unnamed and without meaning. The participant-observer then synthesizes or integrates this "formed" subsidiary information into a meaningful context, i.e. he interprets the dimensions. The results of this MDS phase did, as hoped, clarify the original apparent contradictions.

Conclusions

The ESS study followed a human science paradigm, as outlined in Table I, rather than the more traditional natural science paradigm. Virtually everyone involved in the study was a participant-observer. In my P-O role I used interviews, brainstorming, and Delphi techniques in addition to personal experience to derive a functional structure reflecting attribute interrelationships. MDS and various rank-order techniques helped to organize and structure a semantic context so that the input information could be integrated and synthesized into a new phenomenal aspect.

The P-O role is an integral part of the human science paradigm, hence by explicitly incorporating the P-O role in systems in methodologies we also adopt the human science paradigm. This implies a shift in our use of technology as suggested by Table I. For example, in addition to measurement and analysis systems, we would also want systems specifically designed to help extract meaning from observations and facilitate the explicative process. We will need to develop holistic communication skills, i.e., ways to communicate complex phenomena and interactions in as holistic a fashion as possible [20]. We should also explore more creative uses of gaming and simulation [20].

Pulling these various ideas together the emergent theme for systems engineering or societal systems study is the need for an integrated approach, i.e., one which combines and utilizes methods of observations from both the physical sciences (the scientific method) and the human sciences. Margaret Mead sums up this point of view as follows.

> "In effect, the basic techniques of observation and recording in the physical and human sciences are complementary. . . . I would argue that it is not by rejecting one or another but by appropriately combining the several methods evolved from these different types of search for knowledge that we are most likely in the long run to achieve a kind of scientific activity that is dominated neither by the arrogance of physical scientists nor by the arrogance of humanists who claim that the activities which concerned them cannot meaningfully be subjected to scientific inquiry" [10].

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Control Algorithm for Precision Insert Operation Robots

TATSUO GOTO, KIYOO TAKEYASU, AND TADAO INOYAMA

***Abstract*—A tactile controlled robot is described which accomplishes precision insertion operations with a clearance of only a few microns. This robot is equipped with a new insertion control unit which integrates positioning ability, sensitivity, and flexibility, both mechanically and electronically. Its most important feature is effective utilization of a flexible mechanism and force sensors. The major usefulness of flexibility in precision insertion operations is proven by a theoretical study. Here, the new insertion control algorithm consists of two types of hole position search methods, a rectilinear search and a two-dimensional multistep search-and-insertion control method using force feedback. Computers are not used for operation of this new robot, only a simple sequence controller is required. These technologies are successfully applied to the assembly of an electric motor.**

I. Introduction

The manufacturing industry, particularly those machinery industries which handle individual solid materials, still largely depends on human abilities for skilled handling of materials especially with regard to the visual and tactile senses. The automation of such processes requires the introduction of handling equipment provided with a visual device and tactile senses in order to skillfully handle and assemble the required parts. From this point of view, several intelligent robots have been developed by Hitachi, for instance, the HIVIP Mk 1 or HI-T-HAND Mk 2 [1].

The packaging robot, HI-T-HAND Mk 2, was used to study the techniques for using basic force tactility in fitting and pressing operations. These techniques have been refined to realize practical insertion control techniques which require even more delicate force tactile control [2], [3]. Research into the problem of dexterity

Manuscript received September 28, 1978; revised April 24, 1979 and September 10, 1979.

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0018-9472/80/0100-0019$00.75 © 1980 IEEE

during the assembling tasks has taken several forms. Inoue performed such experiment as putting a peg into a hole with a computer controlled arm [4]. Paul studied the modeling trajectory calculation and servoing of a computer controlled arm with force feedback [5]. Nevins and Whitney examined the characteristics of a remotely centered compliance (RCC) mechanism for insertion [6], [7].

However, at present, there are no practical search-and-insertion control methods for fitting a shaft to a hole with a micron order clearance. One of the interesting insertion methods is the RCC mechanism which involves fitting a shaft into a chamfered hole. In this method, allowable positioning error is restricted by the chamfer width. Therefore, if the positioning error exceeds the chamfer width, there is no method for locating (searching) the hole. Consequently, insertion operations become completely impossible especially in the case of unchamfered holes.

The present paper describes a unique and concise control algorithm with continuous force feedback for the precision insertion control which requires even more delicate force and tactility than previously demanded. Consequently, a comparably large positioning error is allowable even in the case of unchamfered holes. This new algorithm is then field tested in the newly developed robots. In these robots the advantages of flexibility are incorporated in addition to the tactile functions. Lack of stiffness due to flexible construction has conventionally not been regarded as advantageous for machines from the common sense standpoint. However, utilizing this feature, new assembly robot control technologies have been successfully developed that function with agility approximating that of a skilled worker. This was realized from a comprehensive study of man's superior functions from a bioengineering standpoint.

