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Computer Controlled Bilateral Manipulator*

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Computer control of an artificial hand which is incorporated with the tactile sense and force reflection is studied.

In this experimental system, a digital computer is linked to the analog-type position-servomechanisms of the artificial hand using D/A and A/D converters, so that the position references can be changed repeatedly in the direction of decreasing the measured error signals.

To deal with the versatility of the operation, the software system consists of a supervisory program and many basic program modules which correspond to respective basic manipulations. Furthermore, a symbolic command language which is adequate for such a purpose is prepared.

It has been shown that the greatest difficulties in carrying out the complex and dexterous manipulations such as inserting a pin into a hole, turning a crank, etc., are solved by introducing the concept of bilateral servomechanism into the programming of the control computer.

1. Introduction

Usually, when we think of the control of an artificial hand for the purpose of automatic manipulation of objects, at first, we think only of the control of its motion. If we study this problem further, however, it becomes evident that the control of the forces applied to the object is as important as the control of the motion.

Artificial hands which have been realized up to now⁽¹⁾, are classified into the following two types according to the servo-technique used in them. One is the group of artificial hands⁽²⁾⁽³⁾ which are driven by unilateral position-servomechanisms. The other is the group of manipulators which are driven by force reflecting servomechanisms or bilateral servomechanisms⁽⁴⁾, as we call them. Nowadays, it seems that only the human operated bilateral servo-manipulators⁽⁵⁾ belong to the second type, and almost all the automatically controlled artificial hands belong to the first type. Hence, by the lack of force reflection, ordinary automatically controlled hands cannot carry out such dexterous manipulations as fitting a pin into a hole or turning a crank.

In this paper, to solve the above mentioned problem, the computer controlled bilateral servomechanism is studied. In this experimental system, a digital computer is linked to analog-type position-servomechanisms of the artificial hand using D/A and A/D converters so that the position references can be changed repeatedly in the directions of decreasing the measured error signals. Consequently, it has been shown that the greatest difficulties in carrying out these dexterous manipulations are solved by introducing the concept of bilateral servomechanisms into the programming of the control computer.

2. The computer controlled bilateral servomechanism

2.1 The necessity of the force reflection

From the point of view of the control engineering, manipulations of objects are classified into the following three general types having increasing complexity⁽⁶⁾⁽⁷⁾.

The first type is the handling of diverse solid objects by picking them up with the hand, orienting and placing them at different locations.

The second type of manipulation involves handling solid objects and bringing them into intimate contact with designated objects. Examples are: inserting a pin into a hole, fitting a part

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together with another part in assembling.

The third and still more complicated type of manipulation involves the operation of equipment. In this case, the controls on equipment are generally limited to one or two degrees of freedom, and their path or axis of rotation of the motion of the hand is almost determined by the equipment. A simple example of this kind of manipulation is the turning operation of a crank.

Although the first type of manipulation can be performed by using the position control of the hand with tactile sensors, the manipulations of the second or third type are difficult to accomplish without the capability of adapting to the constraints determined by the objects and imposed on the motion of the hand. It means that to solve this problem, we must study the computer controlled bilateral servomechanism.

2.2 The concept of the computer controlled bilateral servomechanism

For the realization of the bilateral servomechanism, it is necessary to measure the force applied to the object. In this study, the force is estimated through the error signal of the servomechanism. The experimental system is shown in Fig. 1. The motion of the conventional analog-type position-servomechanism can be expressed as follows.

$$J\ddot{\theta} + K_b\dot{\theta} + K_a\theta = K_a \cdot r - \tau_l \quad (1)$$

The symbols used in Eq. (1) are

θ : angle of rotation of the shaft

r : position reference signal

τ_l : external torque

J : moment of inertia

K_a : coefficient of total stiffness

K_b : coefficient of viscous restraint

By the Laplace transformation of Eq. (1), the error signal $e = r - \theta$ becomes

$$e(S) = \frac{JS^2 + K_bS}{JS^2 + K_bS + K_a} \cdot r(S) + \frac{1}{JS^2 + K_bS + K_a} \cdot \tau_l(S) \quad (2)$$

After the response to the change of the position reference has settled, the error becomes nearly

Fig. 1 Block diagram of the computer controlled bilateral servomechanism

$e = \tau_l / K_a$, that is, the external torque in steady state can be estimated proportionally from the measured error signal.

