TREND OF PRECISION POSITIONING TECHNOLOGY

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Abstract *- This paper describes recent precision positioning technology. First, recent precision positioning mechanisms are introduced. Although ball screw mechanisms are widely used in industrial machines, the use of linear motors and the development of planar motors recently increase. Several linear motor mechanisms show the acceleration higher than 10G. The linear motor mechanism developed in my group can move at the higher acceleration than 101G. Next the control methods for precision systems are explained. In many precision positioning systems, it is very important to overcome friction problems. For conventional positioning systems with friction, a practical control named NCTF(nominal characteristic trajectory following) control is introduced. Finally, the self-alignment method using liquid surface tension is introduced as a simple and practical method for self-assembly of microparts..*

Key words*: precision positioning, precision positioning mechanism, control, friction, linear motor, planar motor, microsystem, self-assembly, self-alignment, surface tension*

1. Introduction

Precision positioning systems are fundamental components in industrial machines such as machine tools, measuring machines and semiconductor manufacturing systems. The performances of the machines depend on the positioning systems. Figure 1 shows the change of average accuracy that the word “precision positioning” is considered to indicate. This figure is based on the result of questionnaire survey by JSPE (Oiwa and Katsuki, 2003). The average accuracy of “precision positioning” is better than 1μm from 1990. Many responses to the questionnaire survey about “precision positioning” accuracy are between 0.1μm and 10μm. The difference between precision positioning and normal one is not officially defined. However many researchers studying in the field of precision positioning recognize that precision positioning systems are expected to have the accuracy and/or resolution better than 10μm. “Ultra-precision positioning” systems are often desired to have the accuracy and/or resolution better than 10nm.

Precision positioning systems need to have not only high positioning accuracy and/or resolution but also high acceleration and high velocity. The required acceleration and velocity increase year by year. Figure 2 shows the desired acceleration and velocity in precision positioning systems (Oiwa and Katsuki, 2003). The increasing tendency is remarkable. Many precision positioning systems need to have the acceleration higher than 1G and the velocity higher than 500mm/s. On the market, there are many precision positioning systems which have the ability to move at the higher acceleration and the higher velocity than the required values. The system performances are greatly influenced by the characteristics of mechanisms including actuators, power transmissions and bearings. Thus the improvements of their characteristics are fundamentally important. The role of the controller is to overcome the remaining mechanical problems and to utilize their characteristics for high positioning performance. The importance of the controller increases when the desired system performance is higher and the characteristic of the mechanism is not good enough for precision positioning.

In practical use, the simplicity of the system and the ease to design and understand its controller are also important. Machine elements used in precision positioning systems often have the characteristics that deteriorate their positioning performances, for example, the friction which makes static deviation and low stiffness which causes the vibration.

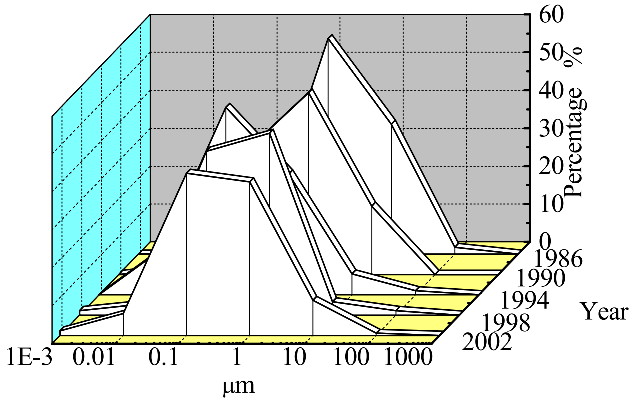


Figure 1. Change of average accuracy that the word “precision positioning” is considered to indicate

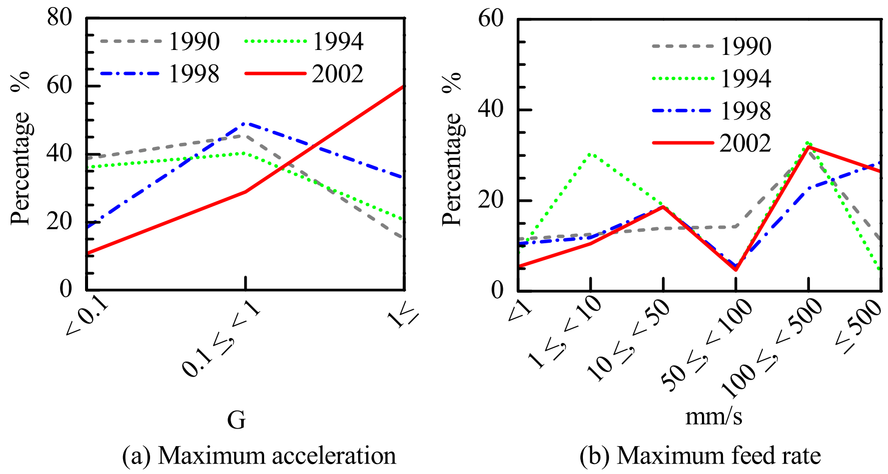


Figure 2. Distribution of specification of precision positioning system

The complexity of the positioning systems and the difficulty to understand their controller make the system maintenance and adjustment difficult. These grades influence the practical system design. Miniaturization of industrial machines is recently one of the important subjects in precision systems. For the subject, the high grades of these characteristics are useful.

