Applications of Magnetic Bearings in Robotics

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Abstract

Magnetic bearings have the ability to support objects without mechanical contact. In addition they have the functions of controlling the stiffness and damping of levitation and controlling the position and attitude of the supported object with an accuracy of a micro meter or submicrons. By taking advantages of these characteristics of magnetic bearings, robots are expected to improve their abilities, to expand the field of activity in clean rooms and in vacuums, and to have good tools for the tasks which need precise manipulation. In this paper the following researches and attempts which are related to applications of magnetic bearings in robotics are introduced. These are: development of clean room robot of which joints are composed of magnetic bearings, development of super clean actuators which have the function of magnetic bearings and stepping motors in one construction, and development of magnetically supported intelligent hand as an end effector of robots to do precise assembling.

Clean Room Robot

Cleanliness of production environment is said to greatly affect the reliability and yield rate of semi-conductor circuits. Since the integration of semi-conductor circuit is increasing and the width of the circuit pattern reaching the order of sub-micron, prevention of dust and oil vapor generation in clean rooms is becoming an even greater necessity. Human operators being the greatest source of contaminant, it is desirable to replace them by robots and automated machines. However, when even greater degree of cleanliness of environment is needed, dust and oil generation from the machines can not be overlooked. So, the robots to be used in super clean rooms should not contaminate the air.

There are two ways to avoid the dust generation from robots. The first and conventional one is applying sealing technique to separate the inside of a robot where dusts and oil vapor are generated from motors, gears, ball screws, and guides etc. from the outside of the robot where cleanliness is required. Most of the commercialized clean room robots are made based on the method and also keep the inside pressure of robots lower than the pressure of clean room to prevent escape of dusts. The second and ideal one is to develop inherently clean robots by using magnetic bearings and magnetic levitation to eliminate mechanical contacts which are the worst source of dusts.

The clean room robot installing magnetic bearings in its joints is more expansive than the conventional sealed robots. But, the increasing demand for perfection of cleanliness will choose the robot with magnetic bearings. And since the robots without mechanical contacts need no lubricant, they are also suitable for applications in a vacuum and in space.

In order to make the clean room robot, it is also necessary to use clean actuators, which will be described later. Under gravitation, it is not easy to support all links of multi-link robot by installing a magnetic bearing to each joint. Therefore, as the first step, we [1] designed and constructed the parallel link robot of which upper two joints are composed of magnetic bearings as shown in Fig.1.

The construction of the robot manipulator is shown in Fig. 2. Links 1 and 2 are driven by DC motors at joints 1 and 2 respectively. Joint 3, 4, and 5 are passive joints without driving mechanism. Magnetic bearings are applied to joints 4 and 5. Joints 1, 2, and 3 are composed of usual ball bearings. As the air flow of clean rooms is made downward, joints 4 and 5 are the most important joints to be clean. Link 4 is completely levitated by the two magnetic bearings.

Links 1 and 3 have equal length of 300 mm. The length of link 2 and the distance between joint 4 and joint 5 are 170 mm.

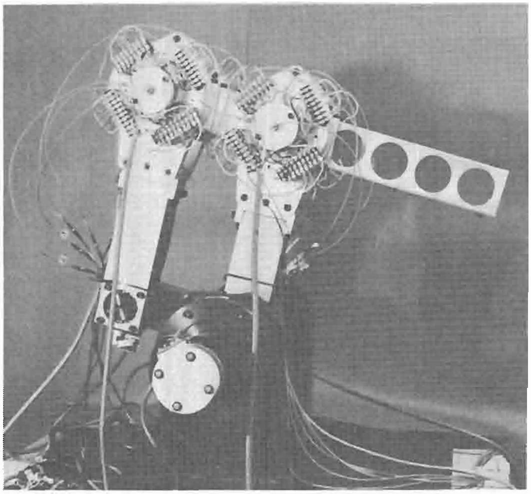


Fig. 1. Prototype of clean room robot with magnetic bearings.

