Miniature Robots for a Desktop Flexible Micro Manufacturing System

Hisayuki Aoyama, Futoshi Iwata, and Akira Sasaki

This article describes the basic structure and performance of miniature robots which incorporate micro-tools and micro-probes to produce micro-devices such as LSI materials. In the experiment, typical results at the microscopic level, such as fine grating and micro indenting, are demonstrated. It is suggested that a strategy of combining aspects in a centralized and distributed manner might be useful to increase both productivity and flexibility in manufacturing. The architecture, based on a production process including capability recognition, initial planning, grouping, and dispatching to the working area, will be described to control multiple miniature robots under graphical simulation for the desktop precise flexible micro manufacturing system.

Introduction

In the field of precise manufacturing, the demand for machines with much higher accuracy is increasing, especially for producing specialized components of semiconductor micro-devices. Such products need very high positioning resolution for the mechanical stage and structure. However, conventional techniques to improve the resolution and stability, such as tool servo, temperature control and vibration isolation, require high cost and considerable energy for microscopic production sizes. As an alternative approach to this problem, our group has developed many miniature robots with the practical characteristics of micro functions. They have the potential to perform accurate and fine operations with great cost-saving benefits at the level of nanometers, because the lack of mechanical structure can provide high mechanical stability [1]. Small robots, however, have less mobility and can perform only simple functions since they have poor capacity of loading space and driving force. Therefore, a number of small robots should be employed over the workpiece and governed to accomplish given tasks according to a collaborative behavior scheme with certain working formation of serial, parallel, and surrounding. Then one can organize such multiple robots under specified planning and scheduling schemes which are well-known in a macro size factory model, including distributed properties for flexible manufacturing. But when we realize such a flexible system, applied to precise production in the desktop environment, we need to consider domain-dependent problems concerning actuation devices, and sensor and feedback techniques at the microscopic level. In addition, we must consider the control architecture which is available for multiple robots, and control processors for actual implementation in manufacturing [2,3,4].

In this article we show that several miniature robots which consist of micro actuators and micro sensors can provide microscopic operations such as micro hammer forming and micro scratching under collaboration of local feedback action for improving operational accuracy. We also consider the framework of a hierarchical distributed system, being designed for desktop flexible manufacturing, where the role of each control processor should be changed according to the production process from the initial phase of global initial planning and scheduling to the final phase of finishing. Finally, graphical simulation is demonstrated for initial planning of grouping and dispatching.

Miniature Robots with Micro Facilities

Basic Structure

In the design of our miniature robot, piezoelectric elements and electromagnets are commonly used for propelling and clamping its body to the workpiece, as illustrated in Fig. 1 [5]. Each is as small as a beetle and weighs approximately 50g. Basically, U-shaped small electromagnets are used for the active legs, whose material and dimension are carefully considered for core-loss minimization. Stacked-type piezo elements are included between two legs. This structure allows them to move on any curved surface, including walls and ceilings, with submicron resolution when exciting those actuators synchronously like an inchworm mechanism. Fig. 2 shows the diagram of exciting these actuators. The magnet Leg1 will move forward by the expansion of piezo element while the magnetic Leg2 clamps at the position by means of magnetic attraction. After expansion of Leg1, the current supplied to magnetic Leg2 is switched to magnetic Leg1. Then the piezo element is contracted so that the remaining magnetic Leg2 moves forward. This sequence can be repeated for the machine to move and also reversed easily by interchanging the front and the rear legs. When the small robot moves up the inclined surface, bias force of magnets enough to clamp its weight should be applied. Hence the magnet force is required for the small walking mechanism to move on any tilted plane without slipping and falling away from the surface. Here we also have to take care of the saturation of the magnetic characteristics and the power dissipation. Higher electrical current means greater heat generation, which induces significant mechanical damage. So we must keep the current as low as possible to prevent thermal effects. The small walker's unique performance of walking on an S-shape curved surface is shown in Fig. 3 [5]. Typical moving speed is approximately 20mm/sec.
when exciting the piezo element at 100Hz with a 20 micron step width. The robot has two piezo elements, one on each side, so that it can steer its body by controlling the width of each piezo. Furthermore, we constructed micro facilities, with off-the-shelf components, into the robot to provide special operation in the microscopic range.

