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A Task-oriented Teleoperation System for Assembly in the Microworld

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Abstract

Operating a robot in the micro/nano-world presents challenges not found in the macro-world. Due to the small dimensions, the operator has no direct access to the objects and must assemble them by teleoperation. To allow a good manipulability, we propose a mixed teleoperation system which is composed of both direct and task-oriented teleoperation modes. The operator is provided with a set of visualization and manipulation tools on a workstation. This paper presents the micro-robot system, discusses some important isues in micro-teleoperation and finally presents some micro-manipulation tasks performed with the system.

***Keywords**: micro-robot, nano-robot, micro-assembly, teleoperation*

1. Introduction

The realization of micro-machines made of micro-mechanical parts is today still limited. Besides the technological difficulties in miniaturization, there is also a lack of tools able to manipulate and assemble micro-parts. The development of micro-robots, i.e. robots with high precision, is thus of great importance. Among the pioneering projects in this field, we can cite the ones of Hatamura [1], Hunter [2], Sato [3] or Johansson [4]. More recently an increase of interest has been observed and several other authors have addressed the problem [5,6,7,8]. The approach to assembly and manipulation tasks in the micro- and nano-world is different to the one followed in the real world. Due to the small dimensions, the operator has no direct access to the objects and a general view of the workspace is usually not available. Therefore, the manipulation of the robot has to be done through teleoperation. Several concepts have already been proposed in the literature in order to teleoperate micro-robots [3,14]. The information on the position of the robot and the objects to be handled has to be provided to the user as well as some manipulation tools allowing to send commands to the robot. Using a pure teleoperation mode is however not always efficient. Moreover, very high precision tasks cannot be achieved by teleoperation only but have to be controlled with a vision feedback. We propose thus in this paper a mixed teleoperation system which is composed of both an open-loop teleoperation and a closed-loop teleoperation mode.

In this paper, we firstly present the nanorobot system used for the experiments. Then, some important issues in microteleopreation are addressed before a description of the user interface developed for the ETH-nanorobot. Some pictures of micro-manipulations performed with the system are also shown.

2. The nanorobot system

A view of the current configuration of the nanorobot designed at the ETH-Zurich (Swiss Federal Institute of Technology) [5] is shown in figure 3. The system is composed of a robot operating under a light microscope equipped with a motorized zoom. To provide the user with visual information, the microscope is mounted with 2 cameras. Their signals are acquired on a Silicon Graphics (SGI) workstation by a Galileo video frame grabber. The images are then analyzed and presented to the operator. A third camera mounted on the side of the microscope provides the user with a side view. A dedicated user interface allows to pilot the robot with high flexibility. For precise movements and for task oriented teleoperation, a vision-based control is used. The vision-based feedback is also realized on the SGI workstation. The workstation is connected with the robot controller by a RS232 line. The controller manages all low level controls, as the driving of the table or the position control of the arms.

2.1. Mechanics of the nanorobot

The robot is composed of 3 independent arms, as shown in figure 1. The first arm is the object carrier, or Abalone arm and has 4 dof. It is composed of Abalone [9], a 3 dof (x,y,ψ) planar mechanism and a z micrometric table. Abalone relies on the impact drive principle [10] and is actuated by 3 piezoelectric elements. Two modes of operation are provided. Within the range of the piezo elements (5 µm, resp. 0.6 mrad) fine positioning with a resolution better than 1 nm can easily be achieved. For larger displacements, the impact drive principle is used. Abalone is placed on a z-stage which is driven by a DC motor with a repeatability of 1 µm. The second arm, or tweezers arm has 3 dof. It is equipped with a microfabricated gripper [11]. A xz-stage driven by 2 DC-motors provides the 2 translations of the tool which can be positioned at the center of the field of view of the light microscope. The repeatability of the device is 1 µm. A piezoelectric rotating actuator [9], allows the rotation of the gripper about the y axis of the stage with a resolution of 0.1 µrad. The third arm, or pipette arm has 2 translational dof only provided by a yz-stage driven by 2 DC-motors. It is mounted with a pipette connected with a vacuum control unit [12]. The positioning repeatability is 1 µm.

This configuration offers actually redundancy between the 3 arms. This is needed to allow each tool to be moved to or retracted from the field of view of the microscope. Rough motions can be achieved by all of the arms. Fine motions are executed by moving Abalone only.