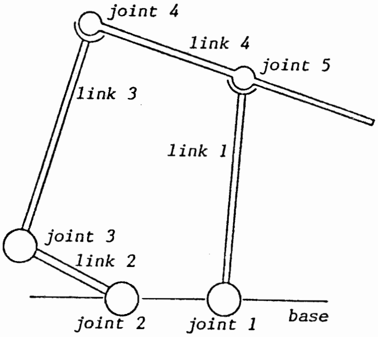


Fig. 2. Construction of the prototype of parallel link clean room robot.

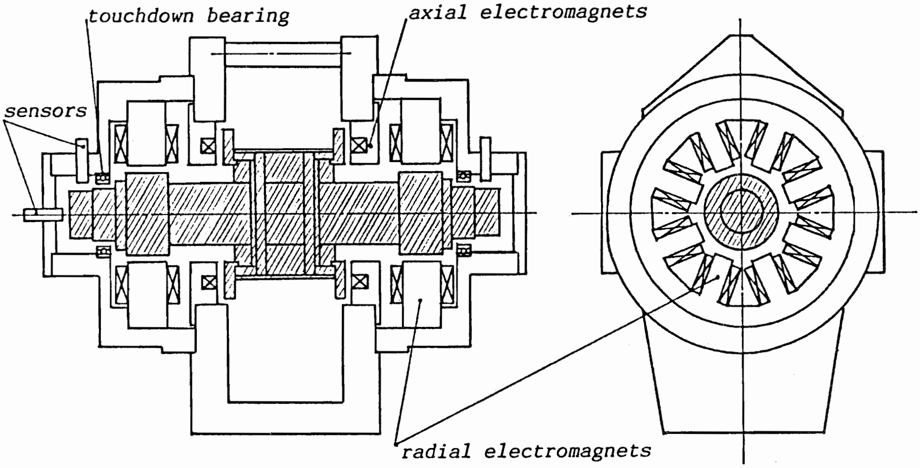


Fig. 3. Structure of the magnetic bearings of the joint.

The structure of the magnetic bearings of joints 4 and 5 is shown in Fig. 3. It is composed of two radial bearing units and one axial bearing unit. And the axial one is located between the radial ones. The rotors of the magnetic bearings of joint 4 and joint 5 are installed into the link 4 as shown in Fig. 4. The air gaps of the electromagnets are 0.7 mm and the rotor can move ±0.5 mm in radial direction and ±0.7 in the axial direction. Mass of a stator is 6 kg, that of a rotor is 1.3 kg, and the total mass of the link 4 is approximately 5 kg.

The gap sensors are eddy current type with resolution of 0.5µm. All of the five degrees of freedom of each magnetic bearing are controlled actively by means of 32 bit micro computer.

So far the levitation of the link 4 has been succeeded. The clean room robots using magnetic bearings are expected to have the advantages and functions beside the cleanliness as follows, so studies are continuing to investigate the functions by using the developed prototype.

1) Being free from troublesome problems of frictional forces.
2) Function of micro manipulation of work piece by active rotor position control of the magnetic bearings.
3) Function of controlling exerting forces and stiffnesses at the handling point (tip of link 4).
4) Function of sensing of forces acting on the robot.
5) Function of active vibration control of robot arm.

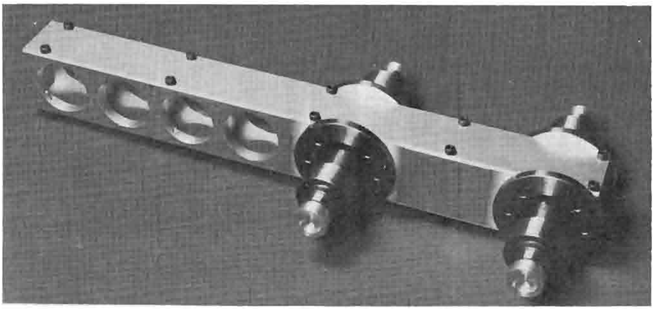


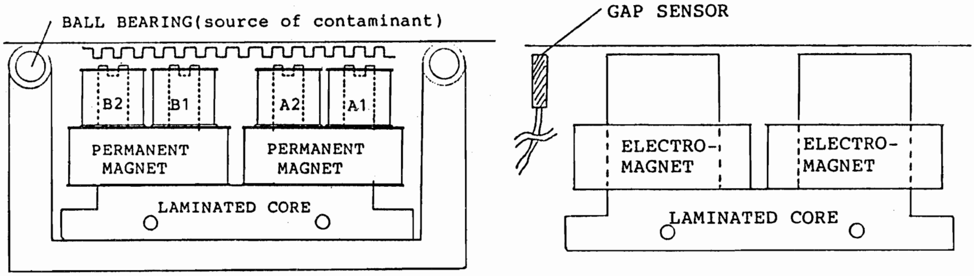
Fig. 4. Photo of the link 4 with magnetic bearing stators.