This paper describes recent precision positioning technology. First, recent precision positioning mechanisms are shown. Next the control methods for precision positioning systems are explained. In many precision positioning systems, it is very important to overcome friction problems. For conventional positioning systems with friction, a practical control named NCTF(nominal characteristic trajectory following) control is introduced. Finally, the self-alignment method using liquid surface tension is introduced as a simple and practical method for self-assembly of microparts.

2. Precision positioning mechanism

2. 1 Trend of precision positioning mechanism

In precision positioning systems with a long working range, lead screws are widely used as a part of a driving unit. Especially, ball screws are most often used with linear ball/roller bearings. These type mechanisms are built in the high speed measuring machine which can move at 1.8G and at 1.8m/s (Mitutoyo Co., 1998). Some machine tools have twin ball screw driving units for large thrust and high acceleration. Basically, ball screw mechanisms have higher robustness to disturbance force than linear motor ones (Horiuchi, 2001). However, the positioning mechanisms comprising electromagnetic linear motors are increasing as desired acceleration and velocity increase.

The use of the linear motor reduces the number of the machine elements that make the system stiffness low and cause the vibration. Because many positioning mechanisms include machine elements having mechanical contact such as ball bearings, solving the friction problem is a very important subject in precision positioning. Effective and fundamental solution is to use non-contact elements. In an ultra-precision machine tool and semiconductor manufacturing systems, linear motors (Wakui, 2001; Fukuda, 1998; Takeuchi and Hirano, 2003) and aerostatic bearing lead screws (Sawada, 2004) as driving units and aerostatic bearings are used so that the system are completely free from friction. The planar motors can have lighter driving weight and fewer machine elements than stacked type of multi-degree-of-freedom systems using single-degree-of-freedom linear motors. They are suitable for high speed and high precision positioning systems. Recently planar motors have been being studied as next generation ultra-precision precision systems(For example, Shinno et al., 2004; Teng et al., 2004; Gao et al., 2004; Tomita et al., 1994; Wang, 2000).

Fine mechanisms comprising piezoelectric actuators and elastic hinges are also free from friction and suitable for precision positioning systems with a short working range. This kind of mechanism is often used as an auxiliary unit for improvement of the characteristic of the mechanism with a long working range. Fast tool servos which control the tool tip motion (For example, Woronko and Altintas, 2003; Woody and Smith, 2004; Kim et al., 2004) are one of the units and built in conventional machine tools so as to improve their machining accuracy. The units with a piezoelectric actuator are also used in the mechanisms with friction for ultra-precision and high speed positioning (For example, Sato and Shimokohbe, 1997; Nakashima, 2001; Sato et al., 2000; Shimokohbe et al., 1997; Okazaki et al., 2004; Takeda et al., 2002). The lead screw mechanisms including the piezoelectric actuator drive units between the nuts have the ability to control the backlash for friction and stiffness adjustments and to precisely compensate positioning error (Sato and Shimokohbe, 1997; Nakashima, 2001).

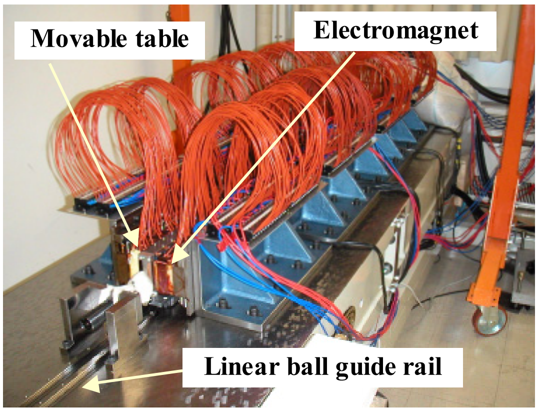


Figure 3. Experimental ultrahigh acceleration and high speed linear motor mechanism

Using the piezoelectric actuators, high accurate and high stiffness bearings have been developed (For example, Tomita et al., 1994; Mizumoto et al., 2004; Sato et al., 1996; Park et al., 2004). Electromagnetic actuators can play the same roles as the piezoelectric actuators (For example, Hashizume and Shinno, 2001; Yoshimoto, 2004; Lee and Gweon, 2000) and have been applied to precision active magnetic bearings (For example, Zhang et al., 2004; Xu and Nonami, 2003; Denkena et al., 2004). Damping adjustment units also have been studied for improvement of vibration characteristic of positioning system (Hashizume and Shinno, 2000; Matsubara et al., 2004; Zhang et al., 2004).

