Proceedings of the 11th
KACC, October 1996

3-DOF Automatic Printed Board Positioning System Using Impact Drive Mechanism

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Abstract There is a tendency nowadays to produce increasingly miniaturized electronic equipment which incorporate parts that have to be precisely positioned, like lenses, heads and CCD's in scanners, printers, copiers, VCR's, optical fiber modules, etc.

In contrast to the production process of precision parts, which is currently being carried out automatically, the assemblage process is still being performed by specially skilled technicians. The assemblage process comprises normally the following steps: firstly, the parts are roughly positioned and partially fixed, secondly, the parts are manually nudged towards the target position and finally glued, screwed or welded.

This paper presents a system that uses six piezo Impact Drive Mechanisms for accurate micro positioning within three degrees of freedom (lateral and longitudinal translation and rotation). The system is designed to positioning a printed circuit board with an accuracy better than 3 μm (for translations), 5 mrad (for rotation).

Keywords Piezo Electric Elements, Impact Mechanism, Precise Positioning, Adaptive Control, Image Processing

1. INTRODUCTION

Today, to manipulate an object most robots make use of the so called "pick and place" method, which consists of grasping an object, move it to the desired position and then release it.

By looking at human beings we can see that it is sometimes preferable to push an object rather than to lift it. In fact, this is the common way particularly for heavy objects or when the moving distances are very small. We adopt this idea for the design of an automatic precision positioning system, for the manipulation of printed circuit boards in three degrees of freedom (lateral and longitudinal translation and rotation). The board is kept partially fixed by the force of four springs that push Teflon washers against it. Six impact actuators distributed along its circumference are then able to move the board to the desired position. In the end of the positioning process the board is firmly screwed or bonded. This approach makes possible to assembly a part accurately without using extra parts or devices attached to the side of the object to move.

These kind of actuators combine the dry friction with the impulsive force created by a piezoelectric element to generate the movement. Unlike the common piezo actuators, they are not limited in stroke, hence, they can be used in the nano- to millimeter range. This advantage, in addition to their simple structure, makes them highly suitable for micro actuators.

In contrast to the common micro stages which generate a flat output force pattern, the impact drive actuators produce a thrust force that is much more effective to move tighten objects. Another advantage of these actuators is that the mechanical support structure can be lighter than the one necessary for a micro-stage, which results in more compact systems.

In the following section we will present a short review of related work, the principle of the Impact Drive Mechanism (IDM) actuator and its experimental motion characteristics. In section 3 and 4 we will describe the experimental setup and the adopted feedback control strategy. We close this paper with some conclusions.

1.1. Related Work

The problem of making an object slide to a desired position has been little explored.

In 1985, Higuchi presented the first experimental application of the pushing method. In his work an electromagnetic coil is used to deliver impulses to an object in order to obtain micro positioning [1].

Later on, using piezoelectric elements instead of the electromagnetic coils, other applications have been reported [2].

Huang et al. [3] analyses the problem of how to strike the object and the initial velocity required to make it reach a desired configuration. Considerations about the controllability of the pushing technique can be found in [4].

2. PIEZO IMPACT ACTUATORS

Piezotranslator units are becoming increasingly important in positioning technology. The advantages of these elements can be summed up as: very fast response, large force output (up to 5 tons), high efficiency (no energy is absorbed to maintain the expansion) and resolutions up to nm range can be achieved.

The main disadvantage is that the stroke is limited to a few hundred micrometers making them useless for many positioning applications. Various solutions have been presented to solve this problem among them, the mechanical amplification and the inchworm mechanism are most notable.

For our application the solution for the problem of limited stroke is sought in the combination of fast contraction or expansion of a low voltage piezoelectric element with the friction force. The resulting mechanism, termed as Impact Drive, can move in a plane, forward or backward, by employing solely one piezo and without the need of any additional devices. The direction of the movement and the step size depend on the applied voltage pattern.

The mechanism consists of three elements: the main body, a piezoelectric element and a weight.

The motion is carried out according to the following steps, as illustrated in Fig. 1:

a) from the stationary position, a rapid expansion of the piezoelectric element is performed causing the movement of the main body against the friction force;
b) subsequently, the piezo contracts slowly such that the resulting reaction force does not exceed the static friction and therefore causes the main body to remain in its prior position;
c) an abrupt termination of the contraction may cause the main body to move an additional step.

