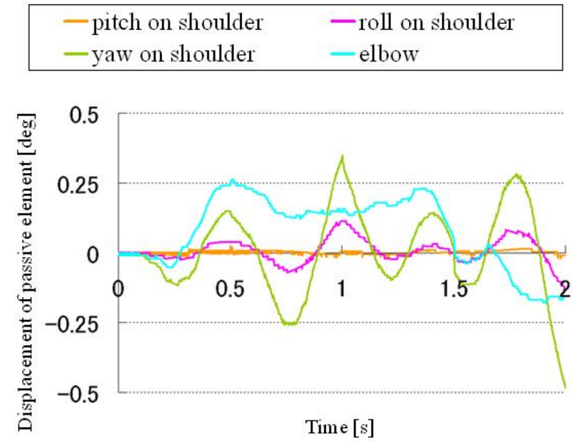
(d) With active BE contact, with cylindrical palmer prehension, and with elbow-joint movement

We evaluated the suppression of the negative effect of the passive elements in terms of the values of the displacement of the elements. These values were measured by the angle sensor implemented in the robot body. In addition, the difference between the actual and reference value of the contact force and the trajectory of the working point was also evaluated. These values were measured by using a commercial pen-tablet, which was placed on a typical dining table. The pen used in this experiment was the structural object of the pen and a hollow cylinder made of aluminum. The total weight was 117 g and its diameter was 30 mm. The reference trajectory was a square, 40 mm on a side. The working time to execute the task was 2 s, and the rapid movement was required to the task-execution system.

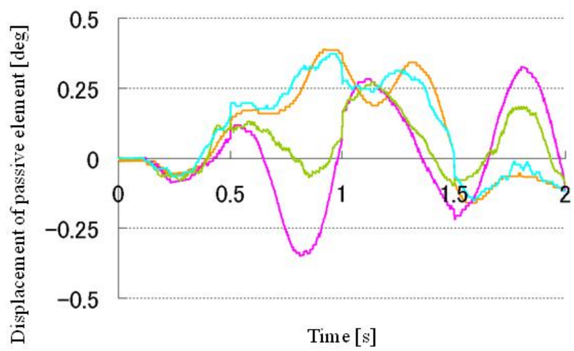
The experimental results are shown in Fig. 8. The x-axis indicates time (in seconds), and the y-axis indicates the displacement of the mechanical passive element (in degress). From the graph for conditions (a) and (b), it is clear that the displacements of the shoulder pitch and the roll joint are significantly suppressed by the active BE contact. However, there is no difference between the displacement of the shoulder yaw joint under condition (a) and the one under condition (b). This is because the contact point on the elbow joint can roll on the table along the round shape of the elbow shell. Compared the graphs for conditions (a) and (c) regarding the displacements of the elbow joint reveals that the peak values are almost the same, but the oscillation occurs under condition (c). This oscillation derives from the active movement of the elbow joint.

To validate the effect of the finger movement, the displacements of the passive element under conditions (c) and (d) were compared. Under condition (c), both the peak values and the oscillation on the shoulder pitch and roll joint are suppressed. The oscillation on the shoulder yaw joint under condition (c) is the almost same as the one under condition (d), but the peak value on the shoulder yaw joint is suppressed under condition (c). The peak value on the elbow joint under condition (c) is almost the same as the one under condition (d). The oscillation on the elbow joint under condition (c) is suppressed. The effect of using more DOFs for the task execution is shown by these results.