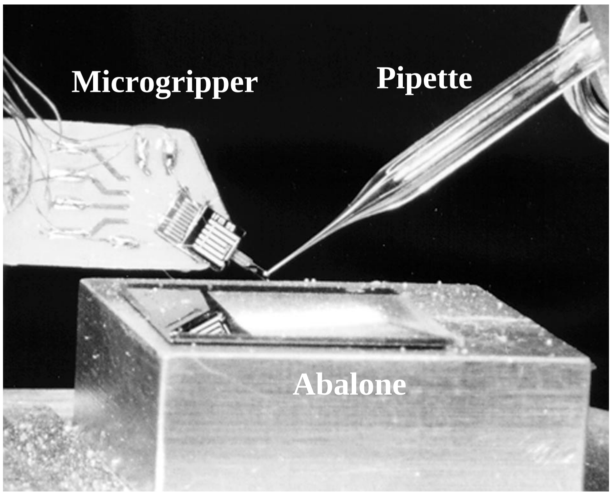

Fig.1: The 3 arms of the nanorobot working together

2.2. Vision-based control

For high precision movements and for task oriented teleoperation, the robot has to be controlled automatically. In the microworld it is imperative to use a sensor able to measure the relative distance between the tool center point and the object to grasp [5]. In our approach, we use the images provided by two stereo cameras to measure this distance. For highly accurate manipulations the parameters describing the relationship between the image frame and the frame attached to the robot must be continuously and accurately updated. These parameters are unknown a priori and are not directly measurable, but can be deduced by observing the scene change during motion [16]. The final position accuracy is better than 300 nm for translations in x and y and 0.1 degree for the rotation about z. This very high accuracy of position measurement, which exceeds the resolution of the light-microscope, is achieved with a least-square template matching algorithm [13].

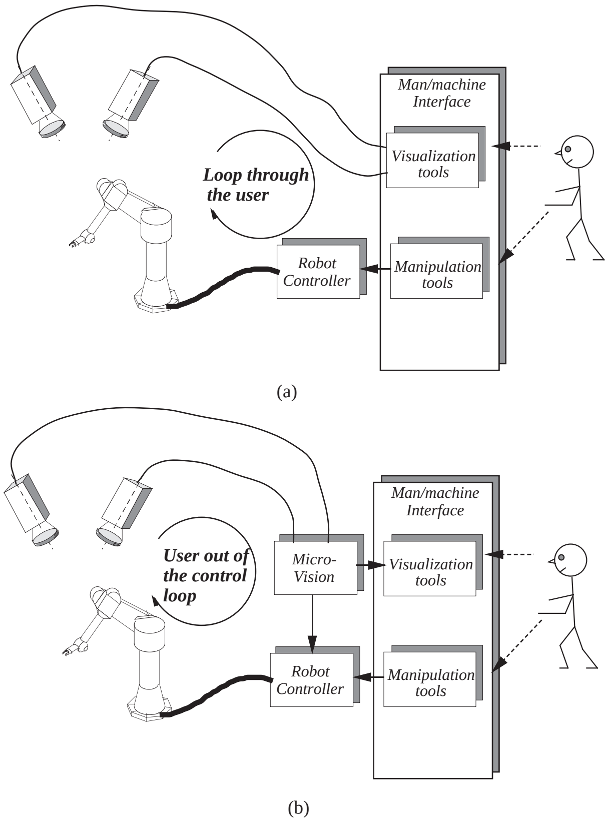

Fig.2: Two modes of interaction with a micro-robot: (a) teleoperated, (b) semi-autonomous.

3. Strategies in micro-teleoperation

The micro-world requires operations to be performed under a microscope. As described by Sato [3], the microscope is the dominant device in micro-handling systems for the following reasons: 1) it is the largest and heaviest system component, 2) its field of view is much smaller than the system, 3) higher is the magnification ratio, smaller is the working distance. This limits actually the workspace of the robot to the field of view of the microscope. Thus, contrarily to macro-robotics the robot surrounds its workspace, and therefore the tools only (or part of them) are seen during manipulation tasks. The image is usually provided to the user on a monitor. The most natural way for the user to give commands to the robot is then in the image coordinates directly. As a consequence, ***the microrobot should be teleoperated in the image space***.