II. General Principle

There are a lot of difficulties in the insert operation with regard to the relative positioning of two different objects. Even after successful positioning, difficulty still remains due to the fact that insertion sometimes becomes impossible. This is because of jamming which occurs as a result of the minimal clearance. Consequently, operations requiring micrometer level precision have been regarded as beyond the ability of conventional industrial robots or automatic assembling machines.

In insertion operations done by the human hand, the following actions are performed properly. The worker unconsciously performs a rough positioning between a hole and a shaft by sight, fits the tip of the shaft into the hole using the dexterity of the fingers and controls insertion by a delicate sense of touch.

There are three factors that are required for the insertion operation as shown in Fig. 1. The functions of these factors must be well-balanced. In the case of hand work, an inexperienced worker fails to properly combine a delicate sense of touch with the control function. This usually results in time consuming repetition, the so-called rubbing motion before insertion is effected. Skilled workers usually make good use of their dexterity and the delicate tactile senses of their fingers.

A schematic construction of the assembly robot system (HI-T-HAND Expert-2) is shown in Fig. 2. This robot is composed of a main robot, auxiliary robot, and parts supply devices. The auxiliary robot picks up the object with a hole from the parts supply device and secures it in the working position. The main robot picks up the shaft and performs the insertion operation.

The positioning mechanism of the main robot is driven by the step motors, one step corresponding to a rectilinear movement of 50 μm. This positioning mechanism and holding device (fingers)

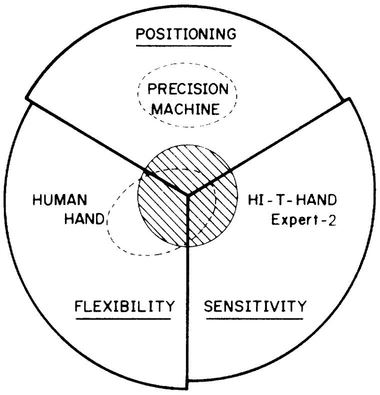

Fig. 1. Required functional factors for insertion operation.

are coupled through a flexible wrist construction using a cross type plate spring. The plate spring is fitted with four force sensors (strain gauges), which are capable of detecting relative displacement or inclination in triaxial (X, Y, Z) directions. Making use of these sensors and the flexible wrist, the relative positions of the shaft and the confronting hole are detected, and the insert operation is performed by correcting and controlling each center position and direction.

A schematic diagram of the controller is shown in Fig. 3. The instructions necessary for the insert operation are stored in a read-only memory (ROM), the same as for other grasping and carrying motions. The step motors for driving the positioning mechanism are controlled according to the specific algorithm shown in Table I.

Here a_{x1}, a_{x2}, a_{y1}, and a_{y2} are the output of the force sensors. $(a_{x1} - a_{x2})$ and $(a_{y1} - a_{y2})$ correspond to the X and Y direction displacements or inclinations, respectively. $2\Delta x$ and $2\Delta y$ are the predetermined widths of the dead zone where no correction of the positioning displacements is performed. These values are examined later. K_x and K_y are the effective spring constants of the flexible wrist in their respective directions (see nomenclature). The Z direction force signal is derived from the formula

$$f_z = |a_{x1}| + |a_{x2}| + |a_{y1}| + |a_{y2}|. \tag{1}$$

This signal is compared with the three predetermined threshold values f_{z1}, f_{z2}, and f_{z3}. The ordinary insertion force is controlled by a comparator having hysteresis between the lower level f_{z1} and the upper level f_{z2}. This hysteresis is useful for detecting the end of the search stage described later. f_{z3} is the critical level for detecting anything unusual. When the Z direction force signal f_z exceeds the f_{z3} level, the Z direction step motor is reversed to decrease the reaction force to the f_{z2} level.

$\pm X$, $\pm Y$, and $\pm Z$ in Table I mean to drive the positioning mechanism in the $\pm X$, $\pm Y$, or $\pm Z$ directions, respectively. Correction of the X and Y direction displacement is performed only under the conditions where $f_{z1} < f_z \leq f_{z2}$.

