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Swarm Control for Automatic Drilling Operation by Multiple Micro Robots

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Abstract

Recently the demand for micro parts fabrication is increasing because many products are miniaturized due to its portable use. A new production system such as "Desktop Factory" is very interesting term in the micro system assembly. Micro robotics system has the potential performance to play the important role in such application with respect to transporting, manipulating and depositing the micro objects. We have developed an automatic drilling system organized by multiple micro robots for many years. In this paper, the swarm control technique for many micro robots can help to execute the micro drilling task on the desktop. This swarm control with the combination of centralized and distributed manners can provide some benefits with accurate and flexible micro fabrication.

1 Introduction

For the demands of modern portable consumer products, the development of production facility for micro scale parts machining and assembling is much of interesting because one of the major trends in industry is to make the products much smaller with low cost. In fact with increasing these miniaturization, it is well known that it should be more difficult for the conventional size mechanisms to manipulate and assemble such small workpieces since they should suffer from the mechanical accurate limitation due to such fabrication error, friction and thermal expansion as well as large energy consumption during operation. Even if it will be possible to improve the machine performances, then it needs much of cost for maintenance [Donaldson *et al.*,1986] . As an alternative solution to this problem, miniature robots which are equipped with micro sensor, manipulator and tool can play an effective role in such small scale production system with much of flexibility and low cost. For these technical backgrounds, there several projects which are associated with miniaturized novel facilities on the desktop have been reported [Kitahara *et al.*, 1998], [Hatamura *et al.*, 1998] . A microrobot based microassembly station under an optical microscope is one of typical styles for the practical application of simple micro parts assembling task although they almost are still in the beginning stage[Fatikow e*t al.*, 1996] ,[Martel *et al.*, 1999]. On the other hand, the practical production facility such as micro drilling operation by the conventional machine tool is based on the combination of the spacial positioning mechanisms for both the tool and the sample relatively with the standardized mechanical slide axes. However the special architecture, layout and strategy not analogous to the conventional manner should be considered for the micro robots system to provide the same function.

In this paper, a new concept of swarm control for the automatic micro drilling system where several piezoelectric-driven miniature robots are employed for transporting the target workpiece, holding the micro drill and cooperating to drive it is introduced. Here the micro robots which consist of a pair of piezoelements for fine locomotion and electromagnets for clamping the surface are developed to provide the positioning resolution at the level of sub-micron. This arrangement can also allow the robot to move not only on the plane surface but vertical wall and ceiling as well. Additionally a micro drill with the reduction gear, a micro motor with the pinion gear and a sample holder are set on each precise locomotion mechanism . In the primary experiment, the special automatic task to perform several small through-holes drilling operation under the CCD camera vision based position feedback system will be discussed to investigate its basic performance and feasibility.

2 Drilling operation by multiple micro robots

2.1 System overview

In Fig.1, an overview of the microrobots-based micro drilling system on going development is illustrated. Each of small robots currently employed in this system has a pair of piezo elements and electromagnets for moving precisely like an inchworm, and is specialized to care of one or two specified accurate operations. This mechanism can provide fine mobility with the microscopic stepping motion and stable clamping on the surface during