Development of Super Clean Actuators

In order to complete the clean room robots clean actuators are indispensable for driving and positioning. For robots and automated machines in clean rooms, vacuums, and space, we [2] developed new actuators which have the functions of magnetic bearings and the functions of stepping motors in one construction. The rotor of the motor is suspended exactly like usual a magnetic bearing and can rotate completely like a stepping motor. In this paper, the structure and the design of the actuators are presented with introduction of some prototypes.

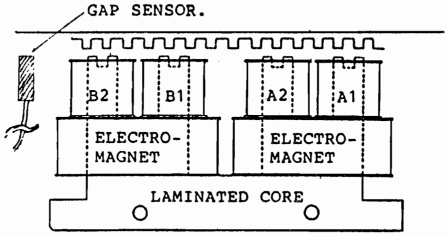
Explanation of the idea and basic construction of the actuator will be done in the case of a linear motor. A conventional linear PM (Permanent Magnet) stepping motor is shown in Fig.5a. Propulsive force is gained by superposition of the magnetic flux generated by the currents of coils onto the magnetic flux generated by the permanent magnets. A strong attractive force, approximately ten times of the maximum propulsive force, acts between the mover and stator. Ball bearings, which are the source of dusts and oil vapor, are used to maintain a constant gap. Fig.5b shows a concept of an active magnetic suspension. The current of the electromagnet is controlled according to the output of gap sensor to keep the gap. Fig.5c shows the basic element of the super clean actuators. Its structure is quite similar to that of PM stepping motor except that the permanent magnets are replaced by electromagnets (main coils). By controlling the current of main coils based on gap sensor signal, mover is expected to levitate with a constant gap in spite of the toothed pole structure inherent to stepping motors. The developed super clean actuator may be regard as an amalgam of stepping motor and magnetic bearing.

The schema and structure of the element of the actuators are shown in Fig.6. Six coils are wound to the laminated core. A pair of lager coils (main coils) connected in series produce main magnetic flux. Coils A1 and A2 are connected in series and when one coil produces a magnetic flux in the same direc-



a) PM stepping motor

b) Active magnetic suspension



C) Basic element of super clean actuator

Fig. 5. Basic idea of super clean actuator (magnetically suspended stepping motor).

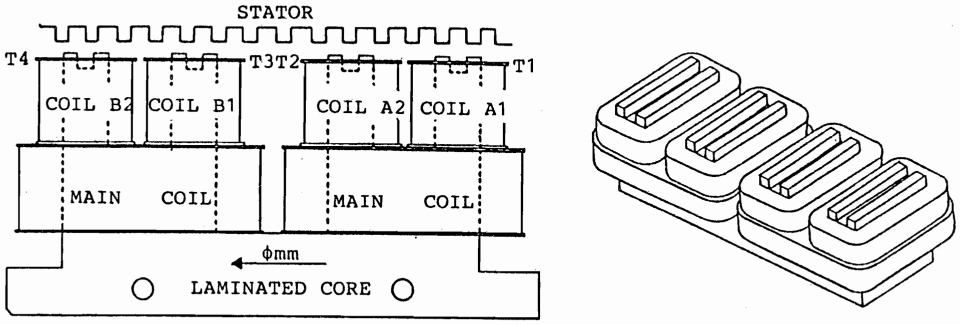


Fig. 6. Basic structure of super clean actuator element.

tion as the main flux, the other produces a magnetic flux against the main flux. The same applies for coils B1 and B2. The core has four toothed poles. Let one pitch of the teeth be expressed as 2pi radian, then the phase relation of the toothed poles are presented as T2-T1= 1 pi rad., T3-T1= $-\frac{1}{2}$ pi rad., and T4-T1= $\frac{1}{2}$ pi rad. The equivalent circuit of the magnetic circuit of the element is shown in Fig. 7.