Another aspect linked to the small field of view is that a small portion of the working area only can be seen at

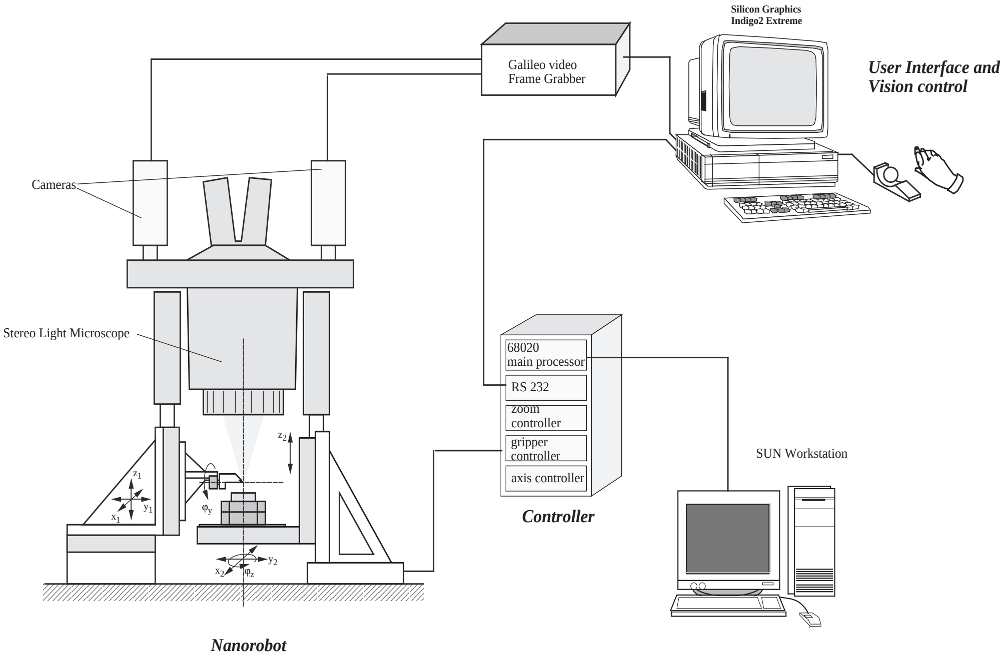

Fig.3: Set-up of the nanorobot system

the same time. This is often constraining and unpleasant for the operator, especially when the parts to be manipulated have to be carried from distant places. For easier operability, a ***map of the whole working area has to be provided to the user***. By pointing to a specific portion of the map, the operator should be able to specify which area he would like to have under the microscope. The robot should then move automatically under vision control to the specified location. The map can be provided in two ways: 1) with a low magnification picture of the area, or 2) with a solid model view of the scene. For the latter, correspondence between objects in the model and objects of the real world has to be frequently updated. Micro-objects and micro-tools are very fragile and have thus to be handled with care. Therefore, a ***direct teleoperation***, as proposed in figure 2.a, must be avoided for operations where collisions between the components of the robot are possible. In direct teleoperation, the user is inside the control loop, and thus all movements or commands of the operator are executed as this by the robot. A better solution for operating in the microworld is to have the user outside the control loop, as shown in figure 2.b. The operator gives then “high level” commands to the robot, such as: move to goal through a set of passing points, move in a specific direction until getting into contact with the object, pick object, release object, and so on. In this case, we speak of ***task oriented teleoperation***. This requires however a certain autonomy of the robot system such as automatic control of movements and is thus more difficult to program than the direct teleoperation. For some tasks, dedicated sensors are necessary.

Forces acting in the microworld are different than the ones we are used to in the macroworld. Gravity is almost negligible compared to adhesion or electrostatic forces when objects are smaller than 100 µm [15]. Phenomenons such as objects sticking together or sticking to the handling tool have thus to be expected. Due to elasticity of the tools, if too big forces are applied to sticking objects, they can be flicked off and never be found again. It is hence necessary to have ***force monitoring*** or ***force feedback*** capabilities.

In this section we discussed some important issues in the teleoperation of microrobots. We will now show how this has been implemented in our robot system. A special attention will be put on the comparison of the two teleoperation modes.

4. User interface

The user interface consists of a set of visualization tools and manipulation tools programmed on a Silicon Graphics workstation. Both direct and task-oriented teleoperation modes are available. We present first the visualization tools before discussing the teleoperation modes.

4.1. Visualization tools

Visualization tools can considerably improve the speed, accuracy and simplicity of teleoperation tasks [17]. In our system, two live video images are presented simultaneously to the user, a top view and a side view. The side view is displayed on a separate monitor on the side of the SGI screen. It turned out to be very useful to visualize the height of the objects and is mostly used by the operator in docking phases. The top view is displayed directly on the screen of the SGI. A status panel providing information on the position of each arm relative to a specified origin is also available.