2. 2 High acceleration precision positioning mechanism

Large lead ball screw and twin ball screw driving units can be used for high speed mechanisms whose maximum acceleration is a few G. However some linear motor mechanisms show much higher acceleration than 10G. The positioning mechanisms comprising the linear motors and linear ball bearings are increasing as desired acceleration and velocity increase. Some linear motors on the market has the thrust density (Peak force / Movable mass) higher than 400N/kg (GE Fanuc Automation, 2002; Shicoh Engineering Co., 2002) and the tunnel actuator of which maximum acceleration is 40G has developed (Hitac Magazine, 2004). Figure 3 shows the experimental ultrahigh acceleration and high speed linear motor mechanism developed in my research group. The table mass is 4.79kg. The working range is about 1.5m. As an actuator of the mechanism, PM synchronous linear motor has been developed for large thrust. The experimental linear motor mechanism has the ability to move at the acceleration higher than 990m/s^2 (101G) and at the velocity higher than 12m/s.

High accelerated motion of the table produces large reaction force which vibrates the surface plate and deteriorates the accuracy of the table motion. The reduction of the vibration is important for precision positioning. Thus the semiconductor manufacturing systems have the anti-reaction force units for canceling the effect of reaction forces to the stages and driving the stages accurately at high speed (Fukuda, 1998).

3. Control for precision positioning mechanisms

3. 1 Trend of precision positioning control

Up to date, in order to realize higher control performance than conventional control systems based on classical control theory, many kinds of advanced controller design methods have been proposed. And then their control methods have been applied to the precision positioning mechanisms for evaluation of their performances. However the classical controllers such as PID and lead-lag controllers are still most widely used (For example, Oiwa and Katsuki, 2003; Horiuchi, 2001). In many industrial machines with electromagnetic motors, the controller comprising the PI element for velocity control and the P element for position control are built (For example, Ito and Shiraishi, 2000). And then notch filters, friction compensators and a feedforward element as a path generator are often added. Controllers based on classical control theory have simple structures, high adaptability and ease in understanding and adjusting control parameters. These features are very significant in industrial application.

Elastic hinge mechanisms with piezoelectric actuators can be considered to be second order linear systems and used as precise and fine motion mechanisms . Because of their simplicity, PID controllers are applied to the piezoelectric actuator driven mechanism such as a fine adjustment stage (For example, Oiwa and Ootawa, 2001), inchworm drive mechanisms (For example, Okazaki and Kitahara, 2000; Lim et al., 2004), a walking drive mechanism (Shamoto and Moriwaki, 1997) and a squeeze air bearing (For example, Isobe and Kyusojin, 2004).

Recently, the robust controllers with disturbance observers and friction compensators are often used in precision systems. In their controllers, the positioning performances depend on the suitability of the reference model. Machine elements with friction are included in many precision positioning systems. The nonlinear friction is a typical disturbance force that deteriorates the performance of positioning systems. Thus the reduction of the friction effect is an

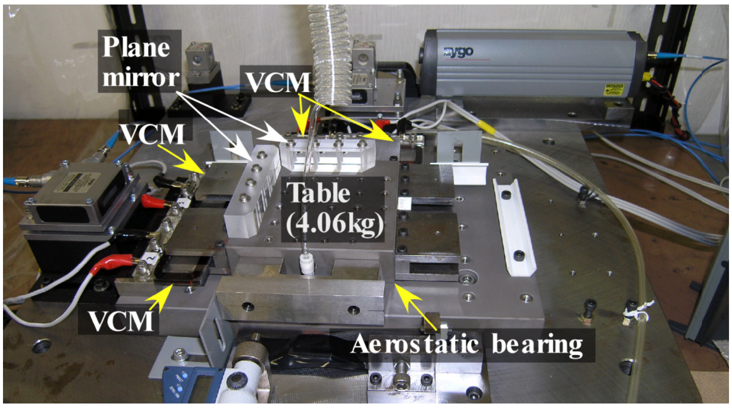
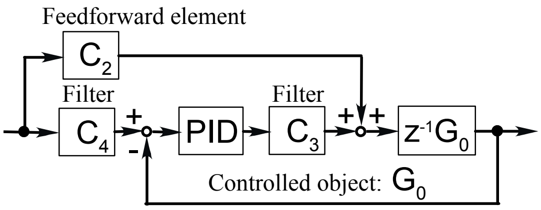
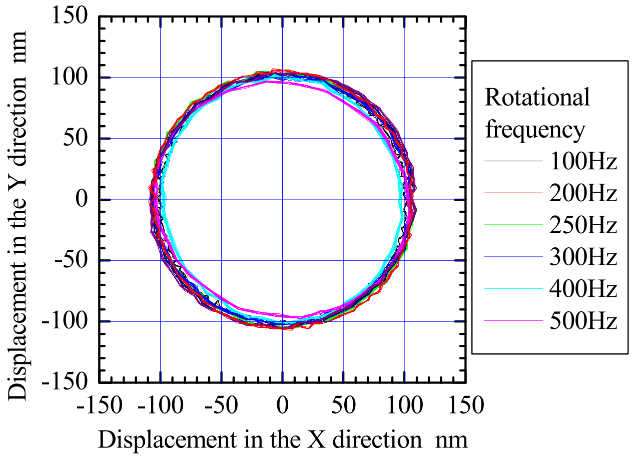