Now, let us consider a system in which a digital computer is linked to the position-servomechanism using D/A and A/D converters. In such a system, the following three control modes are easily realized according to the programming of the control computer.

(A) Position control mode: In this mode, the computed data may be converted to an analog-signal and given to the servomechanism as the position reference signals.

(B) Torque measuring mode: The error signal which is measured after the lapse of the settling time, may be considered proportional to the external torque.

(C) Bilateral control mode: By changing the position reference signal repeatedly in the direction of decreasing the error signal caused by the external torque, the rotation of the shaft may be determined by the external torque. In other words, the computed position reference is

Fig. 2 Flow-chart of the bilateral control mode

Fig. 3 Position reference and error signal in the bilateral control mode

considered to be not the actual reference but a variable to be controlled by the external condition. The flow-chart of this programming procedure is represented in Fig. 2. In this flow-chart, at first it is determined whether the bilateral control mode may be used or not. In the case of the bilateral control mode, the initial error signal is measured and stored. This initial error gives the initial force caused by the weight of the manipulator itself and other inherent factors. If an additive error is caused by the external force, the position reference is changed repeatedly in the direction of decreasing the difference of the measured error signal from the initial error.

Examples of the error signal caused by the external torque and of the position reference signal are illustrated in Fig. 3. The cycle time T_c of this mode is about

$$T_c = (\text{A/D conversion time}) \\ + (\text{D/A conversion time}) \\ + (\text{waiting time; about 125 m sec}) \\ + (\text{computing time; negligible})$$

Fig. 4 Whole view of the experimental system

2.3 Application of the bilateral concept to the control of the artificial hand

In the control of a many-degrees-of-freedom servo-system, a great increase in the possibility of the servo-system will be expected from the use of those control modes in adequate combination. Especially, this effect will be remarkable in the control of such dexterous manipulations as of the second and of the third type. In this study, the availability of this bilateral concept is proved by the experiments on the following examples.

- (1) Turning a crank
- (2) The motion in which the position of the hand is required to be guided by the object; example is the motion of pulling a pin out of a hole.
- (3) The motion of orienting a pin grasped by the hand for fitting it into a hole.
- (4) The control for teaching the position to the hand, by moving it directly.
- (5) To determine whether the object grasped by the hand collides with any other object or not.
- (6) To determine whether the object grasped by the hand is constrained from any external object or not.
- (7) Classification of objects according to their weight.

3. Computer control of an artificial hand

3.1 The experimental system

This experimental system, represented in Fig. 4, consists of a small digital computer, a control unit and a slave unit of an electric servo-manipulator.

As shown in Fig. 5, this manipulator, manufactured by Mitsubishi Electric Co. Ltd., has the following seven degrees of freedom of motion: up-down, forward-backward, right-left, rotation of the wrist, swing motion of the wrist and squeezing motion.

Twenty-eight micro switches which are mounted on the hand provide the tactile sense of 15 bits. The arrangements of these sensory organs are shown in Fig. 7.

A CLOAP-2000E small computer manufactured by the Hitachi Ltd. is used for controlling the manipulator. The core memory unit contains 4096 words, the word length is 18 bits, the memory cycle time is 3μ sec, and typical execution times are 6μ sec for addition, 29μ sec for multiplication and 53μ sec for division.

The block diagram of this experimental system is shown in Fig. 6. As shown in Fig. 6,

Fig. 5 Artificial hand

all the servomechanisms are linked to a digital computer using D/A and A/D converters, so that the position of the hand can be determined not only by the computer but also by the objects.

