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High Precision Robots for Automated Handling of Micro Objects

Alain Codourey, Wolfgang Zesch, Roland Büchi, R. Siegwart
Inst. of Robotics, ETH-Zürich, CLA, 8092 Zürich
Tel. +41 1 632 69 89, Fax +41 1 632 10 87
e-mail: codourey@ifr.mavt.ethz.ch, zesch@ifr.mavt.ethz.ch

Abstract

Nanotechnology is a key issue in today's and tomorrow's development of advanced products. Soon new tools will be needed to automatically handle and assemble micro-sized objects with nanometer precision, or simply to give human beings the capability of operating in those tiny dimensions. Seeing emerging applications in this field, the Swiss Federal Institute of Technology at Zurich (ETHZ) decided to focus an interdisciplinary project on the theme "Nanorobotics", i.e. automated handling of microparts with nanometer resolution.

In this paper, after a short description of the goals and the approach taken in this project, some important aspects of the design of high precision robots are stressed. It is especially shown that if a minimum of 6 independent degrees-of-freedom (dof) is required to freely position an object in space, redundant robots will lead to less complicated and more efficient mechanical structures. It is then shown, that if a global sensor is used, measuring the relation gripper-object, the only requirement for the mechanical structure is a good resolution.

Finally, two new 3 dof planar robot designs are presented. Both of them have unlimited range of motion while having a resolution down to 10 nm. One of them has been controlled using a vision feedback under a light microscope and showed very promising results.

Keywords

Nano Robot, Micro Robot, Micro Assembly, Precision Mechanism

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1. Introduction

The development of advanced products requires more and more accuracy and the tendency moves toward smaller components. Today, most of those tiny mechanical structures are machined directly into a silicon wafer using chemically based machining techniques which created the success of the micro-electronics industry in the past. Unfortunately, these techniques allow only plane machining, so that 3 dimensional structures are very difficult to realize. Building 3D components often requires an assembly phase, i.e.manipulating the objects in space applying forces during the attachment process. While the problem is already solved for the "human-sized" components by using robots or assembly machines, there is still a lack of tools for tiny structures which require high accuracy to be assembled. Thus the development of micro- and nano-robots with high precision is of high importance. Envisioned applications are:

- mounting of hybrid chips (e.g. Laser diodes), microsensors and micromachines
- positioning and mounting of optoelectronic devices
- microsurgery
- sorting of biological cells for diagnosis

In order to gain experience and to bring new tools for the assembly of micromachines, a project has been started at the Swiss Federal Institute of Technology (ETHZ). The goal is to realize a nano-robot for the handling of micro-objects with ten nanometers accuracy. After a short description of the project, considerations on the design of high precision robots will be stressed. A new kind of robot with 3 degrees-of-freedom is then presented, as well as its control system.

2. The ETHZ-Polyproject

Seeing emerging applications in micro- and nanotechnology, the Swiss Federal Institute of Technology in Zürich ETHZ decided to focus an interdisciplinary project on the theme “Nanorobotics”, i.e automated handling of microparts with nanometer resolution. The goal of the project is to design and build a nano-robot system (Fig.1) with the following specifications:

- resolution better than 10 nm within a workspace of 1 cm^3
- a minimum of 5 degrees of freedom (dof) for positioning the tool
- micro-machined gripper with integrated sensors to pick and place micro-sized objects
- suitable for vacuum and clean room conditions
- small size, to fit into a scanning electron microscope’s (SEM) workspace

The system is composed of a robot operating under a light microscope or a stereo SEM. A stereo vision module and probably additional sensors (laser interferometer) will be used to locate the objects and the robot gripper. This information is sent to the main control computer which will move the robot in an appropriate way. The commands are given by a human operator through a virtual reality-based user interface. Stereo views, force and sound are among the feedback signals that will be provided to the user. It will thus be possible to use the system either as a teleoperated (like in [Sato 93 and Morishita 93]) or as a semi-automatic mode of operation. In the latter, only final and/or intermediate goals will be specified by the user, the control being made by the stereo vision feedback.

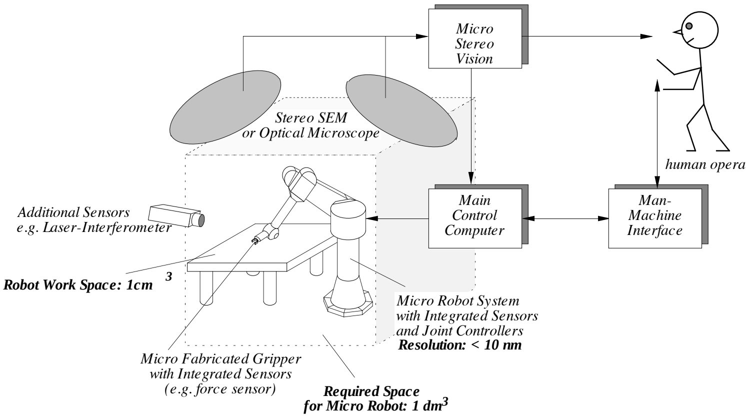

Fig.1: The Nanorobot System

The handling of small octahedral shaped diamonds with a size of about 50 µm is a benchmark that has been specified giving consistency to the project. These diamonds have to be placed into holes etched into a silicon wafer, for epitaxial growing of pure diamond. Orientation and position must be controlled.