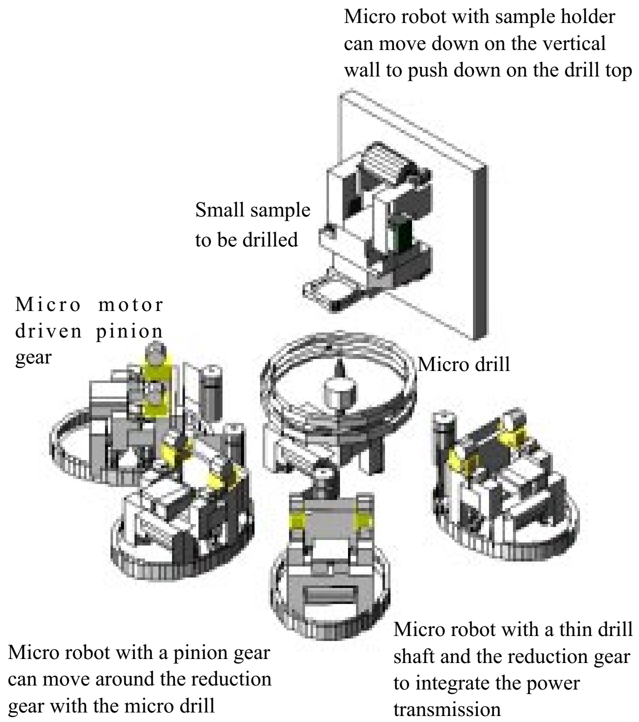

Fig.1 Overview of microrobots based micro drilling system

operation even on the vertical wall and the ceiling over the wide working range, although the target surface is limited as ferromagnetic material. The typical step width at 100V input voltage to the piezo element is about 10 micron, thus it can move at the speed of 1.5mm/s when exciting at 150Hz[Aoyama *et al.*, 1993] . Also the different step width of each piezo element can provide the steering motion. However the electricity and control signal to the robot are still supplied by the wire due to the high voltage to piezo element and high current to electromagnet while it should be improved by the advanced technology in the future. In such micro robots system, it is essential to incorporate with the visual monitoring instrument such CCD camera and the computer facilities to control them[Aoyama *et al.*, 1999]although this visual monitoring system is so complicated. Thus we develop a simple acoustic oriented navigation. In order to realize the actual drilling task, three types of small robots were developed. One of them has a thin drill with the reduction gear on the axis, the others have a pinon gear driven by micro DC motor. The small workpiece to be machined is held on the small robot which can move on the vertical wall. After the positions of both the workpiece and the drill top relatively are decided, the small robots with micro motor can approach to the robot with the drill to drive it. Then the robot on the vertical wall can transport the workpiece down to the drill top and feed it carefully to accomplish the through-hole drilling although more details of the control sequence and the process will be mentioned in the following session.

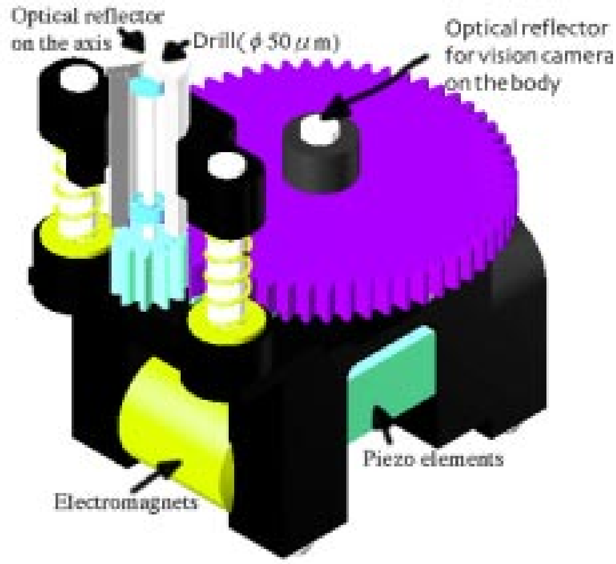

Fig.2 Miniature robots with micro drill and reduction gear

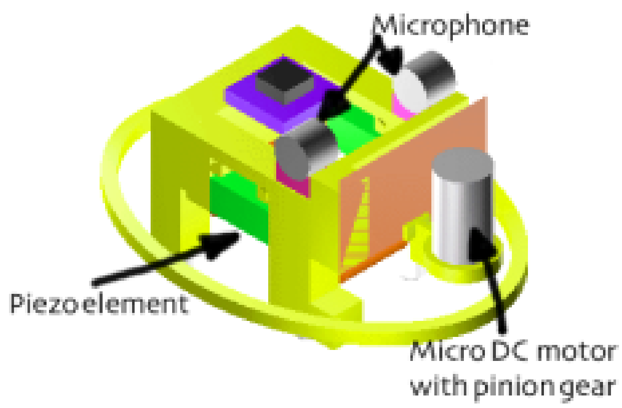

Fig.3 Miniture robots with a DC motor and microphone

2.2 Micro dill with reduction gear

The small robot which has a micro drill with reduction gear on the axis is illustrated in Fig.2. Here the small drill with the diameter of 0.5mm to 0.05mm can be supported by the simple bearing unit on the main body and the reduction gear is attached on the drill shaft. The large size gear can offer the roles of the power transmission as well as multipoint gear contacts simultaneously in any direction when other small robots with a micro DC motor driven pinion gear shown in the next session are approaching it. Therefore the thin drill on the small robot can be transported at the specified position and then be rotated by the cooperation of several small robots to generate enough torque for drilling. And the circular plate with the same diameter of the reduction gear is fixed on the body to keep the appropriate distance between the motor shaft and the drill axis. When the small robot with the pinion gear is approaching to the robot with the reduction gear, at first the motor outer case can be touch in this circular bumper to keep the appropriate gap between two gears