**Micro Hammer Forming**

Fig. 4 shows a miniature robot with a micro hammer which is actuated by a small electromagnetic coil. A hardened steel ball, 2 mm in diameter, is attached at the end of the hammer and driven to make an impact motion to the sample material when an impulse signal is applied. Two degrees of freedom of the hammer motion, in the direction of impact motion and in the lateral direction, are to be controlled with scanning range of 1 mm so that microscopic indenting within the range of 1 mm² could be generated. A typical experimental result is shown in Fig. 5, which demonstrates the performance of dotting the character "E" in 500 square microns on the metal sample [6].

**Surface Roughness Measurement**

Our tiny robot shown in Fig. 6 has a micro sensor for investigating surface topography of the specified samples [7]. It incorporates small optical devices (LED, light spot detector, micro lens, mirror, and diamond stylus) which provide a simple optical pick-up for surface height monitoring. Here we use the well-known technique of deflecting a light beam through a grain rod lens [8]. The reflected beam at the cantilever with stylus is measured by the spot detector. In the experiment, we succeeded in obtaining a surface roughness curve along the machine path on the wall plane, after combining the measured height change at the robot body and the coordinate position of the moving robot, which was identified by using a CCD camera and a special image analyzer, as depicted in Fig. 7.
Micro Cutting and Accurate Position Monitoring in Local Area

Fig. 8 also shows a small robot with a single diamond tool, driven by a micro stepping motor for producing accurate fine grooves [9]. The machining unit, which includes a micro-diamond tool of 0.5 micron radius and a stepping motor, is also positioned by the piezo element with resolution of better than 0.01 micron. The robot generates fine-scratched grooves, spaced less than 1 micron apart, perpendicular to the moving direction, using a flying micro tool. When the robot moves with the precise step in the specified working area, we need the help of another robot to monitor the motion of the active robot. For this purpose, a miniature robot with an optical displacement detector, composed of a micro LED, PD, and fiber on its head, is designed and fabricated as shown in Fig. 9. It is maneuvered to approach the working robot, whose motion must be measured, and generates the signal indicating displacement ranging from 0 to 1000 micron. Then the closed-loop system, with feedback control in local, can improve tool positioning accuracy between two small robots. This collaborating action successfully provided the ultra fine grooves in Fig. 10, where each line space was controlled to 1 micron [10]. If absolute accuracy over the working field is required, another instrument which can measure the position of the miniature robot with a displacement sensor should be employed. This combination of local and global feedback loops
Combining Centralized and Distributed Control

In order to manage the many small robots mentioned above, we also have to consider how to plan, schedule, and control them using multiple feedback loops, both local and global. There are a lot of research issues which deal with multiple robot motion planning and navigation [10], man-robot and robot-robot communication [11,12], autonomous robots [13], task recognition and decomposition [14], swarm robot intelligence [15], and intelligent planning and dynamic scheduling for flexible manufacturing [16]. But when we consider the actual application of miniature robots to a micro device manufacturing process, we might organize the system under the strategy based on a combination of centralized and distributed techniques [17] because we need both productivity from the viewpoint of a determinate top-down approach and flexibility from that of an evolutionary bottom-up approach. It seems that many planning and scheduling methods have been proposed for such a complicated problem.

Fig. 11 shows the scheme for our scale-down factory model from the viewpoint of the hierarchical levels, production process, and spatial volume, which are factors commonly used in examining such a flexible manufacturing system. Here it is assumed that this system is composed of an operator and a network of processor modules, miniature robots, and monitoring instruments. The first priority of this project is the establishment of a miniature robot system which can be practically applied to micro device fabrication in the desktop environment. However, we must overcome many technical hurdles, such as complete integration of the computation device, energy source, and tool and sensing elements packaged into a miniature robot, and control of many robots with multiple layers of controller structures.