Attractive force and propulsive force of the motor element can be calculated as the derivatives of the magnetic co-energy by H (gap direction) and X (traveling direction) respectively. The calculated value of the attractive force is shown in Fig.8. Due to the toothed pole structure, the attractive force acting on each toothed pole fluctuates severely as the line indicated by F1 along the direction of X. However, summation of the forces of four poles is rather constant and insensitive to change of position X. This comes from the phase relationship of the toothed poles. It was found from calculation that the fluctuation of the total attractive force takes minimum value when ratio of tooth width to pitch lies between 0.45 and 0.5. From the numerical analyses and experimental results related to the attractive force [2], it is confirmed that active control of magnetic suspension can be realized only by controlling current of the main coil independently of traveling position X.

Driving of the motor can be done in exactly the same manner as 2 phase PM stepping motor by using coil A (A1+A2) and coil B (B1+B2). The driving method commonly called mini-step drive or micro-step drive, where the currents are provided like sinusoidal forms, is preferable to this actuator. Rapid change of the currents of coil A and coil B may disturb the calm suspension. And micro-step drive is also desirable for precise positioning and smooth movement.

Since the element shown in Fig.6 has no function of attitude control in itself, totally contactless suspension of a rigid body requires several elements or co-use of electromagnets.

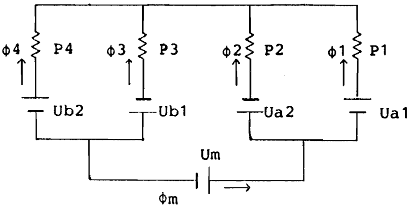


Fig. 7. Equivalent circuit of magnetic circuit of the basic element.

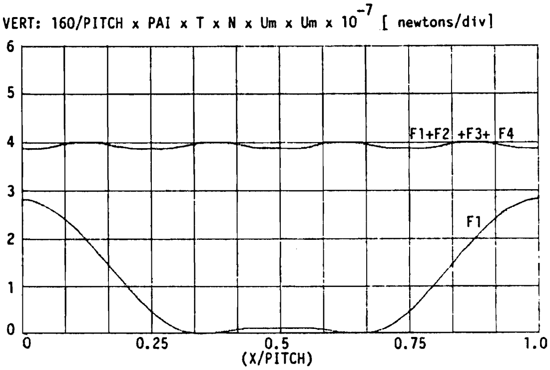


Fig. 8. Calculated value of attractive force.

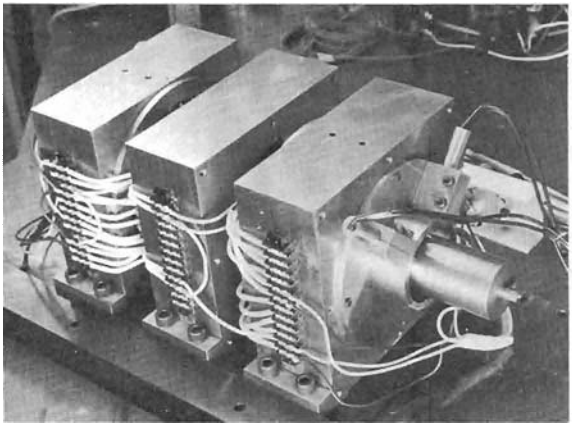


Fig. 9. Prototype of super clean rotary motor.

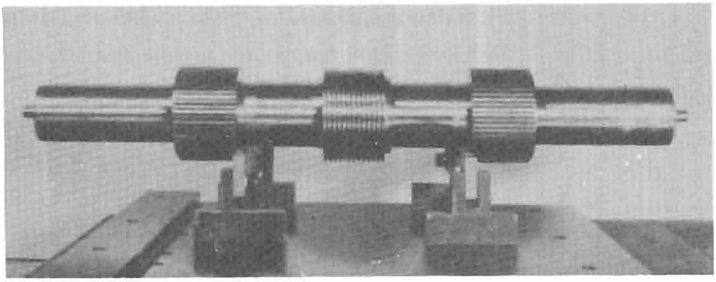


Fig. 10. Rotor of the prototype of super clean rotary motor.