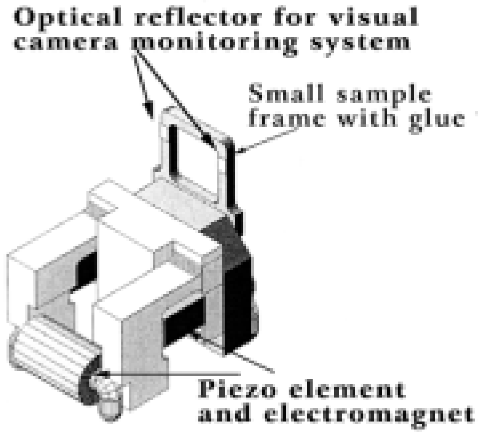

Fig.4 Miniature robot with a micro motor driven pinion gear

for smooth rotation. This simple mechanical arrangement can provide easy distance keeping between two robots in any direction without the external navigating property. In fact, it seems that the simple and reliable strategy is better for such multiple micro robots system rather than the vision based feedback property resulting in high cost and complicated system. There, however, are attached the two small reflectors on the circular plate which should be monitored by the CCD camera vision system to control the robot to the specified location because the relative position between the drill top and the workpiece to be machined is subject of the required task. And this small robot has a simple micro buzzer of 1 KHz sound frequency on its body to identify the location to the other small robots.

2.3 Micro motor with pinion gear and microphones

The small robot which is incorporated with a micro pinion geared DC motor and a pair of microphones with primary electronics are shown in Fig.3. When the buzzer is active, then the differential signal from two microphones is compared and used for switching each of the piezo actuation. This simple sequence can make it possible to navigate the robot to move the sound signal source.

A micro DC motor which is commercially available as a pager motor is equipped on the leaf spring in which the mechanical ON-OFF switch is implemented. This switch can provide the trigger signal for two actions, one is for stopping the small robot locomotion and the other is for activating the micro DC motor, when the small robot comes into contact with the reduction gear of the thin drill. Further more when all of the contact point of two gears on the robots switches are turning on simultaneously, the current to those micro DC motors can be supplied with the help of simple logic electronics. This arrangement also can provide the simple action control in local area without any computational facility although they should be roughly navigated for heading and approaching to the target destination by using new swarm control system by the acoustic oriented navigation as mentioned later. Basically

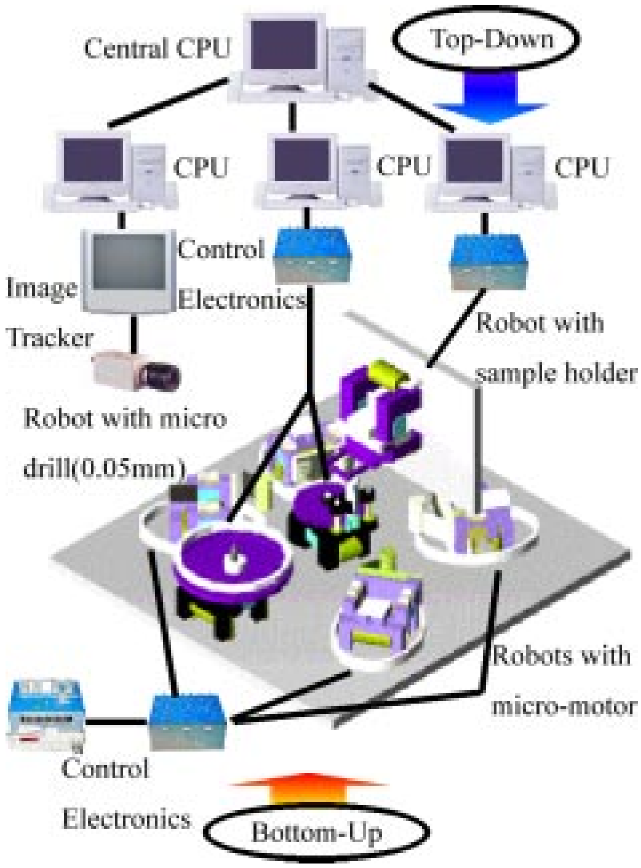

Fig.5 Control system incorporated with CCD camera vision monitorng system and several PCs.

it should be not serious for them to be damaged mechanically by the collision each other, since the piezo driven miniature robots have a low moving speed and a small mass. However the oval outer bumper is attached on the body to decrease the possibility of dead locking.