In the actual experimental setup, the microprocessor tip and power source are not implemented yet, but they are capable of being remote-controlled by micro-computers which are linked together by using a shared-memory bus port as shown in Fig. 12. This configuration, well-known as a blackboard communication method, should allow rapid parallel processing asynchronously between the microcomputers, but its application must be limited within the desktop environment. Several microcomputers are to be composed into three levels of hierarchical structure [18] in our system so that they can provide efficient interface to an operator for making the in-
Initial Planning and Scheduling

In this section, we discuss the part of global planning and scheduling which should be deliberated mainly at the level of the highest processor in the first phase, although determining the next process phases for execution is an ongoing development. Fig. 14 shows the structure of on-line simulation for global initial planning which we implement in our system [19]. Here it is assumed that many small robots with simple micro effectors, such as machining tools, probes, and manipulators, are distributed over the work field. The task from the operator should be limited to simple operations which consist of primitive actions generated from miniature robots in this stage. The central main processor can acquire various information, such as specification and actual performance of each small robot, and some machine status through the communication ports, from the lower-level processors which are responsible for machine control. On the other hand, an operator can give his task to the main processor, which should be decomposed to the element of motion compatible with that of the engaged miniature robot. Then the requirement from the operator should be compared to the ability and the operational function of the small robots by the task matching table, where it is decided whether the system can accept or reject the given task. In case of acceptance, the robots should be allocated to each task with the priority given by the operator through experience. Therefore, more small robots should be allocated to the task with higher priority.

When robots are approaching the designated working area in order to organize the working group, it is assumed that they can get their dynamic spatial coordinate positions which are broadcast from the central processor and the monitoring instrument, so they can be informed of other robots in the near field and move autonomously to the target area by using selected collision-avoidance techniques, even though they do not have a vision sensor. Obviously, if a range sensor is implanted in the small robots, they can sense other robots nearby. This knowledge should then be taken into account, although it depends on the technical advancement of sensory elements.

In this dispatching module, graphical simulation can be carried out, and we can evaluate the initial plan based on criteria such as robustness, resource utilization, waiting time, and deadlock. If the operator is not satisfied with the results, he can choose other parameters within the limit of machine performance or navigation strategies. Here, simple collision-avoidance and path-control techniques, as summarized in Fig. 15 [20] are applied, whereby each robot can move toward the goal. If a given robot finds that many robots are heading in its direction, then it may look...
Fig. 15. Navigation and formation control.

Fig. 16. Graphical simulation for initial planning of multiple miniature robots with single precise tasks.

around and change its heading to the left or the right. Even when several robots are heading for a collision in a critical situation, the robot with the lower priority is controlled to stop so that others will succeed in gathering into the specified area to make the specified formation without a collision. After several trials of initial planning and scheduling of different types of rules and navigation are investigated, we can derive the optimal planning data which must be available to the execution stage in the next process phase. In the simulation result of Fig. 16, 18 small robots with the higher-priority task of fine-machining are moving toward the specified working area A, whereas six robots with the lower-priority task of micro-forming are moving to area B. The remaining one with no job is standing by.

Conclusions and Future Plans

In this article we have described a basic structure using several miniature robots with micro tools and sensors. They succeed in microscopic operations such as micro-indenting, micro-cutting, and surface monitoring. The concept of the control architecture, which is based on the combination of centralized and distributed planning and executing in each phase of the production process, was introduced. Also, graphical simulation for the initial planning and scheduling, which includes task decomposition, task matching, task allocation and grouping, and dispatching robots to the specified working area, was demonstrated. We are currently striving to construct a complete system toward desktop flexible manufacturing organized by miniature robots with micro tools and sensors to produce useful micro-devices.

References


Hisayuki Aoyama was born in Japan in 1958. He obtained the Dr. Eng. from Tokyo Institute of Technology in 1988. In 1983 he joined the Research Laboratory of Precision and Intelligence at the Tokyo Institute of Technology. In 1988 he became an associate professor at Shizuoka University. Currently his interests are in micro robotic systems, microfabrication, and precision machinery and instruments. He is a member of the Japan Society of Mechanical Engineering, Robotics Engineering, Control and Instrument, and Precision Engineering.

Futoshi Iwata was born in Japan in 1967. He obtained his master’s degree from Shizuoka University in 1992, then joined Fujitsu Co. as a special engineer of LSI production. Since 1994 he has joined Aoyama’s research group as a research associate. His interests are in microtribology and scanning probe microscopy.

Akira Sasaki was born in 1943. He obtained his Ph.D. from the Tokyo Institute of Technology in 1974. He became professor of mechanical engineering in 1987, and has been a member of the Japan Society of Applied Physics, Optical Engineering, and Precision Engineering. His interests include nonlinear micro optics and scanning probe microscopy and its application to engineering metrology.