By this time we have made and tested more than 6 types of super clean actuators based on the idea. Two of them are linear motion type and the others are rotary type. Here two typical examples will be explained.

The first prototype of super clean rotary motor is shown in Fig. 9. It consists of three stator blocks and a rotor shown in Fig. 10. The two outer side blocks are stepping motor units whose stator core is shown in Fig. 11. Each unit is composed of four basic elements shown in Fig. 6. The unit has the same function of radial bearing unit of common totally active magnetic bearing in addition to the function of stepping motor. And it has two capacitance type gap sensors for active magnetic suspension. The block at the center is used for passive thrust position control by means of circular grooves. Since it has also the function of a radial bearing unit, one of the outer side blocks is able to leave out. But experiments were done mainly by using the outer units as radial bearings.

When preset gap was 0.25 mm, gap fluctuation has been confirmed to be no greater than 4 µm p-p at an angular velocity of 0 to 40 pi rad/sec (velocity of rotor surface is 0 to 5 m/sec). Stiffness of suspension in the gap direction was 6 N/µm. Its maximum torque was about 1.0 Nm. And angular positioning accuracy was almost the same as usual stepping motors.

The other example is shown in Fig. 12. It was developed by NSK for presentation in robot show. The rotor is suspended magnetically like the first example. But the construction is outer rotor type. On the upper part of inner surface of the rotor cylinder teeth are made so as to control the rotary motion. And on the lower part of both the inner and outer surfaces of the rotor cylinder circular grooves are machined in order to control the height position (axial motion) of the arm. Four eddy current type gap sensors are used. Rotary motion and up and down motion of the rotor are controlled by means of the function of stepping motor. The other freedoms are controlled actively like magnetic bearings.

On the top of the rotor an arm is attached. Though it has only two degrees of freedom of large motion control, it can do simple tasks in clean rooms and vacuums. So it may be the simplest clean room robot by itself.

Since the super clean actuators are completely friction free, they have the possibility to be the ideal actuators for DD (Direct Drive) robots where frictions of bearings are obstacle to precise motion control.

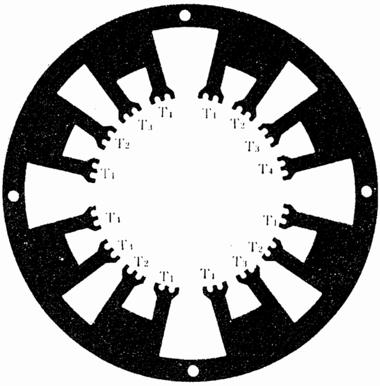


Fig. 11. Stator core.

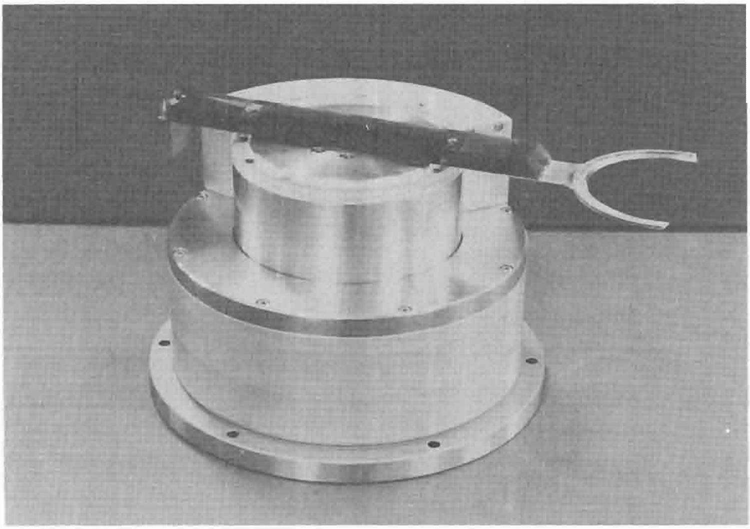


Fig. 12. Super clean actuator with both rotary and thrust motions in one body.