In order to allow the user to know its absolute position at all times, a global map of the scene has to be provided to the user. The map can be a low magnification image or a solid model. Thus, feeding and working place can be seen simultaneously on the screen. By pointing with the mouse to a specific portion of the map, the user specifies in which area he would like to work next. The robot is then moved under vision control so that the desired area is brought in the field of view of the microscope. In our case, we choose a solid model as the global view. The advantage is that the solid model is very easy to manipulate. Other view points are easily selected and it is easy to move a cursor in the 3D model. It has three visualization ports: two orthogonal views (top and side, as for the cameras) and a perspective view. On the perspective view, the user has the capability to change the view point, zoom in and out, and set a home view point. The orthogonal views can also be zoomed as well as translated. A drawback of this solution is that a correspondence between the model and the real scene is needed. In our approach, the model does not require high precision, and thus only a rough estimation of the position of the objects and tools is needed. When motions are performed, the final approach is precisely controlled by the vision control. Using a low magnification image of the scene has the advantage that no correspondence is needed. However, it is more difficult to specify a position in the space with this technique.

4.2. Direct teleoperation

A good set of visualization tools provides a mean for identifying objects, goals and motion paths. Manipulation tools are the complement required to perform these actions precisely. These manipulation tools allow the user to perform both rough and fine linear and angular maneuvers. The work table as well as the gripping tools can be moved in open-loop mode by using the robot control panel or a spaceball. The control panel is divided into 4 areas as shown in figure 4: the top one for piloting Abalone, the middle and bottom ones for the manipulation of the handling tools, i.e. the gripper and the pipette. The right area is used to select the linear and angular increments of each step. As discussed in section 3, the teleoperation is realized in the image space. Thus the commands given by the operator have to be transformed in compatible movements of the robot. A coordinate transformation is thus needed. In our case, the robot is built such that almost all translational axes are orthogonal to each other and aligned with the image coordinate system. The only transformation that occurs is for Abalone because it is free to move with 3 dof on the plane (x,y,ψ). Since the commands are given to Abalone in a coordinate system attached to it, the translational commands have to be multiplied by a rotation matrix of angle ψ before being executed.

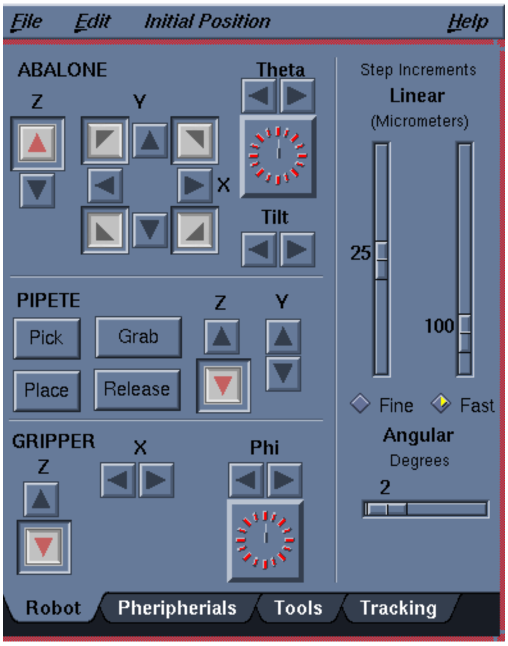

Fig.4: Robot control panel for direct teleoperation

In the direct teleoperation mode, the movements of Abalone are performed open-loop using the impact drive principle. In this case, the accuracy of motion is about 1% of the total traveled distance and it consequently deviates from the estimated position. Particularly the angle has to be frequently updated to keep the coordinates right. In order to do that, a special update function is provided. The robot performs several movements while a vision algorithm tracks features on the robot. From these movements, a new estimate of the angle and the position of Abalone is calculated and the coordinate transformation is updated.

A second manipulation tool is a 6 degree of freedom spaceball. It is used to control the X,Y,Z and rotational position of Abalone. The user can disable the translations on the Z axis as well as the rotational movements. The magnitude of the linear and angular movements is related to the pressure applied to the control device. A sensitivity factor is also included in order to adapt to different users. The absolute position information on the control panel as well as the absolute position of the 3D model are also updated.

Three reference systems can be selected by the operator: Abalone, pipette or gripper. The motions of the other arms are then performed relatively to the selected reference system.

4.3. Task oriented teleoperation

For precise motions, and to increase the speed and safety of operation, a task oriented teleoperation is implemented. This mode of operation consists in a series of tasks performed automatically by the system but supervised by the operator. In our system, some tasks have been defined such as: 1) pick object, 2) place object and 3) move to goal through a set of passing points. All these actions are performed with the aid of a vision control. The procedure for the third task is depicted in figure 5. An object is selected directly on the image. A goal position for this object is then also specified graphically using the mouse. Two passing points with tolerances for both the position and orientation of the object are then selected. The robot is then driven automatically toward the first passing point. Its movement is precisely controlled by vision feedback. The procedure stops when the goal position has been reached with the user's selected accuracy. In this mode, positioning accuracy better than 300 nm is achieved. This is far beyond the resolution of the microscope and is not realizable by direct teleoperation.