3.2 Commands for controlling the hand

One of the important purposes of this experiment is to realize a general purpose artificial hand which can carry out dexterous manipulations automatically, such as inserting a pin into a hole and turning a crank. In this control system, for insuring the system versatility, the software system consists of a supervisory program and many basic program modules which correspond to respective basic manipulations.

According to the motion study about the machine-operated manipulations, it becomes clear that they can be classified into the following groups: Transfer, Grasp, Release, Engage, Disengage, Search, and Test. With further considerations, several typical manipulations for each group have been selected, and they are programmed as basic control modules.

Furthermore, in order to facilitate the selection and execution of these basic modules, symbolic commands are prepared. As represented in Fig. 8, these symbolic commands are composed of the following three fields: operation symbol, parameter field and label field. Each of these fields is used respectively for representing the

Fig. 6 Block diagram of the experimental system (r_i : position reference, e_i : error signal)

Fig. 7 Arrangement of the tactile sense organs

Fig. 8 Format of the symbolic command

f_a : Does the hand contact with any object?
 f_o : Does the outside of the hand contact with any object?

Fig. 9 Flow-chart of the program module for "GSG"

kind of manipulation, the parameters such as the grasping force, and the name of the reference position.

By the way, let us give a pet-name "Tokky" to this experimental system. Then the following symbolic commands are considered as a particular language which Tokky can understand.

(1) Commands for manipulating objects

Transfer: TH (move to the appointed position). TS, TC (move to the appointed position with tactile sensing). TT (transfer the object along the path which may be determined by any other object). CRK (turn a crank).

Grasp: G, GSP, GR, GT (grasp an object).

Search and Grasp: SG, GSG (search and grasp an object).

Release: R (open the hand). RC (release the object when the external force is applied to it). RCP (put the object on the appointed place).

Engage: E, ER (insert a pin into a hole).

Disengage: D, DF (pull out a pin from a hole).

Test: TST (classify the object grasped by the hand according to its weight or size).

(2) Commands for the sequence control. UJ (jump to the appointed command). CJ (jump to the appointed command according to the result of the former command). JS (jump to the subroutine which is written using these symbolic commands). HLT (halt). END (end of the task).

(3) Commands for making the reference data. In this system, the table of labels is prepared for converting the name, which is appointed in the label field of the command, to the actual data. However, it is a very important problem how to make this label-table. In this experiment, the following two methods are prepared for making it easily.

DPS: We can teach the position and its name, by moving the artificial hand directly with our hand. This method is insured by using all the degrees of freedom of the hand in the bilateral control mode.

DPR: We can teach the position and its name through teletype.

Other commands in this class are explained in the following. DPN (store the name only). DPA (move to the central point between the initial and the appointed position). LTC (clear the label-table). PRL (print the labels in the table). PDT (punch out the contents of the label-table). LDC (this is the command for correcting the data in the table, so that it can be used for computing the data of the position

during the automatic execution).

(4) Commands for automatic execution of the programmed manipulation.

RDT, ROT, RMT: These commands are used respectively for loading the data, commands or the message.

TWR, TWC, TWS: These commands are used for automatic execution of the programmed manipulation, respectively, in repetitive, cyclic or stepwise mode.

3.3 Some examples of the basic program modules

In this section, as examples of the three general types of the manipulation mentioned above, the basic program modules for executing the following manipulations, such as grasping an object, inserting a pin into a hole and turning a crank, are explained.