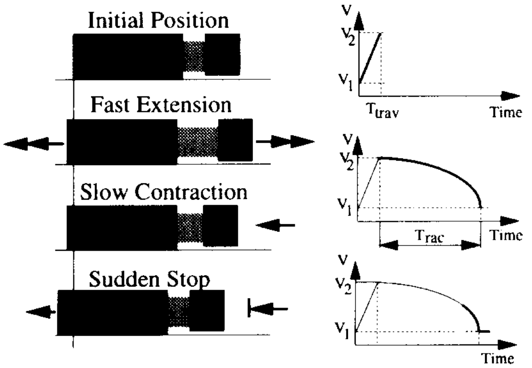

Fig. 1. Operation procedure of the Impact Drive Mechanism

The value of the masses, the friction force, the piezo characteristics and its dimensions define the step size ranging from nano- to micrometer.

In order to move in the opposite direction, it is necessary to perform a fast contraction after a slow extension, instead of a slow contraction after a fast extension.

The voltage waveform supplied to the piezos is composed of two phases which are characterized by the following parameters:

-Ttrav which denotes the time that the main body moves as a direct result of a fast expansion/compression;

-Trac, which is the time required for the piezo to recover its original shape.

Figure 2 depicts the measured forward movement of one of these actuators. The waveform parameters are listed in the Table I, while Table II shows the piezo electric element characteristics.

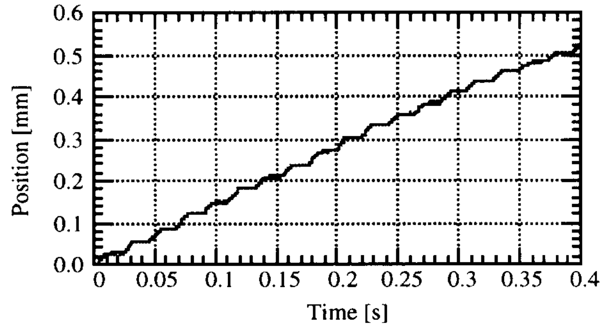

Fig. 2. Forward movement of one actuator without external load

Table I. Waveform parameters

Period	21.3	T [ms]
Traverse time	50	Ttrav[μs]
Acceleration Time	1.4	Trac [ms]
Lower Voltage	10	V_1 [V]
Higher Voltage	140	V_2 [V]

Table II. Piezo characteristics

Resonance frequency	9±3	kHz
Maximum extension	36±6	μm
Capacitance	3.8±20%	μF

2.1. Actuators Parameters

The step size can be controlled by various methods. The first method is to control the amount of the fast expansion/compression on the basis of the applied voltage. By keeping V_1 fixed, this corresponds to vary V_2 as desired. The other methods are based on controlling the time T_{rac} for the slow compression/expansion phase and changing the load. The last one is in our case defined by the springs that clamp the board. Hereafter we will analyze each of these methods.

2.1.1. Relation between voltage and step size

The expansion of the piezo, and consequently the step size of the IDM, is approximately linear with the applied voltage. Figure 3 shows the forward movement of the piezo without external load as a function of V_2. According to the results, the step size can be varied between approximately 1 μm and 27 μm for voltage magnitudes up to 145 V.

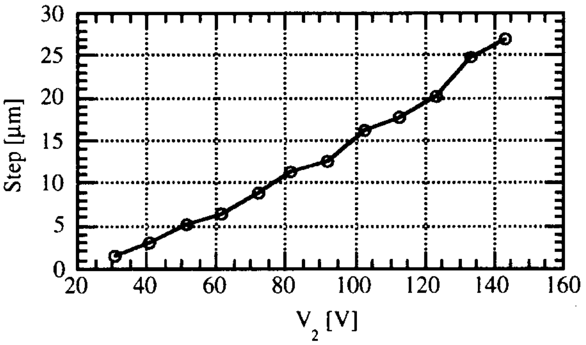

Fig. 3. Relation between applied voltage and step size

2.1.2. Relation between the Trac and step size

The slow compression of the piezo is defined by the nonlinear equation (1):

$$\Delta V = \frac{1}{2} R_{ac} \cdot T_{rac}^{2} \qquad (1)$$

where ΔV is the voltage difference and R_{ac} is the *acceleration* parameter.