Figure 4. Planar motor mechanism for compact nano-machine tool



(a) 2DOF Control system



(b) Experimental circular motion of the table

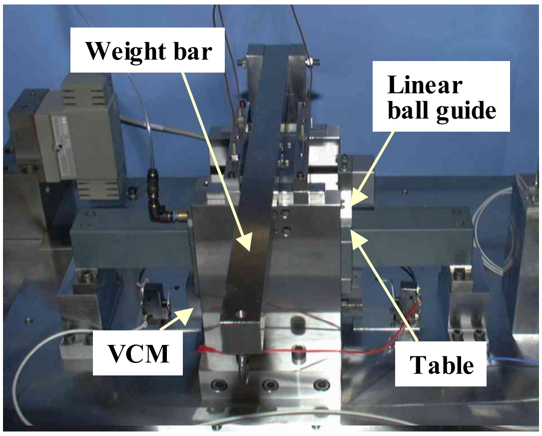
Figure 5. Control system for the planar motor mechanism and its experimental results

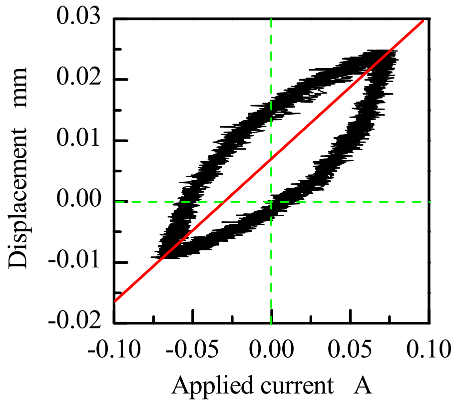
important subject of the controllers for the systems. In section 3.3 and 3.4, the precision positioning control of the mechanisms with friction is described. A sliding mode controller is also a model based robust controller and the use of sliding model controllers increases in precision positioning systems (For example, Woronko and Altintas, 2003; Chen et al., 2004; Altintas, 2000; Tan et al., 2002). However a suitable path generator needs to be designed and used because the reference model (Hyper plane) is often expressed as a linear system. When the mechanisms move at high acceleration, the controller needs to be designed based on the dynamic characteristic of the system including the surface plate for precision positioning (For example, Wakui, 2003; Matsubara et al., 2004; Yamamoto et al., 2004).

3. 2 Control of non-contact mechanism (ultra-precision positioning mechanism)

In semiconductor manufacturing systems that suitable machine elements for precision positioning are built in, these controllers have been widely used (Horiuchi, 2001; Technical Committee of Ultra Precision Positioning, JSPE, 2000). Figure 4 shows an ultra-precision positioning planar motor mechanism for a compact nano-machine tool (Sato et al., 2005; Maeda et al., 2005). This table is supported by a aerostatic bearing and driven by VCMs. Thus this is free from friction. Figure 5(a) shows the 2DOF control system based on classical control theory for the mechanism The controller includes PID elements, bandpass filters and feedforward elements. Figure 5(b) demonstrates the circular motion of the control system. This result shows the table system can move accurately, using the 2DOF controller.

Many advanced controller design methods are often proposed for linear systems. Non-contact mechanisms can be considered to be linear systems in a short working range in which their actuators do not show the saturation characteristic. Thus it is relatively easy to design the advanced controllers for the mechanisms with short working ranges and to realize precision positioning systems with the mechanisms although sufficient knowledge of their control theories is required. The precision magnetic bearings have been controlled with state feedback control (For example, Zhang, 2004; Denkena et al., 2004), repetitive control (For example, Zhang, 2004) and sliding mode control (For example, Xu, 2003) methods and their performances have been evaluated.