3.3.1 Program module for the command "GSG"

As an example of the manipulation of the first type, the basic program module for "GSG" is illustrated in the following. When this command is given, at first, Tokky moves forward a little distance and tries to grasp, and if he fails in this trial, he searches near the initial position for grasping the object. The flow-chart of this module is shown in Fig. 9.

apr: Tokky moves his hand to an adequate position for grasping the object under tactile feedback. (cf. Fig. 11)

cls: Tokky grasps the object. In this module, by using tactile feedback, the position and orientation of the hand are adjusted properly for grasping the object without moving it. (cf. Fig. 10)

Fig. 10 The example of the tactile feedback motion synchronized with the closing motion of the hand

Fig. 11 The example of the correcting motion of the approach

tsq: Initial approach routine.

sch: The local search with tactile sensing is carried out. (cf. Fig. 12)

opn: Tokky opens his fingers.

3.3.2 Program module for the command "ER"

This example belongs to the second type of manipulation. In this module, Tokky tries to insert a pin into a hole, and in the case of failing in the first trial, he repeats this trial along the corrected path of search, up to five times. The flow-chart of this module is illustrated in Fig. 13.

twt: Tokky tilts the pin in his hand for facilitating the aligning motion.

rq: Tokky lets down his hand until the pin in his hand collides with the ground. It is determined whether the pin collides with the

Fig. 12 The path of the local search

Fig. 13 Flow-chart of the program module for "ER"

Fig. 14 Tokky searches a hole and puts the end of the pin at the edge of the hole

ground or not, according to the measured error signal.

alg: Tokky moves the pin in his hand along the path, represented in Fig. 14, until the torque of twist exceeds a pre-determined threshold level.

res: Tokky resets the orientation of the pin, holding the close contact between the pin and the edge of the hole. In this case, the motion of A-direction (cf. Fig. 15) is controlled in the position control mode, and the motion of B-direction is controlled in the bilateral control mode, so that the position in the B-direction may be determined by the motion of A-direction.

con: Tokky pushes down the pin. Also, in this case the motions of F-B and R-L direction (cf. Fig. 5) are controlled in the bilateral control mode, so that the motion of the hand may be guided by the hole.

chk: Tokky checks whether the pin is inserted in the hole or not. In this routine, if the increment of the error caused by the twist-motion of the wrist exceeds the pre-determined threshold, the insertion is considered to be secure.

dc: In the case of failing in the trial of insertion, the data of initial position of this manipulation are modified for the purpose of changing the path of search.

th: Tokky moves his hand to the corrected initial position.

3.3.3 Turning a crank

In this example of the third type, the hand

Fig. 15 Tokky resets the orientation of the pin keeping close contact with the hole

Fig. 16 Correction of the reference path for turning a crank

Fig. 17 Error signal on the turning motion of the crank

must move along a circle determined by the crank. If the reference position input given by the computer deviates from this circle, a position error signal will be induced, and the reference should be changed in the direction of decreasing the error signal, so that the hand will move along the circle determined by the crank. To materialize such control, the concept of bilateral servomechanisms should be introduced into the programming of the control computer.

For example, in Fig. 16, X-motion and Y-motion are controlled respectively in the position control mode and in the bilateral control mode, so that the error signal of the Y-motion caused by the position control of the X-motion can be changed repeatedly in the direction of decreasing it. Consequently, the propositional reference path represented by the dotted line can be corrected to the accommodated zig-zag path, with the progress of rotation.

By controlling three freedoms of the hand in the bilateral control mode according to the above mentioned idea, the experiment of turning a crank is performed. This motion is shown in Fig. 18. And also, the error signals of the X

Fig. 18 The motion of the turning operation of a crank

and Y motion are illustrated in Fig. 17. As readers can see from the data, one of the error signals is usually held at nearly zero. It means that the motion of this direction is used to keep the hand on the trajectory determined by the crank, and the motion of the other freedom is used for driving the crank.

3.4 The system program

In order to insure the system versatility, the program of this experimental system is composed of the following four elements.

- (1) Supervisory program.
- (2) Sets of the basic program modules for executing the corresponding symbolic command.
- (3) Table for the program storage. This "program" means the one which is written with the above mentioned symbolic commands.