Magnetically Supported Intelligent Hand

Magnetically supported intelligent hand is a new end effector for robots to do precise assembling by using magnetic bearings. In the assembling process, usually it is very difficult to align a part to another part. So it is necessary to correct the attitude and position of the part. The developed hand can achieve very precise assembling tasks by correcting the the alignment errors automatically by means of both passive method and active method. For the passive method, the magnetic bearing supports one of the mates with appropriate compliances like RCC. And for the active correction, the magnetic bearing manipulates the part according to information of forces acting between the mates. The force can also detected by the currents of coils and air gaps of the magnetic bearing without using additional force sensors. In this paper conception of the hand will be described, and its structure, control system, functions, and the experimental system will be explained.

Insertion operation is a basic task of assembling and it is a kind of geometric problem. If a couple of mating parts could be aligned perfectly, insertion operation would always be done successfully. In actual cases, however, cost and technical limitations make the initial perfect alignment impractical. Successful insertion requires that the initial misalignment shown in Fig. 13 should be automatically corrected during the insertion process.

Many methods to correct the initial misalignment have been suggested. They can be classified into two methods: A) passive method using elasticity which absorbs the alignment errors passively, B) active method using sensory feedback to correct the errors actively. The Remote Center Compliance (RCC) is one of the devices estimated most highly for insertion operation due to its simplicity and performance. It is a mechanical elastic device of the passive method developed by Whitney and Nevins [3] [4]. Many similar mechanical elastic devices have been developed.

We [5] have developed the magnetically supported intelligent hand (MSIH) which has the function corresponding to that of RCC. Further, it has the advanced RCC function and the other useful functions explained later. It has the unique structure shown in Fig. 14 incorporating a magnetic bearing. It is composed of a hand shaft, two radial magnetic bearing units and one axial magnetic bearing unit. The hand shaft which hold a work piece with its gripper is supported by the magnetic bearing. Five gap sensors are installed and five degrees of freedom of motions of the shaft are controlled actively.

In most cases of the passive insertion method, a part is supported compliantly and it is tilted and translated by the mating forces and moments during the insertion process to correct misalignment between parts to mate. If certain symmetry conditions are satisfied, then support system can be represented mathematically by a compliance center and compliances at and around the compliance center. In the RCC theory, it is suggested that the optimum location of the compliance center is a point close to the tip of the supported part and it is concluded that the RCC has the ability to reduce mating forces and the chance of jamming by the function shown in Fig. 15.

The MSIH can posses a function corresponding to that of the RCC. In addition to that, it can easily and intentionally move the compliance center and change the support stiffness by altering the control parameters of the magnetic bearing. Whereas the mechanical RCC devices have a fixed compliance center and stiffnesses, the MSIH has the flexibility to be adapted to many kinds of parts.

The MSIH can realize more effective passive insertion by controlling the compliance during an insertion operation. And it is posible to support a work piece stiffly during transportation by the robot, whose arm is connected to the MSIH, to insertion spot, but flexibly during insertion in order to save the settling time of vibration of the hand shaft caused by the rapid robot motion.

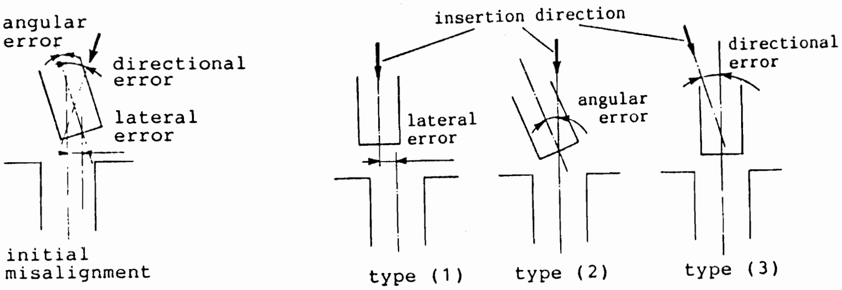


Fig. 13. Errors of misalignment and three types of errors.