(a) Linear motor mechanism with ball guides (b) Microscopic static characteristic

Figure 6. A precision positioning mechanism with friction and its microscopic characteristic

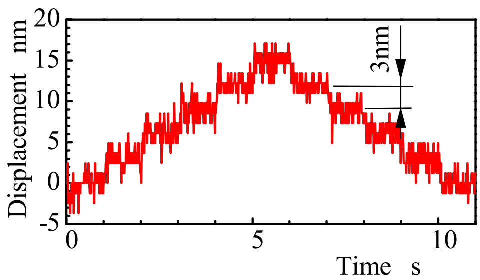


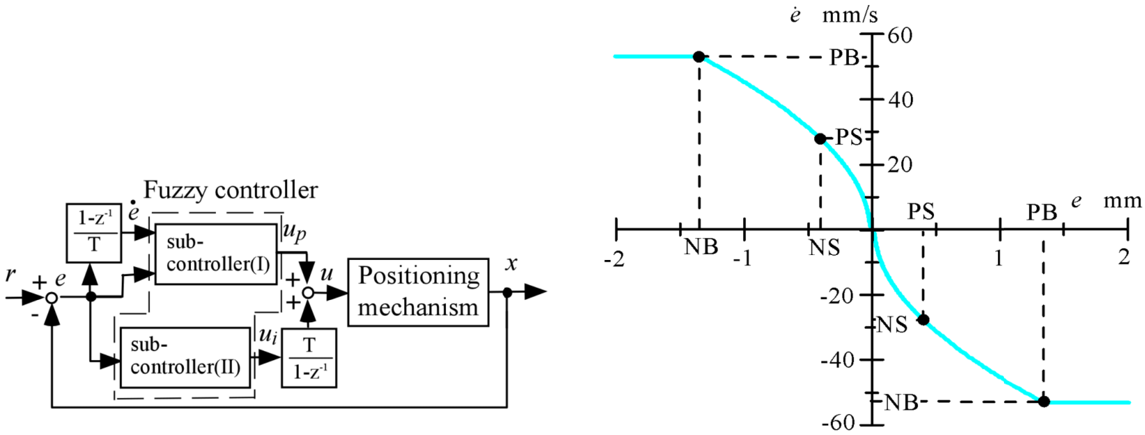
Figure 7. Stepwise response of the steel belt drive mechanism using the PI controller

3.3 Precision positioning of the mechanisms with friction

General precision positioning mechanisms have friction characteristic deteriorating their positioning performance. Many researches for dynamic models and compensation methods of friction characteristics and the effect of control methods on the positioning performances of the mechanisms with friction have been reported (Armstrong-Heouvry, 1994). The precision positioning using the mechanisms with friction is still a important current topic in the research field of precision positioning technology. Friction characteristic comprises a macroscopic characteristic consisting of coulomb friction, viscous friction and Stribeck friction, and a microscopic characteristic named the nonlinear spring behavior or the spring-like behavior. Especially, the application and the analysis of the microscopic characteristic are still studied in the field of precision positioning.

The microscopic characteristic has been observed in linear ball bearings (For example, Futami et al., 1990; Tanaka, 2004), a ball screw (For example, Fukada, 2002), a DC motor (For example, Shimokohbe et al., 1999; Rao and Ro, 1995), a gear (Sato et al., 2000; Armstrong-Heouvry, 1994) and a sliding bearing (Okazaki and Kakuta, 1997). In a short working range, the mechanism characteristic is often expressed as a second-order system and it is relatively easy to nanometer-position the mechanism with friction in the short working range although the quantitative characteristic of the friction is influenced by the condition of the contact areas. Figure 6(a) shows the linear motor mechanism with ball bearing guides for evaluation of microscopic characteristic (Sato et al., 2004). The microscopic characteristic is observed in the ball bearing guides. It is shown in Fig.6(b). This characteristic is useful for ultra-precision PTP positioning. The mechanism with a microscopic characteristic is generally expressed as the second order model in the short working range. Figure 7 shows the closed-loop response of the mechanism with roller guides to a 3nm stepwise input. The closed-loop system with the conventional PI controller has the positioning resolution better than 3nm in a short working range.