By imposing a sudden stop at the end of the slow contraction an additional displacement will occur. This effect is maximized for values of R_{ac} of about 7×10^7 V/s² (T_{rac}=1.9 ms). For lower values of R_{ac} (T_{rac} high), the impact is smaller and therefore the displacement as well. For higher values of R_{ac} a decrease in step size takes place as can be observed in Fig. 4.

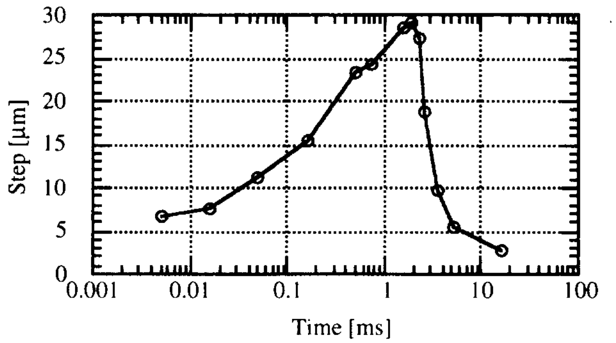

Fig. 4. Relation between Ttrac and step size

The explanation for this decrease lies in the fact that the inertial force, which is generated during the return of the weight, exceeds the friction force causing the main body to be returned in the direction opposite to the advancing direction. In order to increase the friction force and hence decrease the time Trac, a spring is placed such that its force is added to the weight.

Mathematically we can write:

$$F = m_w \cdot a \tag{2}$$

$$f_a = \mu \cdot (mg + N) \tag{3}$$

where F denotes the reaction force, m_w represents the mass of the weight, a is the acceleration, f_a denotes the friction force, μ is the friction coefficient, m denotes the total mass, g is the gravitational constant and N a spring force (used to increase the friction).

To make efficient use of the mechanism the following inequality should be obeyed:

$$F \leq f_a \tag{4}$$

The relation between the parameter R_{ac} and the acceleration a is given by:

$$R_{ac} = \frac{a}{\Delta l} \times \Delta V \tag{5}$$

where Δl is the piezo elongation.
Using (2), (3) and (5), we can rewrite (4) as:

$$R_{ac} \leq \frac{\Delta V \cdot \mu(mg + N)}{\Delta l \cdot m_w} \tag{6}$$

2.1.3. Relation between the load and the step size

Keeping constant the above refereed parameters V_2 and T_{rac} and changing solely the pre-tension of the springs that clamp the board, i. e., the holding friction, the step size will also change accordingly. Fig. 5 shows the experimental relation between the holding friction force and the resulting step size.

This effect can be used to get a better positioning resolution (small steps). However should be notice that by increasing the resolution the time necessary for positioning also increases.

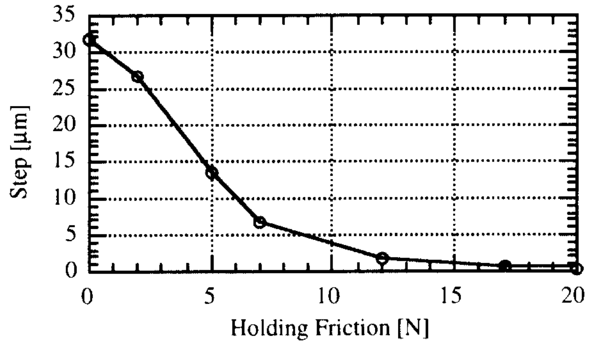

Fig. 5. Actuator step size for variable holding friction force

3. EXPERIMENTAL SETUP

Figure 6 depicts a system overview of the proposed precision positioning system. The object to be moved is a printed circuit board with the dimensions of 100x150x1.6 mm and a mass of 74g to which a target with the size of 1.4x1 mm is attached. The friction force acting on the board is adjusted by four springs that loosely clamp it. The piezo actuators are positioned along the circumference of the board, each having a stroke of ±2 mm and the dimensions of 115 (length) x 40 (width) x 45(high) mm.