III. Mathematical Model

There have been some kinematic analyses of the rigid peg-in-hole insertion problem [3], [7]. However, it is now important to study the behavior of flexible mechanisms in insertion control. In order to briefly estimate some of the control parameters, a two-dimensional representation of the flexible mechanism and the shaft inserted into a hole is depicted in Fig. 4. Here, P_m represents the end effector of the positioning mechanism. The flexible mechanism is supposed to be composed of suspension springs in the X and Z directions. At the coupling point P_O, these springs are

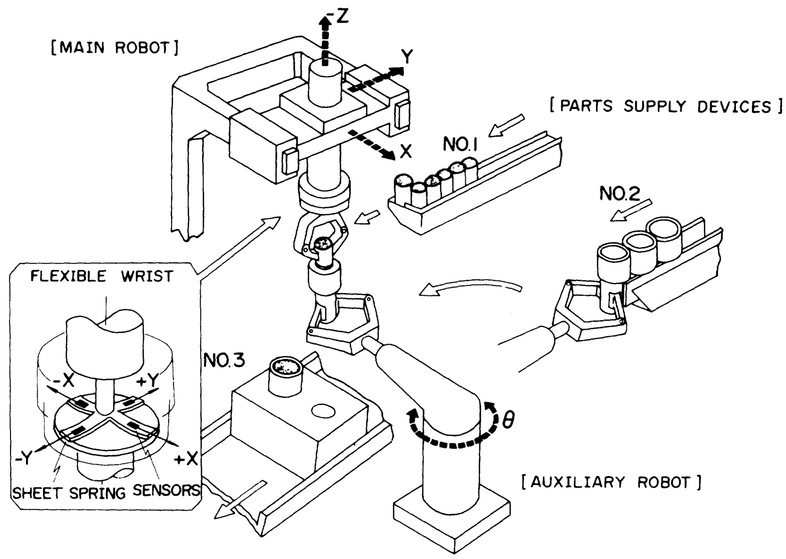

Fig. 2. Construction of "HI-T-HAND" Expert-2.

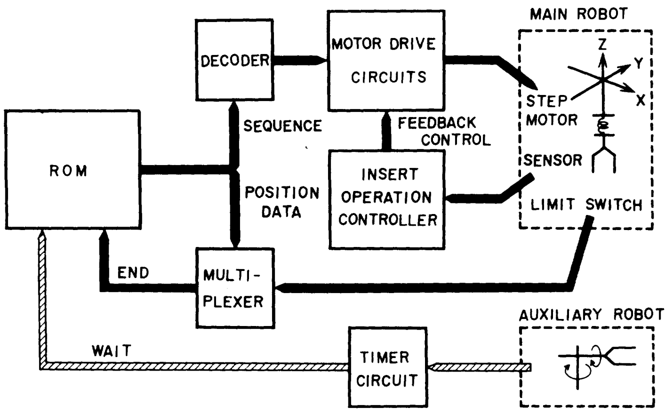

Fig. 3. Schematic diagram of controller.

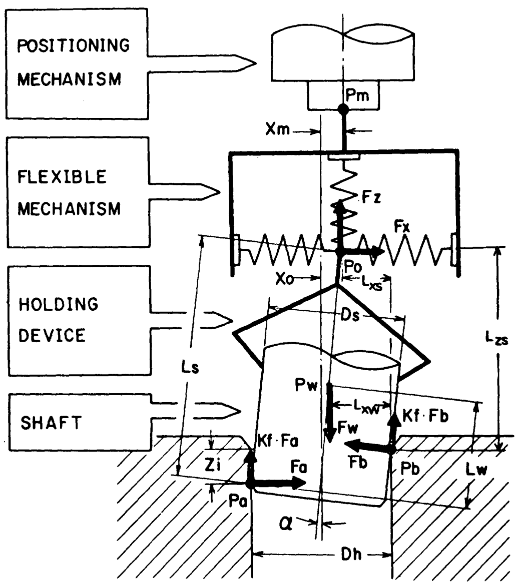

Fig. 4. Two-dimensional representation insertion operation.

TABLE I
CONTROL OF THE POSITIONING MECHANISM CORRESPONDING TO THE FORCE SENSOR PATTERN

SENSOR PATTERN	$f_z = \lvert a_{x1}\rvert + \lvert a_{x2}\rvert + \lvert a_{y1}\rvert + \lvert a_{y2}\rvert$			
	$f_z < f_{z1}$	$f_{z1} \leq f_z < f_{z2}$	$f_{z1} < f_z \leq f_{z2}$	$f_z \geq f_{z3}$
$\lvert a_{x1} - a_{x2}\rvert \leq K_x \cdot \Delta x$	Z	Z	STOP	-Z
$\lvert a_{y1} - a_{y2}\rvert \leq K_y \cdot \Delta y$	Z	Z	STOP	-Z
$\lvert a_{x1} - a_{x2}\rvert > K_x \cdot \Delta x$	Z	$\left[\frac{a_{x1} - a_{x2}}{\lvert a_{x1} - a_{x2}\rvert}\right] \cdot X$		-Z
$\lvert a_{y1} - a_{y2}\rvert > K_y \cdot \Delta y$	Z	$\left[\frac{a_{y1} - a_{y2}}{\lvert a_{y1} - a_{y2}\rvert}\right] \cdot Y$		-Z

connected to a holding device that grasps the shaft. P_W represents the center of gravity for both the shaft and holding device.