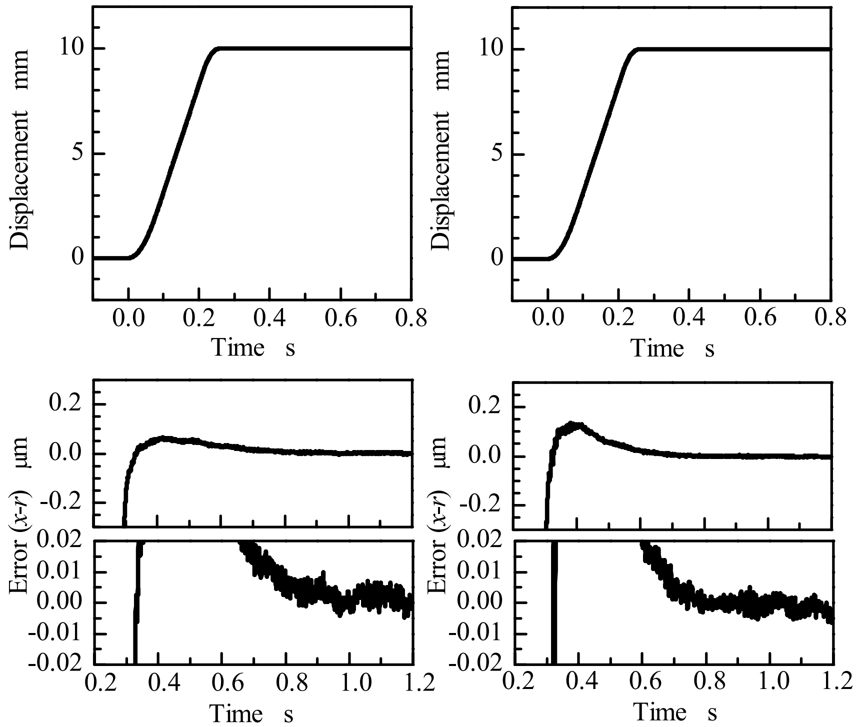
For precision positioning of the mechanism with friction in a long working range, variable structure controllers comprising sub-controllers are conventional ones. The active sub-controller depends on the state values, for example, positioning error (For example, Chang et al., 1997; Yoshida et al., 1993). Recently, the researches using controllers with disturbance observers (For example, Sato et al., 2000; Makino et al., 2001) and friction compensators based on the friction characteristics (For example, Ro et al., 2000; Chen et al., 2004; Han, 2002; Tsuruta et al., 2003; Suzuki et al., 2004) increase. These additional compensators are often used with PID compensators. General precision mechanisms



(a) Fuzzy control system

(b) Design of fuzzy rule set with phase plane

Figure 8. Fuzzy control system design for a ball screw positioning mechanism (Sato et al., 1998)



(a) Normal condition

(b) 1.85 times mass

Figure 9. 10mm step responses of the ball screw mechanism with the fuzzy controllers near the reference position (Sato et al., 1998)

are also influenced by the saturation characteristic of the actuator driver. Additional compensators such as a path generator and a disturbance observer can be used to reduce these nonlinear effects.

The suitable nonlinear reference trajectory is useful to solve the problems caused by the nonlinear effects. Figure 8(a) shows the fuzzy control system for a ball screw mechanism (Sato et al., 1998). The fuzzy rule sets for P and I elements are determined based on a suitable nonlinear reference trajectory on phase plane (Fig.8(b)). The trajectory is determined from the suitable step response of the controlled object. Figure 9 shows the experimental responses of the fuzzy control system in Fig.8(a) to a 10mm step input. In the experiment of Fig.9(a), the mechanism was used under the normal condition. The table mass in Fig.9(b) was 1.85 times as heavy as that in Fig.9(a). The response of Fig.9(b) is almost similar to that of Fig.9(a). The positioning errors in Figs.9(a) and 9(b) is smaller than 10nm. These results prove that the fuzzy control system has high robustness to the change of the mass and high accurate positioning performance.