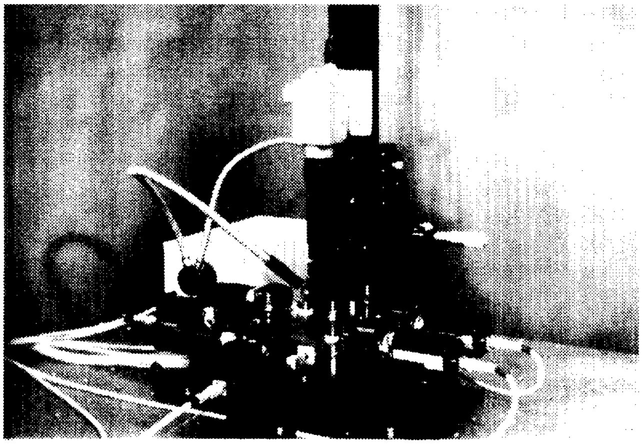

Fig. 6. System overview

A CCD camera (620x480 pixels) which serves as a feedback positioning sensor is mounted above the board. The visible area measures about 3.42x4.68 mm, and the displacement resolution is 8.95 µm per pixel. The image is processed by a stand-alone unit - NAIS B110P (Fig. 7) which evaluates the target center coordinates (X, Y, θ). The image can be processed in both, binary mode and gray level mode. The binary mode is faster, however, its resolution is equal to the pixel size, while in gray mode the resolution is 0.1 pixel. Three gap sensors are also installed to increase the position resolution measurements up to 0.5 µm.

To drive the IDM we use an amplifier that converts the waveform signal, between 0-7 V, coming from the computer, to an output of 0-140V with a maximum current of 20A.

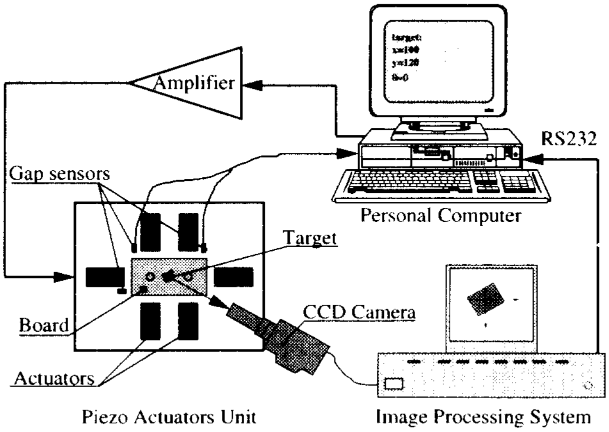

Fig. 7. System components and interconnections

The control is based on personal computer equipped with analog and digital I/O data acquisition boards.

From the errors between the target and desired position the computer selects the actuators to be moved and calculates the number of cycles to generate.

4. CONTROL ALGORITHM

Similarly to the common industrial precision assemblage process, the positioning task is executed according to the following steps: firstly, the board is partially fixed using springs, secondly, it is nudged towards the desired position and finally screwed, tightened or glued.

The control process is divided in three phases:

I. Initialization

Because the initial position of every actuator is unknown, it is necessary to initialize them to a known position by moving all actuators to the position that they touch the board (this state is detected through the micro-switches installed at their extremities).

This is followed by the evaluation of the board's position and corresponding error vector $\varepsilon=[\varepsilon_x, \varepsilon_y, \varepsilon_\theta]^T$.

II. Initial Positioning

Suppose that the step movement induced by each actuator along each axis and rotation are denoted by the elements of the vector $P=[P_{ix}, P_{iy}, P_{i\theta}]^T$ where *i* is an integer from 1 to 6 representing the actuator number.