When point P_m has a relative positioning error X_m to the axis of the hole, the shaft is inclined at an angle α, so that

$$\alpha = \tan^{-1}\sqrt{Z_i^2 + D_h^2 - D_s^2}/D_s - \tan^{-1} Z_i/D_h$$
$$= \tan^{-1}\sqrt{(Z_{iD}^2 + 1)/(1 - K_c)^2 - 1} - \tan^{-1} Z_{iD}. \quad (2)$$

The reactive force F_x which acts on point P_O in the X direction can be written as

$$F_x = K_x\{X_m + D_h/2 - (D_s/2)\cos\alpha - L_s \sin\alpha\}$$
$$= K_x D_h\{X_{mD} + 0.5 - 0.5(1 - K_c)\cos\alpha - L_{sD}\sin\alpha\}. \quad (3)$$

The state of equilibrium in Fig. 4 is formulated as follows:

$$F_x + F_a = F_b(\cos\alpha - K_f \sin\alpha)$$
$$F_w - F_z - K_f F_a = F_b(K_f\cos\alpha + \sin\alpha) \quad (4)$$
$$L_{xs}F_z - L_{xw}F_w + L_{zs}F_x = (Z_i - K_f D_h)\cdot F_a$$

where

$$L_{xs} = D_h - (D_s/2)\cos\alpha - L_s\sin\alpha$$
$$L_{xw} = D_h - (D_s/2)\cos\alpha - L_w\sin\alpha \quad (5)$$
$$L_{zs} = L_s\cos\alpha - (D_s/2)\sin\alpha - Z_i.$$

Then F_{xc}, the critical value of F_x to prevent jamming, corresponding to the insertion depth, is calculated

$$F_{xc} = \frac{\{(Z_{iD} - K_f)/(K_f + Q) + L_{xsD}\}F_i + (L_{xwD} - L_{xsD})F_w}{Q(Z_{iD} - K_f)/(K_f + Q) + L_{zsD}} \quad (6)$$

where

$$F_i = F_w - F_z$$
$$Q = (\sin\alpha + K_f\cos\alpha)/(\cos\alpha - K_f\sin\alpha) \quad (7)$$
$$L_{xsD} = L_{xs}/D_h,\ L_{xwD} = L_{xw}/D_h,\ L_{zsD} = L_{zs}/D_h,$$

then, F_i determines the value of f_{z2} described earlier.

The X direction reactive force F_x given by (3) must be smaller than the value of F_{xc} for every insertion depth. Therefore, the maximum displacement tolerance corresponding to the insertion depth can be calculated by combining (3) and (6). For example, when $L_{sD} = 5$, $L_w/D_h = 2.5$, $K_f = 0.2$, $F_i/K_x D_h = 2.5$, $F_w/K_x D_h = 0.25$, and $K_c = 0.0005$, the normalized reactive force ($F_x/K_x D_h$), the critical value to prevent jamming ($F_{xc}/K_x D_h$) and the maximum displacement tolerance (X_{mDC}) for corresponding insertion depths are shown in Figs. 5 and 6. The maximum positioning error X_{mD} must be less than X_{mDC} corresponding to the respective insertion depth. Therefore, the positioning mechanism is controlled to make F_x smaller than F_{xc} by force feedback [2] or by a searching procedure [3].

Each expression and the theoretical results are utilized to briefly design and estimate the control parameters required for practical application as follows: when X_{mD} is decreased to the minimum value of X_{mDC} shown in Fig. 6, F_x is no longer larger than F_{xc} and there is no need to correct the positioning error X_{mD}. This minimum value of X_{mDC} restricts the maximum widths of the dead zone, Δx and Δy, described earlier. On the other hand, the maximum value of X_{mDC} restricts the maximum allowable displacement between the center of a hole and a shaft.

IV. Control Algorithm

Insertion control in the HI-T-HAND Expert-2 is divided into three stages as shown in Fig. 7.

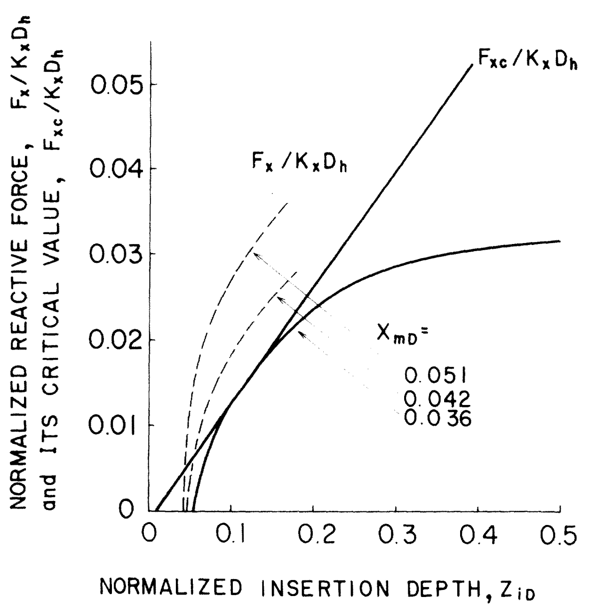

Fig. 5. Reactive force and its critical value to prevent jamming.