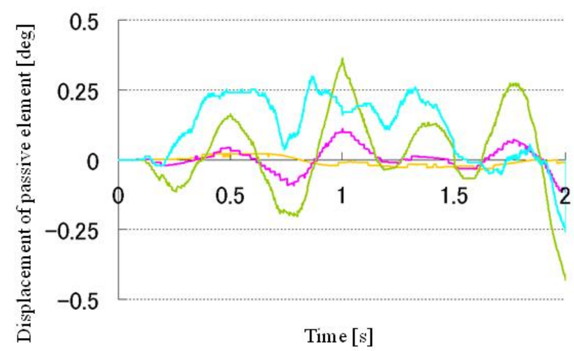
The actual trajectory and the exerted force at the working point measured by the pen-tablet are plotted in Fig. 9. The exerted force is almost constant during the task execution



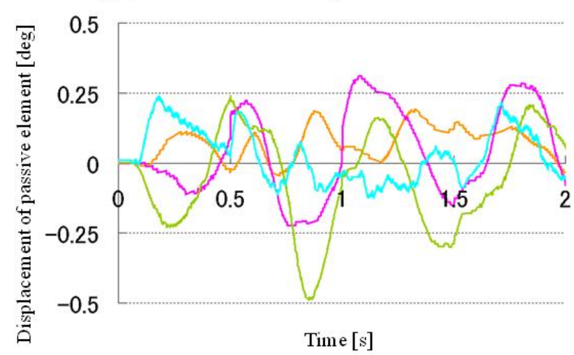
(a) with active BE contact and with the tri-digital grip and without the elbow joint movement



(b) without active BE contact and with the tri-digital grip and without the elbow joint movement



(c) with active BE contact and with the tri-digital grip and with the elbow joint movement



(d) with active BE contact and with the cylindrical palmer prehension and with the elbow joint movement

Fig. 8 Displacement of passive element in physical experiment shown in the left graph in Fig. 9. The positive effect of the mechanical passive element contributes to this result. The actual trajectory is considerably deflected from the reference square shown in the right graph in Fig. 9. This is because of the complicated movement of the contact points on the fingertip surface during pen handling. The pen grasping and handling control method can easily grasp the object pen and maintain contact with it, but precise control of the object posture is a disadvantage of this method. This result demonstrates that, in our future work, we should add a new function to the method for precisely controlling the pen posture.

V. Conclusion and Future Works

A motion-planning method using active BE contact in a humanoid robot was developed. Considering the positive and negative effect of the mechanical passive element, this motion-planning method can make use of the positive effect and suppress the negative effect. The method was applied to the task of writing with a pen (in the manner of a human) by a robot (called “TWENDY-ONE”). The control algorithms for this tool-operation task were also developed. The handling of the pen is treated by these algorithms in terms of DOFs of the hand-arm system. A physical experiment using TWENDY-ONE confirmed that the motion-planning method improves the force control at the working point. At the same time, this result revealed that we have to arrange the pen-handling control algorithms to control the trajectory of the working point more precisely.

Aiming to achieve more dexterous task execution, we are going to investigate the respective roles of the hand and arm and construct a sub-task method for the trajectory control for fine motion of the working point such as that involved in bouncing and flicking in Japanese calligraphy. Additionally, we are going to conduct another trial using the motion-planning method aiming to perform other tasks such as soldering with a soldering gun.

Acknowledgments

Part of this study was supported by the Research Institute for Science and Engineering of Waseda University, the GCOE program "Global Robot Academia" from the Ministry of Education, Culture, Sports, Science and Technology of Japan, and fiscal 2007-2010 Grants-in-Aid for scientific Research by the Japan Society for the Promotion of Science (JSPS) No.19206028. We wish to express our gratitude to all of these organizations.

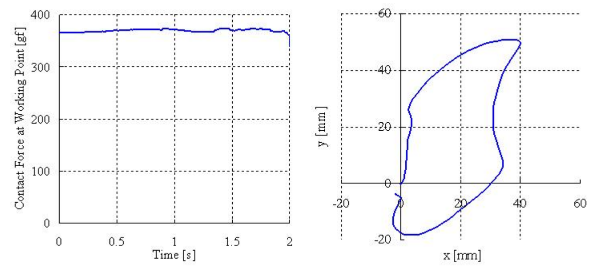


Fig. 9 Actual exerted force and trajectory of working point in physical experiment

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