Fig. 19 General flow-chart of the supervisory program

(4) Table in which the labels and the data are registered.

About 3500 words of core memory unit are consumed to build up all of these elements.

Table 1 Example of the program

No.	Command			Comment
1	TH		A	Move to the point "A"
2	GSG	4		Grasp
3	CJ		1	Jump to 1, if fails in grasping motion
4	TH		B	Transfer to the point "B"
5	RC		B	Release the object when the external force is applied to it.
6	CJ		5	
7	END			End of the task

When we set this system in motion, in the first place, the state of the hand is put in the initial condition automatically, and the control is transferred to the supervisory program represented in Fig. 19. This supervisory program consists of the following two executing routines. One is the "Teletype executive control program" (SUP-1) and the other is the "Automatic executive control program" (SUP-2). Upon receipt of a command through teletype, SUP-1 analyzes this command and the control is transferred to the appropriate program module. Other features of the SUP-1 are to check the error, to convert the label to the appropriate data, and so on.

In the case of the command "TWR, TWC

Fig. 20 Example of the automatic manipulation

or TWS", the control is transferred to SUP-2. The function of SUP-2 is quite similar to that of SUP-1. In fact, the primary difference is that SUP-2 refers the commands stored in the table and controls their executive sequence.

4. Experiments of automatic execution of the dexterous tasks

As mentioned above, any task which is required to be done is easily programmed by using the symbolic commands, as represented in Table 1. And also, the data-making method by the bilateral control mode (DPS) is very useful for making the position reference data in the complex coordinate system such as this manipulator.

In this study, the following manipulations are performed automatically by this experimental system. The numbers in the square parentheses are the numbers of the symbolic commands which are used for the program.

(1) Building blocks. [19]

(2) Building blocks; in this task, Tokky selects the path of transferring, according to the tactile information. [19]

(3) Tokky grasps some object after the global search on the work table, and delivers it to the human hand. [53]

(4) Tokky classifies the object which is delivered by a human into any of four classes according to its weight and size, and puts it on the corresponding place. [32]

(5) Tokky pulls a pin out of a hole and inserts it into another hole. [25] This task is illustrated in Fig. 20.

In this example, at first, Tokky reaches his hand toward the left hole (photo. 1-2) and closes his hand (2-3). If the pin is found, he grasps it again (4-5) and pulls it out (5-6). After he made sure that he succeeded in this operation (7-9), he transfers it to a point above the right hole (9-10). Then, he tilts the pin in his hand to facilitate the aligning motion (10-11), and lets his hand down until the pin in his hand collides with the ground (11-12). Besides, he searches a hole and puts the end of the pin at the edge of a hole (12-13), resets the orientation of the pin in close contact with the hole (13-14) and pushes the pin down (14-15). Finally, he confirms whether the connection has been performed or not, and in the case of success, he

opens his hand and returns to the initial place (15-16). The size of the pin which is used in this experiment is 30 mm in diameter, and the inner diameter of the hole is about 30.8 mm. The motions from 5 to 9 belong to the command DF, and those from 10 to 15 belong to the command ER.

5. Conclusions

In order to let the computer controlled artificial hand carry out dexterous manipulations, the concept of bilateral servomechanism is introduced into the programming of the control computer.

In this experimental system, a small digital computer is linked to analog-type position-servomechanisms of the artificial hand using D/A and A/D converters, so that the position references can be changed repeatedly in the direction of decreasing the measured error signals. It has been shown that the greatest difficulties in carrying out the complex and dexterous manipulations such as inserting a pin into a hole, turning a crank, etc., are solved by applying this concept of the bilateral control mode to the control of the hand.

Next, a general purpose automatic manipulating system is realized. In this system, for the purpose of representing the desired task, the symbolic commands are prepared. Furthermore, it is ascertained from this experiment that the bilateral control mode is very useful for making the position reference data in the system with complex coordinates.

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