2.4 Sample holder

The tiny robot with a sample holder is illustrated in Fig.4. As mentioned in the system overall previously, the small robot with the sample holder can move down and up on the vertical wall to execute for transporting the workpiece onto the drill top and feeding it carefully. At the current status, this holder has no active manipulation facility so the sample is glued on the frame. Additionally the small optical reflectors are attached so that the heading direction of the robot as well as the center point of them corresponding to the drill axis can be identified with the help of the visual monitoring camera.

3. Centralized and distributed control system

It is well-known that the control of such multiple robots system is one of the biggest issues because it contains huge aspects of difficult and complicated problems such navigation [Fukuda *et al.*, 1996] , planning and scheduling[Ranky *et al.*, 1992] , task allocation[Lueth *et* *al.*, 1994] , communications[Li,1994] and other domain dependent problems[Sich *et al.*, 1992]. In order to achieve the specified task here, a part of control system is considered at first so that the system can be partly centralized(visulal based feedback in global) and partly distributed(reflective simple action in local). It is expected that the combination of centralized and distributed architecture can give the effective solution in such multi robots system [Pape *et al.*, 1990]. Figure 5 shows the control system where several micro robots with tools, the CCD camera monitoring instrument, the frame image processor and the computational facilities are organized. For preventing the system to be complicated and expensive, one CCD camera which is mounted on the 45 degrees inclined frame to monitor the small robots on the horizontal plane and the vertical one at the beginning stage. The image of the small reflecting markers on the robots with the drill on the horizontal and the sample on the vertical can be extracted and those X-Y coordinate positions can be passed to the central computer by using the fast real time image processing instruments which is capable of providing the high resolution of 5000 x 5000 over the entire vision area with the refresh rate of 60Hz. Since this layout should cause the image distortion on the camera vision, the appropriate simple numerical compensation based on the geometry is considered to get the coordinate positions of two small robots individually. Thus the over all accuracy is estimated 0.1mm over about 400 x 400mm square. It, however, is essential to implement the advanced instrument system to measure the spatial coordinate position incorporated with multiple CCD camera vision monitoring system and several PCs of all small robots. On the other hand, the small robots with a micro DC motor are not maneuvered by vision based system. They can controlled to move toward the reduction gear of the drill by using the acoustic signal based navigation on the robot, and execute the action by the simple trigger based sequence in local.

4. Acoustic oriented navigation and outer frame guidance

Instead of the vision based control, the acoustic signal based navigation is also applied for navigating several small robots with micro DC motor simultaneously. These small robots can simply go forward to the reduction gear and get back after the operation. A 1kHz sound signal which is generated from the buzzer on the central part of reduction gear can be monitored by the microphone on the small robot with a DC motor. So each small robot can navigate itself to approach automatically by switching the piezo elements. However, this simple navigation causes collision as they concentrate to the same location and are not equipped with the collision avoiding function. Since the moving speed of the robot is very slow, there should be no mechanical damages by collision. In order to navigate the small robot with a pinion gear to the reduction gear, the outer frame guidance technique is applied in addition to the simple acoustic based navigation. Oval

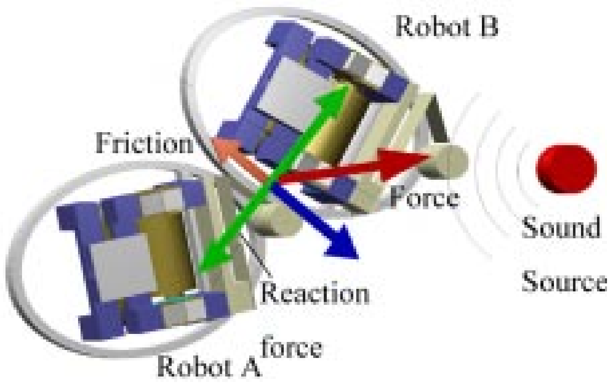

Fig.6 Simple collision model of two small robots with oval outer frame

outer frame is set on each small to provide the smooth contact and guidance. This arrangement allows it to move the target point with geometrical constrain of mechanical contact without any other sensing element although the repeatability should be considered.