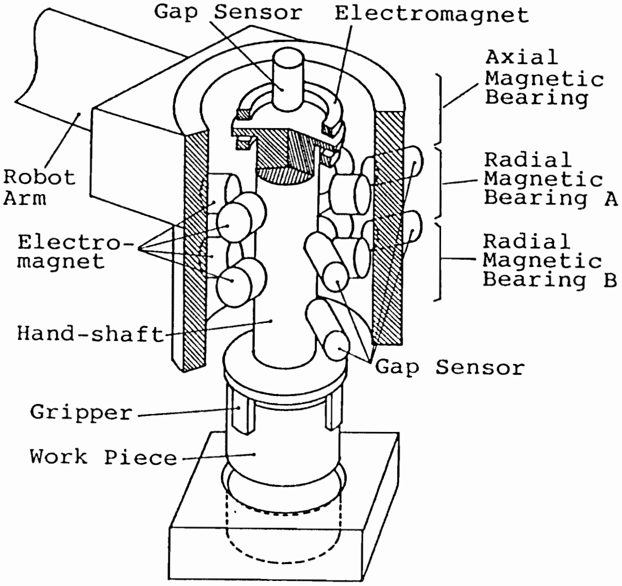


Fig. 14. Structure of magnetically supported intelligent hand.

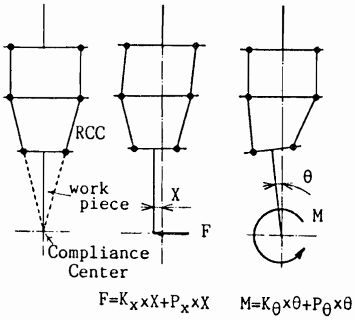


Fig. 15. RCC function.

The MSIH can not give large movements to the work piece, since the air gaps of the magnetic bearing limit the movable range. It can, however, translate and tilt the work piece with a resolving power almost equal to that of gap sensors. The prototype of MSIH has positioning accuracy of 1 µm. This high resolution enables MSIH to do active correction of small errors during insertion. The active insertion method is expected to do such difficult tasks as insertion with very close clearance, mating of parts with large diameters, mating of fragile parts, and press fit insertion.

In order to realize the active insertion, it is necessary to acquire information of misalignment and forces during the process. Position and attitude of the work piece are calculated from the outputs of the gap sensors. The forces and moments acting between parts to mate can be calculated by solving the static force balance equations where magnetic forces of the electromagnets are calculated from the coil currents and the air gaps. Therefore MSIH has the ability to infer the direction and degree of the initial error and to estimate the situation during the insertion process.

The experimental setup is shown in Fig. 16. It is composed of the MSIH and the xyz-positioning system and the control sytem. The cross section of the MSIH is shown in Fig. 17. The average gap of the radial bearing A is 2 mm, that of radial bearing B is 1.1 mm, and that of the axial bearing is 1.6 mm. The mass of the hand shaft is 1.4 kg. On the end of the hand shaft a peg is attached directly for experimental study of insertion.

The xy-table positions a mating part with a hole with resolving power of 1 µm. It is used to set various initial errors between the parts (the peg and the hole). The z positioning device moves the MSIH in the z direction to execute the insertion.

The control system was designed to utilize digital control as much as possible. It is composed of a Digital Signal Processor (DSP) circuit, a personal computer, A/D converter circuits, D/A converter circuits, coil current controller, and xyz-posi-

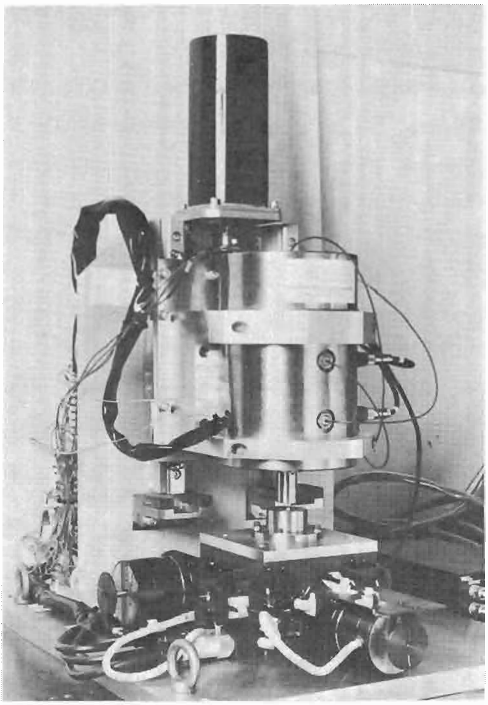


Fig. 16. Experimental setup.