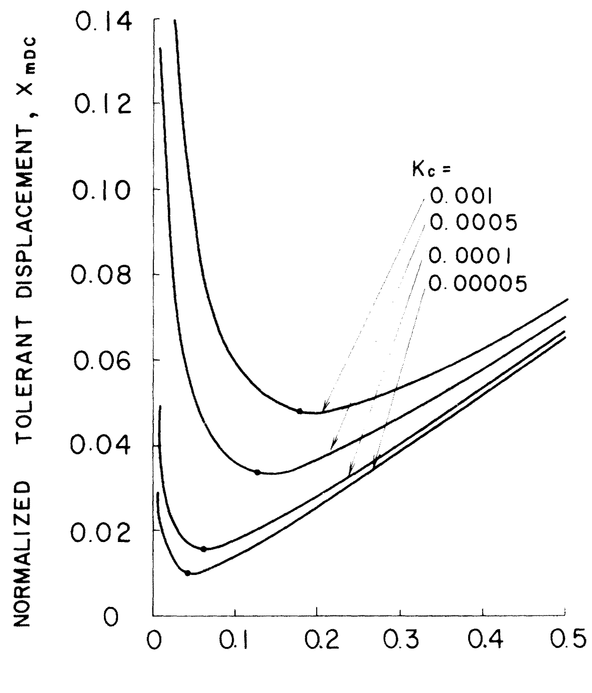

Fig. 6. Maximum tolerant displacement versus insertion depth.

1) Approach Stage

The shaft is brought down in the Z direction to the specified position out of the range of the distribution of anticipated relative error positions between the shaft and the confronting hole, and pushed with a specified force ($f_z = f_{z2}$). Contact thus made at a shifted position facilitates the confirmation of the positioning of the shaft and the confronting hole. First of all, the direction in which the shaft is to be moved so as to find a hole is uniquely determined. The second feature resides in the fact that the process, for detecting whether the shaft is inserted into the hole directly or not, may be eliminated because it is clear that the shaft is never inserted into the hole at this stage.

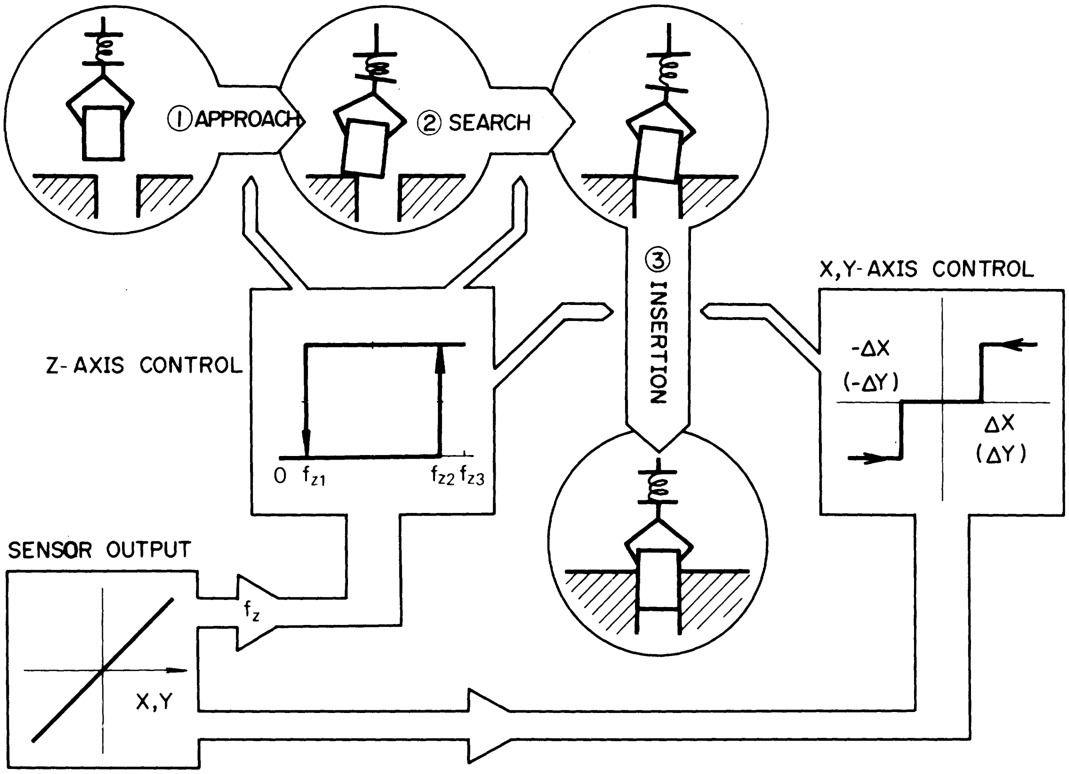

Fig. 7. Control algorithm of insertion operation.