5. Oval frame guidance based on slow collision model

To investigate the path behavior after collision of small robots, the simple collision model as shown in Fig. 6 is considered. It is expected that two robots with contact can generated the pushing force each other which is act as the moment force for the heading change. So the small robot can move to the signal source along the outer frame. With the help of the simple mathematical model, the simulation can give us the motion path possibility with respect to the contact point, the collision angle, the friction coefficient as well as the oval curvature. As the result of the simple simulation as shown in Fig.7, the small robot can contact with another robot and then continue to move the signal source under the acoustic navigation control manner. It is obvious that robots move according to influences such as action-reaction force, moment of inertia, and friction. However under certain conditions such as orthogonal collision and the concentration of many robots, the dead locking is expected. In such case another control system should be implemented to recover.

6. Experiment

Figure 8 shows the result of acoustic navigation with an obstacle. It shows that the robot can move along the outer frame and eventually can evade. In Fig.9, another result of acoustic navigation using 4 small robots is shown. Three small robots succeeded in approaching to the robot with drill gear. When the one robot already arrived at the position, the second one can contact with its outer oval frame and then keep moving along it to the goal. According to this experiment, even after the collision of each robot, they can keep moving along the outer frame until the gears come to contact. Fig. Fig.10 and Fig.11 show the overall experimental set-up including the micro robot with a thin drill on the reduction gear, small robots

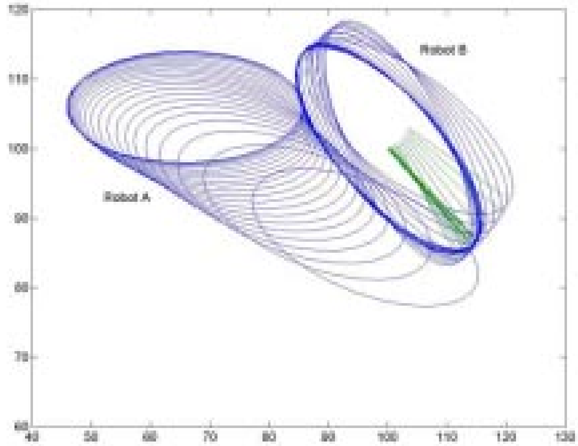

Fig.7 Simulation result of the acoustic navigation model after the collision.

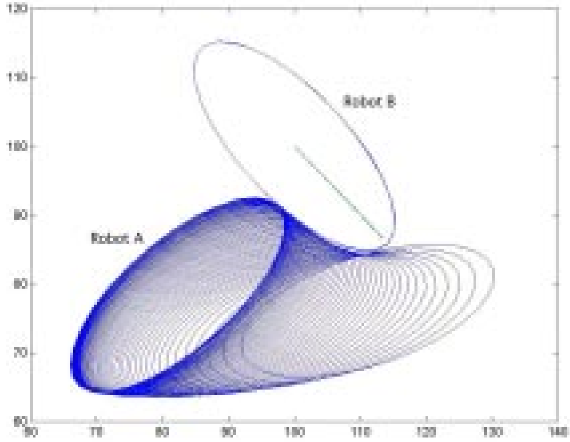

Fig.8 Simulation result of path behavior of the acoustic navigation model(Robot B is fixed)

with a pinion gear on DC motor and tiny robot with the sample holder on the vertical wall. On the top of the set up, the CCD camera instrument is installed to monitor the small robot's position.

Fig.12 shows the result that 15 thin through-holes are successfully drilled on the metal thin plate automatically using the whole system shown as Fig.5. Each hole is designed that the small holes of 0.05mm in diameter can be machined respectively . It is confirmed that the control sequence can control the small robots to transport the sample onto the micro drill top which is also rotated by several small robots with the micro motor driven pinion gear. However the lack of accuracy of the CCD camera based coordinate measuring system caused the error of x-y positioning and the less of repeatability. We need the advanced measuring system with high-resolution and wide working range. And the current system sometimes suffers from the failure in the drill task execution due to the dead locking and the deviation from the assigned path when small robots with the motor driven pinion gear are approaching to the point. We are on going development to improve the system reliability.

As shown in Fig.13, the thin through hole of 0.05mm

Fig.9 Three small robots can approach automatically besed on the combination of acoustic navigation and oval frame guidance

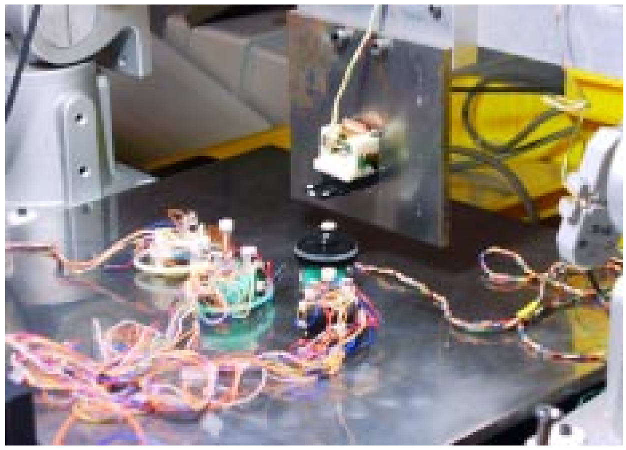

Fig.10 Experimental setup for automatic micro drilling operation by multiple micro robots.