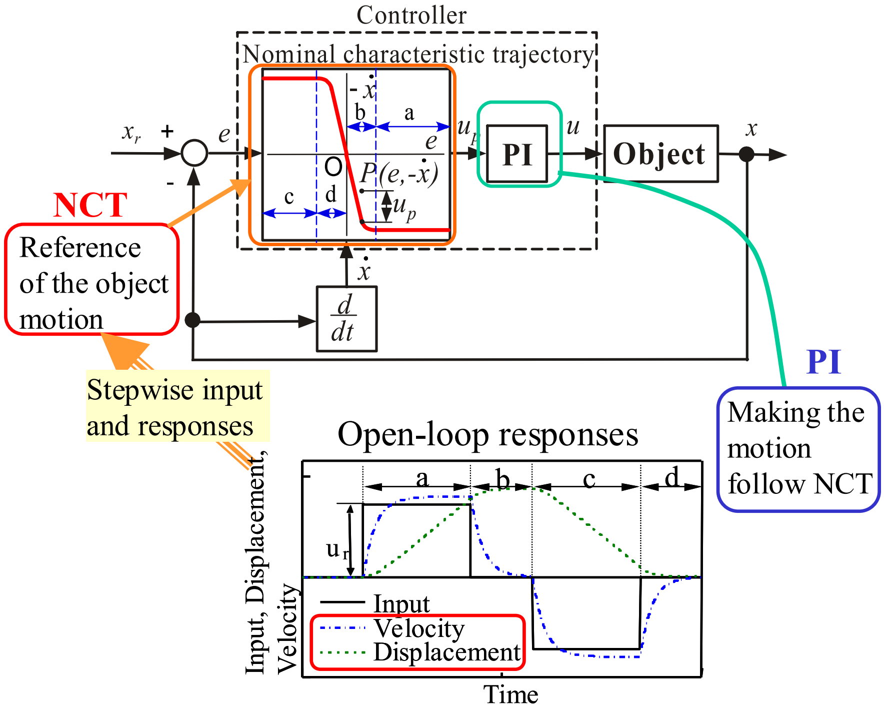


Figure 10. Structure and design procedure of the NCTF control system

3.4 Practical control design for mechanisms with friction

The model based control systems such as the systems with disturbance observers and friction compensators often have high robustness. However the controller design procedures generally require detailed models and the knowledge of modern control theory for determining a suitable reference model and controller parameters. In practical application, the following are required, whose grades influence the selection of the control method: (1) high positioning performance, (2) ease in understanding and designing control parameters, and (3) a simple structure, such as PID controller.

The NCTF(nominal characteristic trajectory following) controller has a simple structure comprising a NCT(nominal characteristic trajectory) and a PI element as a compensator for making the object motion along the NCT. It can satisfy the requirement above-mentioned (Wahyudi et al., 2003; Sato et al., 2002; Sato et al., 2004). Figure 10 shows the structure and the design procedure of the NCTF control system including a motor. The NCT is expressed on phase plane and can be determined from actual open-loop responses of the object without the exact model. When the NCTF control system is linearized at origin, its stability can be discussed based on the linear system. The stability basically depends on the inclination of the NCT at the origin and PI compensator parameters. The stable condition calculated beforehand can be used for determining the compensator parameters. Fundamentally, the system stability depends on the proportional gain. Therefore it is also easy to determine PI parameters by trial and error.

The NCTF controller with a normal PI element shows better positioning performance than conventional PID controllers. In the NCTF controller with a normal PI element, the large integrator gain makes the settling time short. However it makes the overshoot large. The NCTF controller with the suitable conditionally freeze integrator realizes the short settling time and the small or no overshoot of the step response. This NCTF controller designed for one-inertia system shows no overshoot and has higher robustness to the increase in inertia than the PD controller with a simple disturbance observer (Sato, 2004).

The NCTF control system can be also designed so that the system keeps stable under both of microscopic and macroscopic friction characteristics (Sato et al., 2004). For a two-mass system, the PIDD^2 compensator is used instead of the PI compensator. All the PIDD^2 compensator parameters can be determined from the open-loop responses the same as the PI compensator parameters (Sato et al., 2002).

4. Self-alignment for self-assembly of microparts

Microsystems have become an important research field and the microsystems composed of microparts whose materials and shapes differ have been investigated. In order to realize such systems as industrial products, an assembly technique of the microparts is necessary with alignment being a very important task in the assembly. For the alignment, researches using the servomechanisms such as micromanipulators have been reported. However, in general, the servomechanisms are complex and produce heat. Attractive force by surface tension and static electricity can deteriorate alignment accuracy of the mechanisms. For overcoming these problems, self-alignment methods have been studied

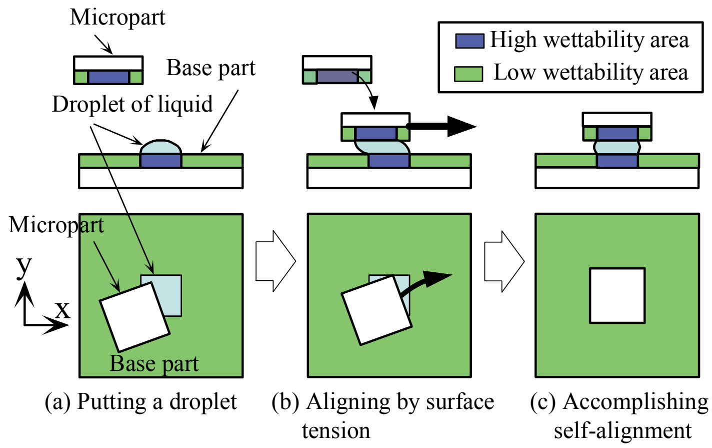


Figure 11. Principle of self-alignment of a micropart using liquid surface tension(Sato et al., 1999; Sato et al., 2003