2) Search Stage

The shaft pressed in the approach stage is moved rectilinearly toward the center of the confronting hole. Then the shaft is slanted by the flexible wrist. Although the Z direction reaction force varies due to surface roughness, the output of the hysteresis curve remains constant during this search stage as shown in Fig. 7. ($f_{z1} < f_z \leq f_{z2}$) when the shaft tip approaches the hole edge, the spring works to push it into the hole. This can be detected by a sudden change in Z direction reaction force ($f_z < f_{z1}$). At this point the search stage comes to an end. Searching is accomplished even if the center of the hole is shifted at a maximum of ± 2 mm in the X and Y directions in the case of a 20 mm diameter shaft.

3) Insertion Stage (Method of Force Feedback)

When positioning is finished by the procedure in stage 2), the shaft remains slanted in the X and Y directions against the Z axis.

Insertion is made in the Z direction, correcting the axial direction of the shaft according to the algorithm shown in Table I. If insertion is made under conditions where axial correction is incomplete, jamming will occur making insertion impossible. Therefore, the pushing force in the Z direction must be controlled within specified limits ($f_{z1} < f_z \leq f_{z2}$).

The output of each sensor during the insert operation is shown in Fig. 8. When procedure 1) is completed with the movement in the Z direction and the pushing force in the Z direction reaches the specified value, procedure 2) is begun. The shaft is moved in the direction of the Y axis and the searching motion is continued until the Z-direction reaction force undergoes a sudden change.

In procedure 3), corrections are made on both the X and Y axes. Insertion is made in the Z direction under conditions where the shaft and the hole axes are aligned. When the positioning mechanism displacement is within the tolerable displacement value of X_{mDC} given in Section III, no further correction is required. The dead zones of the X and Y axis controls are valid in this condition as shown in Fig. 7. Even if the edge of the hole is not chamfered, the insertion operation with a clearance of 10 μm is also attainable.

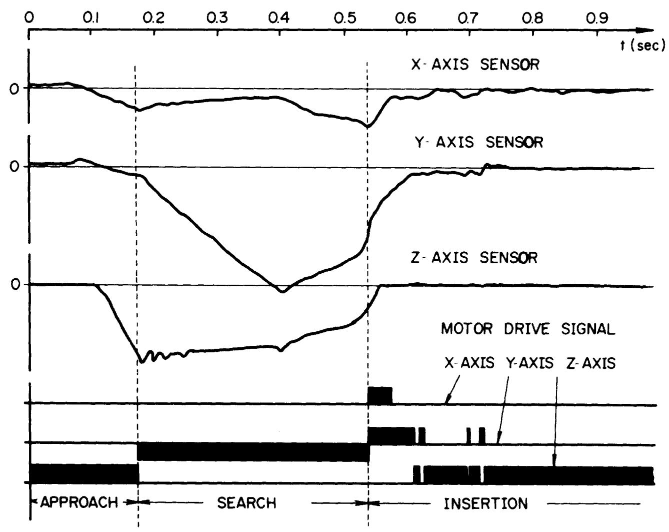

Fig. 8. Typical example of insertion operation.

Although the searching time for procedures 1) and 2) depends on the anticipated distribution of relative positioning errors, the robot completes the operation in almost a constant time, regardless of the clearance dimensions [2]. For instance, when the amount of initial error is ± 2 mm the mean and standard deviations in operation time of HI-T-HAND Expert-2 are 1.07 s and 0.07 s, respectively.

TABLE II
TYPICAL SPECIFICATIONS OF THE INSERTION OPERATION AND PERFORMANCE OF THE ROBOTS

ITEMS \ ROBOT		Expert-2	Expert-6
DIMENSIONS OF PARTS	DIAMETER	20 (mm)	72 (mm)
	CLEARANCE	10 ~ 20 (μm)	3 ~ 10 (μm)
	CLEARANCE RATIO	5×10^{-4}	5×10^{-5}
	WEIGHT	50, 150 (g)	2 (Kg)
ALLOWABLE POSITIONING ERROR		± 2 (mm)	± 3.5 (mm)
OPERATION TIME $\bar{t}$, σ		1.07, 0.07 (s)	4.5, 0.47 (s)
ADDITIONAL FUNCTION		REJECTION	PRESSING

V. ASSEMBLING OPERATIONS

1) *HI-T-HAND Expert-2*

The HI-T-HAND Expert-2 can assemble three kind of parts in sequence. First, the main and auxiliary robots pick up parts No. 1 and No. 2 from the parts supply devices, respectively, and perform the insert operation in the working position. After this first assembly operation is completed, the auxiliary robot hands the assembled object parts No. 1 and No. 2 to the main robot.