diameter can be machined by the collaboration of many micro robots with tools. That should be the great benefit for the micro production system to provide the flexible micro parts with low cost.

7. Conclusion and future works

In this report, the multiple micro robots system for he micro drilling were introduced. Each small robot has the thin drill with reduction gear, the pinion gear with micro DC motor and the sample holder. And the vision based coordinate system and acoustic based local navigation property are implemented to provide the combination of centralized and distributed control.

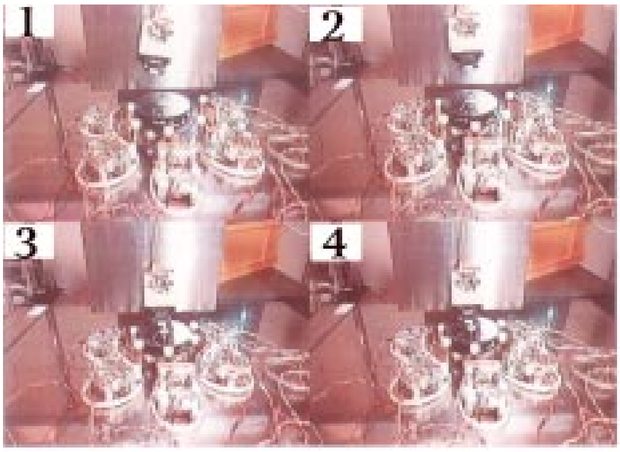

Fig.11 Squential photographs of the micro drilling task operated by small robots with tools.

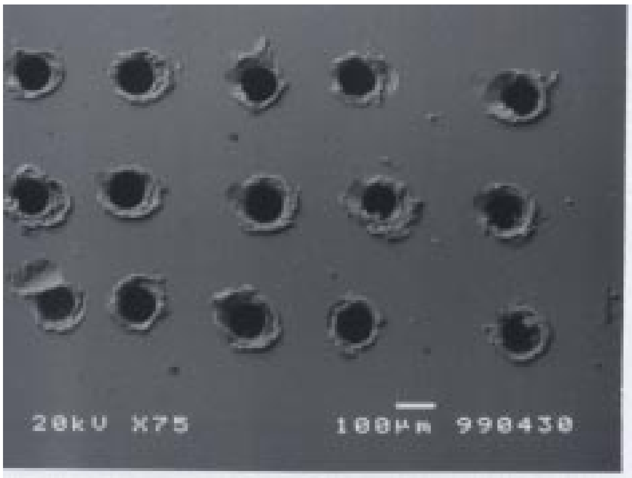

Fig.12 15point micro through-hole machined at in the matrix of 0.2mm pitch

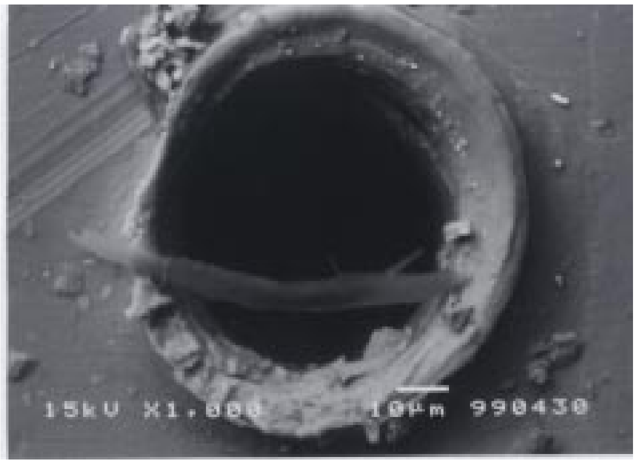

Fig.13 Micro through hole (0.05mm x 1000 SEM image)

As the result, the many thin through holes of 0.05mm can be machined automatically by the proposed multiple micro robots system. In order to improve the reliability and the accuracy, we are developing the accurate coordinate measuring instrument, local sensory elements as well as dead lock recovery property.

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