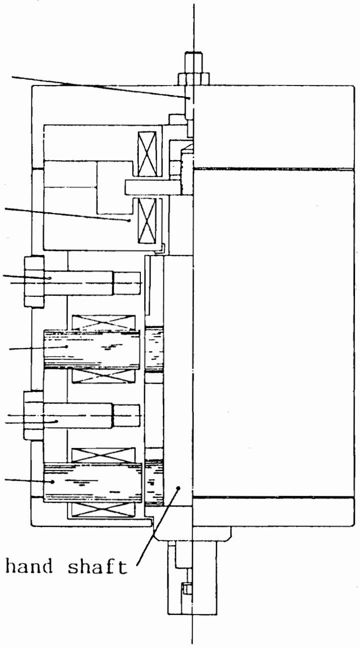


Fig. 17. Cross section of MSIH.

tion controller. All five degrees of freedom of the magnetic bearing is controlled by DSP. Sampling period of DSP for suspension is 60 μsec. Schematic of the control system is shown in Fig. 18. The feedback matrices K and P which determine the compliance matrices and the damping matrices of the suspension is given from the personal computer. Detail of the control system is described in the paper [5].

The hand shaft can be supported magnetically with the accuracy of about ±2 μm by digital control. By using the RCC function of the MSIH, we have succeeded in automated insertion with the experimental system under any following conditions: the diameter of the peg is 19.995 mm, the diameters of the holes are 20.003 mm, 20.013 mm, 20.024 mm, and 20.052 mm, the lateral initial errors are 0.2 mm, 0.35 mm, 0.4 mm, and 0.5 mm.

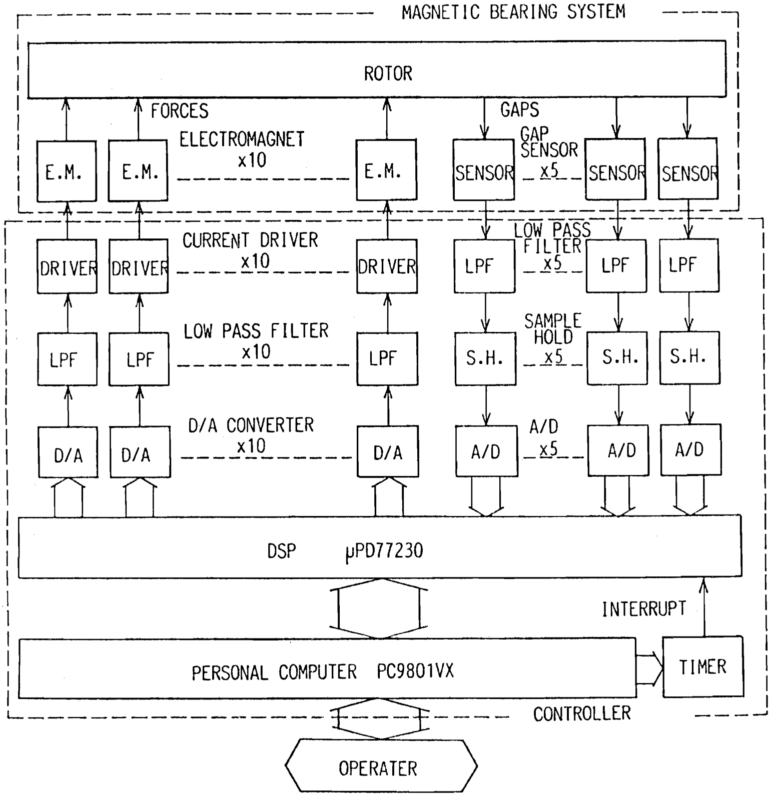


Fig. 18. Control system of MSIH.

Conclusion

The ability and the performance of robots should be progressed by using magnetic bearings for their joints and their end effectors. The examples presented in this paper are only the beginning of the applications of magnetic bearings and magnetic levitation. Further studies and developments are demanded to increase the supportable load, stiffness, and accuracy of positioning of magnetic bearings and to decrease the weight and size of magnetic bearings.

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Special Bearings