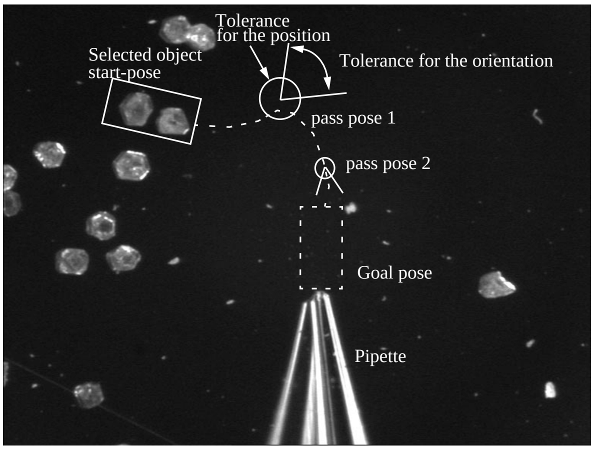

Fig.5: Definition of a path through a set of passing points (task-oriented teleoperation)

5. Results

Several benchmarks were designed to test the object positioning capabilities of the system described above. One benchmark was the positioning of small diamond crystals with size 100 micrometers on a silicon wafer, as shown in figure 6. Two approaches were taken to achieve the task: 1) the diamonds can be shoved on the silicon plate or 2) it can be picked up with the pipette and placed at the right position. Three hours were required to write “ETH” with the first strategy. By picking up the objects this time could be reduced to 30 minutes.

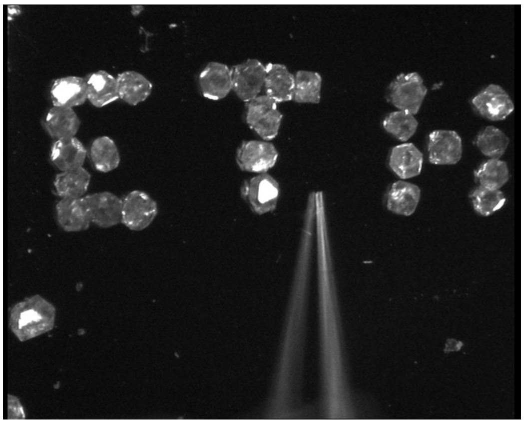

Fig.6: Writing a text by moving diamonds (top view)

Other kinds of tasks performed with the system are the assembly of micro-ball bearings or micro-planetary gears, as shown in figures 7 and 8. For this last task, both of the tools have to work together. The pipette is actually used to correct the orientation of the shaft between the 2 fingers of the microgripper.

There are however some handling problems in the micro world that prevent us from a fully automatic execution of the task. As mentioned before, in the microworld the objects tend to stick to the tool. Since it is difficult to control this automatically, the user has to supervise the process and stop the action if this happens. Another approach would be to combine both task-oriented teleoperation and direct teleoperation in a task sharing teleoperation mode as proposed in [18].

6. Conclusion

The handling of objects in the microworld requires a user interface which allows the operator to visualize the objects and the handling tool and to manipulate them precisely. This article presented some strategies that have to be implemented in order to navigate in the microworld with a high precision robot. The implementation of this tools was described and test results were presented. Both direct teleoperation and task oriented teleoperation modes are provided to the user. It has been shown that using the closed-loop teleoperation mode, operations are performed faster, safer and with higher accuracy. An automatic execution of the task is currently being programmed, but the sticking problems must be solved firstly.

Fig.7: Manipulating a micro-pinion with both a microgripper and a pipette

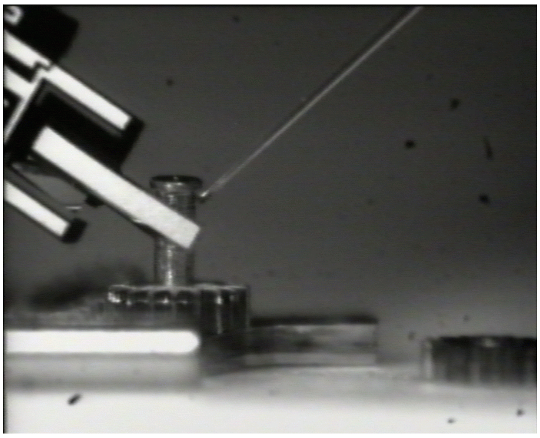

Fig.8: Inserting a shaft into a hole with a microgripper and a pipette

7. Acknowledgment

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