A new position N, after a certain number of pulses T has been applied to the actuator, can then be computed using:

$$N = P \times T \tag{7}$$

The inverse problem, i.e., how to calculate the minimum number of pulses **T** that result in a movement of the actuator equal to the position error ε of the board, is solved through:

$$\text{minimize} \quad \sum_{i=1}^{6} t_i \tag{8}$$

subject to:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_\theta \end{bmatrix} = \begin{bmatrix} P_{1x} & P_{2x} & P_{3x} & P_{4x} & P_{5x} & P_{6x} \\ P_{1y} & P_{2y} & P_{3y} & P_{4y} & P_{5y} & P_{6y} \\ P_{1\theta} & P_{2\theta} & P_{3\theta} & P_{4\theta} & P_{5\theta} & P_{6\theta} \end{bmatrix} \times \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \end{bmatrix} \tag{9}$$

with $t_i \geq 0$, i=1, 2,......, 6

This is a typical linear programming problem, that can be solved using the normal techniques of optimization. The above minimization problem is simplified due to the fact that the board can be moved only by pushing and not by pulling. This implies that only three of the actuators will be responsible for the board's movement, so that three elements of the vector $[t_1, t_2, t_3, t_4, t_5, t_6]$ will be zero while the others will be positive.

Suppose that $t_i \neq 0$ for i=1, 2, 3 and $t_i = 0$ for i = 4, 5, 6 then (9) can be rewritten as:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_\theta \end{bmatrix} = t_1 \begin{bmatrix} P_{1x} \\ P_{1y} \\ P_{1\theta} \end{bmatrix} + t_2 \begin{bmatrix} P_{2x} \\ P_{2y} \\ P_{2\theta} \end{bmatrix} + t_3 \begin{bmatrix} P_{3x} \\ P_{3y} \\ P_{3\theta} \end{bmatrix} \tag{10}$$

By solving the above system of linear equations, we obtain the coefficients t_1, t_2 and t_3. The actuators #4, #5 and #6 will not remain in the same position, but instead they will be pushed by actuators #1, #2 and #3 . In order to improve the board's speed, the actuators #4, #5 and #6 will be moved prior to activation of actuators #1, #2 and #3 such that they do not present any additional load to the latter. The speed improvement can be a factor of 10 or more.

III. Positioning

During this phase the deactivated actuators will not move back as before, but instead, they will be pushed back by the others together with the board, which increases the load and therefore the positioning resolution.

The image is still being processed in binary mode until the board reaches the threshold defined by the user. From that moment two changes will occur: the image is started to be processed in gray level and the adaptive control is activated. The adaptive control keeps the system more stable by updating the actuators step size **P** and allows a more precise positioning.

A simplified block diagram of the control system is presented in Fig. 8.

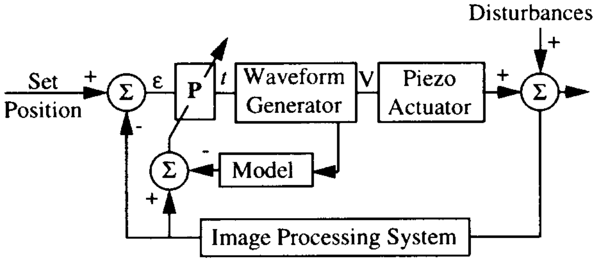

Fig. 8. Block diagram of the implemented adaptive control

Variations in the friction force are the main cause of the disturbances that appear particularly during this phase.

With this control procedure it is possible to position within an error bound of 3 μm for the translations X and Y, and 5 mrad for the rotation θ in about 10 to 15 control cycles.

To increase the positioning precision further, the parameters V_2 or R_{ac} have to be used as control variables in the control system. However, in this case the positioning speed will be reduced.

5. CONCLUSIONS

A device for three degrees of freedom precision positioning of printed circuit boards using the impact drive mechanism and a closed-loop feedback system has been presented. The impact drive mechanism utilizes the impact force of piezoelectric elements and the dry friction to produce the movement. These actuators combine the ability of minute motion, which is a characteristic of common piezo translators, with an unlimited stroke and simple design, making them an interesting choice for many precision applications. A CCD camera based image processing system provides together with gap-sensors the sensory information for position feedback. To achieve a better control performance an adaptive control strategy is adopted. Using this strategy it is possible to position the board within an error bound of 3 μm for the translations X and Y, and 5 mrad for the rotation θ in about 10 to 15 cycles.

Acknowledgments

The authors thanks to M. Munekata, S. Matsuno and H.Ishikawa from Chichiba Onoda company, for their cooperation in this project.

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