Next, the main robot inserts this object into a hole in part No. 3 which is then placed on a pallet conveyor. Repeating these first and second assembly operations, the HI-T-HAND Expert-2 continue to assemble the products composed of three different parts.

Moreover, as variations in the ordinary operation time are so small that misoperation can be detected by watching the operation time. When the operation time exceeds the predetermined value, both robots reject these parts into containers for abnormal parts.

The typical specifications of the insertion operation of these robots are shown in Table II.

2) *HI-T-HAND Expert-6 (Electric Motor Assembly)*

This technology has been successfully applied to the assembling of an electric motor. The operation performed is the fitting of an end-bracket (collar) on the ball-bearing attached to a rotor shaft as shown in Fig. 9. In this case the shaft has one or more step portions. In order to achieve this assembly, control circuits are provided for controlling the positioning mechanism in response to programmed demand data. This demand data is coordinated with signals derived from the force sensors so that displacement or deflection may be eliminated. As a result the collar can be placed on the shaft having a complicated shape.

First, the center of the collar is placed approximately in line with the center of the shaft. The collar is then moved down in the Z direction on the shaft by the positioning mechanism until the top of the shaft pass through the collar. The clearance between the top of the shaft and the collar $(D_{h1} - D_{s1})$ is sufficiently wide ($\simeq$ 4 mm) so that the X-Y positioning mechanism may correct collar position using the point-to-point positioning mode. When the center of the collar is placed at position P_0, for instance, the Z direction reaction force signal detects the contact state. Then the positioning mechanism raises the collar until the collar is not in contact with the top of the shaft. Next, the X-Y positioning

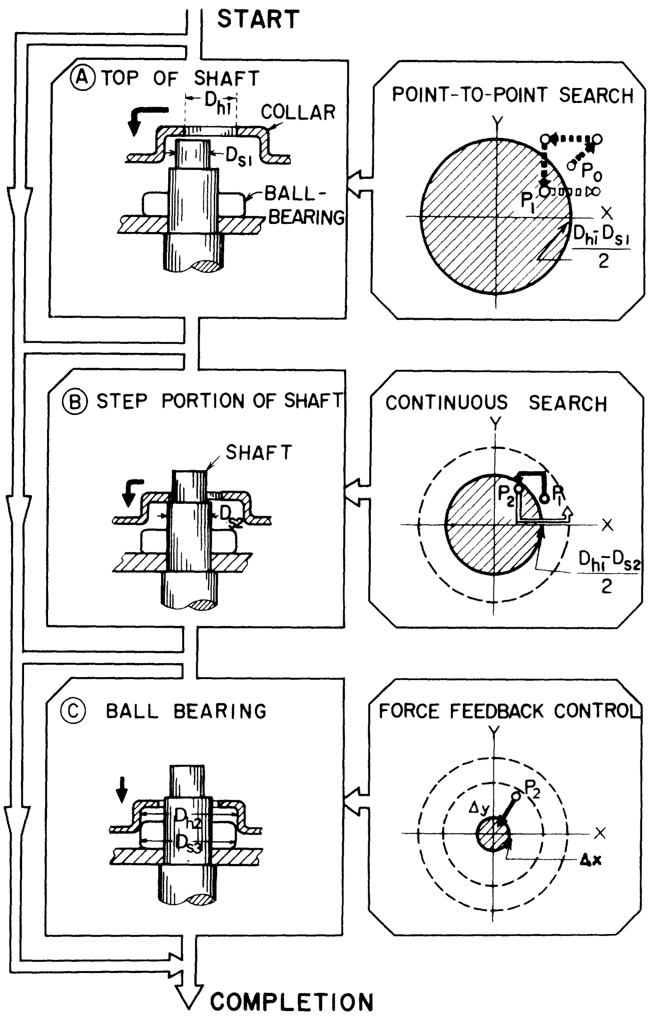

Fig. 9. Multistep insertion control process for electric motor assembly.

mechanism moves the collar in accordance with a point-to-point programmed search pattern as shown in Fig. 9(A). This pattern is stored in the ROM of the controller. The fitting operation is repeatedly attempted at each position of the search pattern until fitting is accomplished at position P_1.