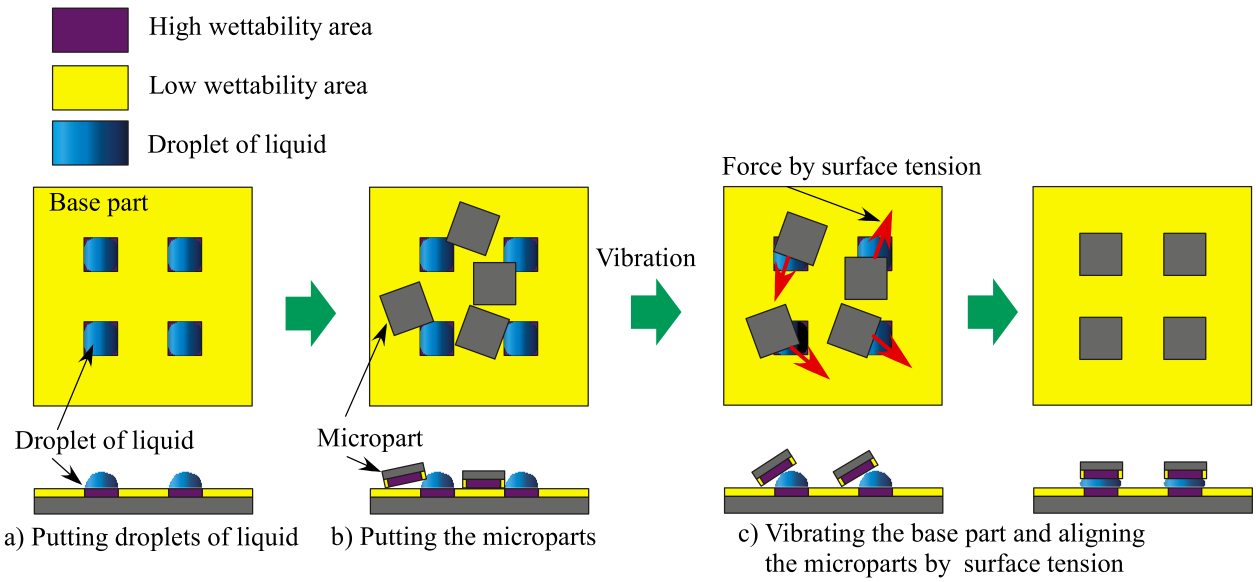


Figure 12. Method of self-alignment of a group of microparts using liquid surface tension (Sato et al., 2004)

using surface tension of liquid (Sato et al., 1999; Hosokawa et al., 1997; Srinivasan et al., 1999) and of molten solder (Wale et al., 1990), magnetic force (Ota et al., 1997) and electrostatic force (Cohn, 1994). In this section, the self-alignment method using liquid surface tension in air is introduced.

Figure 11 shows the principle of the self-alignment method using liquid surface tension (Sato et al., 1999; Sato et al., 2003). The surface of each part used in the method is divided into two areas, namely, high and low wettability areas. In the figure, the pattern of the high wettability area in base part is similar to that in micropart. Using these microparts, the self-alignment is carried out as follows; (1) A droplet of liquid is put on the high wettablity area of base part, (2) Micropart is put on top of base part so that the droplet comes in contact with the high wettability areas of the two parts, (3) Micropart is moved by the liquid surface tension so that the high wettability area pattern of base part overlaps with that of micropart and the alignment is accomplished.

In the alignment, a micropart needs to be put on the base part so that a liquid droplet comes in contact with the high wettability areas of the two parts. It becomes more difficult to put all the microparts under the condition simultaneously as the number of the microparts increases. This can become an obstacle of practical use in mass production although the series alignment can be widely used and reliable.

For overcoming this problem, the vibration force is used with the liquid surface tension in the alignment. Figure 12 shows the method of the self-alignment of a micropart group at a time (Sato et al., 2004). The friction force between the parts may deteriorate the accuracy of the alignment using only liquid surface tension. However the vibration force reduces the bad influence and can improve the alignment accuracy.

For manufacturing 3D microsystems, the out of plane rotational alignment is needed. Standing microparts are often included in 3D microsystems. Liquid surface tension and vibration force are also useful for self-standing of the microparts. The self-standing method is based on the self-alignment one of a micropart group (Sato et al., 2004). In case the length of the micropart is short enough, the micropart can stand up with the only liquid surface tension.

5. Summary

In this paper, recent positioning technologies, mainly, for industrial machines are introduced and discussed. Many kinds of machine elements, actuators and auxiliary units are useful for precision positioning mechanisms in industry. However, in this research field, simplicity of the system is fundamentally important. Simple structure of the mechanism can reduce the number of vibration elements and the movable mass in the systems. Fewer mechanical elements are also basically advantageous to realize high speed servo systems. These make their maintenance and their controller design easy. It is easy to implement simple controllers and in general easy to design and adjust them. Simple and conventional control methods such as PID control ones are generally used for precision positioning systems. NCTF control has been being studied as a simple and high performance control.

In addition, the simplicity benefits the system downsizing which is an important subject of precision engineering. The miniature industrial machines have the advantages such as saving energy and space. However servo systems in the machines fundamentally make the system complex and their downsizing difficult. In self-alignment methods, the remarkable characteristics in a very small working area are used. The utilization of the characteristics is important for the simplicity. The simplicity is an important key word.

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