In the second step, when the Z direction reaction force signal detects resistance due to the step portion of the shaft, the X-Y

positioning mechanism moves the collar continuously to cope with the rather tight clearance, $(D_{h1} - D_{s2})$ ($\simeq 2$ mm) in accordance with a programmed search pattern. This is continued until fitting is accomplished at position P_2, as shown in Fig. 9(B). In the third step, the collar is fitted on the ball bearing both with 2 mm chamfers. The bearing and collar only have a clearance, $(D_{h2} - D_{s3})$ of $3 \sim 10$ μm. In this step, the positioning mechanism is controlled by the force feedback mode until the X and Y direction displacements are decreased to within the specified values of Δx and Δy, as shown in Fig. 9(C). This mode is the same as the one described in Section II earlier.

Moreover, during this operation, the guide pins of the holding device (gripper) are fitted into the screw holes of the stator housing. As a result, both the screw holes of the end-bracket and stator housing are precisely matched. Finally, at the end of the insertion operation, the end-bracket is released from the gripper and pressed until settled simultaneously. A photograph of this robot during the collar fitting operation is shown in Fig. 10.

The time taken for the search operation is dependent on the distribution of relative positioning errors. However the insertion times for the second and the third steps are almost the same as when no positioning error is experienced. The typical specifications of the HI-T-HAND Expert-6 for the insertion operation are included in Table II.

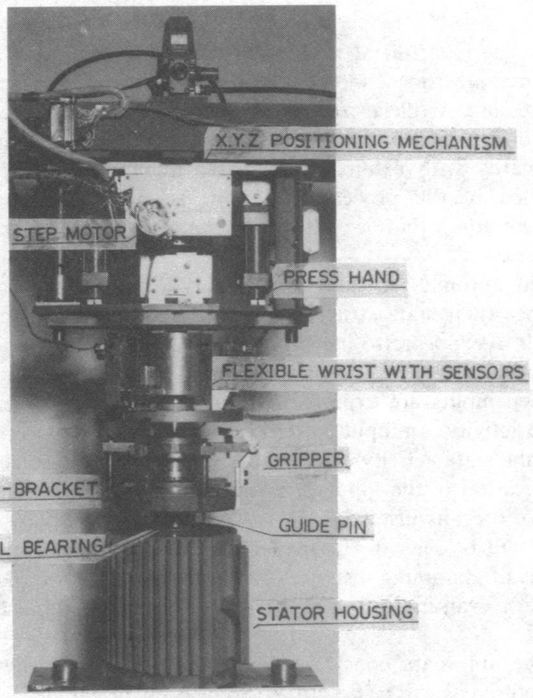

Fig. 10. The electric motor assembling robot.

VI. Conclusion

The development and application of precision insertion robots, "HI-T-HAND" Expert-2 and Expert-6 have been discussed. The prominent features of these robots are the effective use of flexible mechanisms and a simple skillful control algorithm for locating the hole position and for insertion by force feedback even in the case of unchamfered holes.

Theoretical study clarified the notable usefulness of the flexible mechanism in the precision insertion operation. In addition, the maximum tolerant displacement of the positioning mechanism has been calculated.

The use of a sequence controller has made it possible to perform the functions which require a certain degree of skill, even in the case of human operations. This technology has been successfully applied to the assembly of an electric motor. The robot used is capable of multistep insertion operations for parts with a clearance of only $3 \sim 10$ μm.

Nomenclature

- D_h Hole diameter.
- D_s Shaft diameter.
- L_s Effective shaft length, $L_{sD} = L_s/D_h$.
- Z_i Insertion depth, $Z_{iD} = Z_i/D_h$.
- X_m Positioning error of the end effector, $X_{mD} = X_m/D_h$.
- F_x Reactive force in the X direction.
- F_z Reactive force in the Z direction.
- F_w Gravity force of the shaft and holding device.
- F_i Insertion pressure.
- K_c Clearance to diameter ratio $(D_h - D_s)/D_h$.
- K_x Spring constant in the X direction.
- K_f Friction coefficient.
- α Relative inclination of the shaft.

Acknowledgment

The authors are grateful to K. Enomoto of the Narashino Works and T. Tokunaga of the Taga Works, Hitachi, Ltd. for their extensive cooperation during the development and application of these robots.

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Artificial Perception in Adaptive Arrays

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***Abstract*—Arrays of random-access memories (RAM's) are trained to form internal state images of simple externally applied images. It is shown that such arrays are capable of developing a discriminative property which is defined as "artificial perception" in the sense that they enter cycles relatively rapidly (these cycles are closely related to the prototype training images), while unseen inputs lead to instability and unrelated images.**

Manuscript received July 18, 1978; revised May 22, 1979 and September 28, 1979. This work was supported under a U.K. Science Research Council Grant B/RG/8869.

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0018-9472/80/0100-0025$00.75 © 1980 IEEE