In order to achieve these goals, new studies must be launched and new devices be designed. Five topics have thus been identified as subprojects: nanorobot system, vision, contact forces, microtools and mechanical properties of microstructures. In the following sections we will present the robotics part of the project that is the general design aspects and the control of the nanorobot. The different laboratories of the ETHZ involved in the project are: Institute of Robotics, Institute of Mechanics, Image Science Lab, Institute of Cell Biology, Institute of Solid State Physics and the Laboratory for Electronic Engineering and Design.

3. Definitions

Before discussing the problems occurring and the strategies to adopt in high precision robotics, it is worth to recall some basic definitions that must not be confused [Smith 92, Slocum 92]:

- *Resolution*: smallest discernible change in the parameter of interest that can be registered by a particular instrument or the smallest mechanical step the machine can make during point-to-point motion.
- *Repeatability*: a measure of the scatter of results obtained if an attempt is made to exactly repeat a given operation. It is lower-bounded by the resolution.
- *Accuracy*: deviation of the measured respectively the achieved value from the "true" one.
- *Precision*: is in this context used as a synonym for resolution.
- *Dynamic Range*: ratio of range and resolution.

4. Basic considerations for the design of high precision robots

In robotics, like in every controlled systems, the final accuracy is strongly linked to the resolution of the sensor and its location, the behavior of the mechanics and the control algorithm used. We will discuss some of these points in the following.

• Sensors

For classical robots, the sensors are usually at the joint level. Assuming that the links are highly rigid, a geometric model is calculated to transform the sensors information into a position and orientation of the tool center point (TCP) in an absolute cartesian frame. This technique leads to a poor accuracy but to a good repeatability, most of the errors being due to offset miscalibration and link deformation. If higher accuracy is needed, a calibration is often proposed. However, when dealing with nanometer precisions, many sources of errors are not predictable, and cannot be corrected in a calibration process. It is then imperative to use a sensor able to measure, with the desired resolution, the relative distance between the TCP and the object to grasp. Among the sources of error that could affect the precision of the robot we can list:

- friction, mechanical play
- thermal drift
- fabrication tolerances and misalignment
- mechanical deformations due to forces
- vibrations (internal and external) and noise
- sensor errors, miscalibration.

The ideal sensor would measure this relation with the highest possible resolution (at least better than 10 nm), in 6 degrees-of-freedom (dof), and with a very high bandwidth (> 10kHz). Unfortunately, this ideal sensor doesn't exist yet and a compromise, eventually a combination of several sensors, has to be found.

In our approach, we decided to use either a stereo light microscope or a stereo SEM for that purpose. Neither of them is ideal, the light microscope having a poor resolution and the SEM being slow and constraining. This is nevertheless a starting point that have the advantage of providing a stereo view of the scene to the user, enabling a rough teleoperation. Some additional sensors, like force sensors or proximity sensors mounted directly on the gripper (we will call them local sensors) would be of great help but have still to be designed. Scanning tunneling microscopes (STM) and atomic force microscopes (AFM) or derivatives could be among these local sensors in a mean term.

• Mechanics

It is obvious that a good mechanics will lead to better performances of the overall system and will simplify its control. We discuss in the following some important aspects to be aware of.

If the sensor system is able to measure directly the relation between the TCP and the object, the robot must not be accurate anymore. The only requirement is a high resolution, that is the smallest achievable step. This leads to completely new solutions that are much more tolerant in fabrication and are easier to handle. A careful design is however necessary and a special attention has to be put on the elimination of backlash and Coulomb friction. The difference between the dynamic and static friction coefficients is the cause of the stick-slip effect in classical mechanisms. This effect gives a lower limit to the reachable resolution. It is very expensive and almost impossible to go down to nanometers with such drives. New designs must be found trying to avoid friction in the bearings or better, to avoid bearings. Piezoelectric elements are well suited for that purpose and have already been used extensively like in the first STM and AFM [Binnig 86]. Unfortunately, the range of motion is very limited. Several concepts have been proposed to increase it while keeping the high precision. We can mention, for example, the Inchworm® principle (see for ex. [Morishita 93]), the impact drive or inertial drive [Le Letty 94, Higuchi 87] or lever based drives [Scire 78].

In our case, the dynamic range is especially high (120 dB, i.e. 1cm : 10nm), which is really a challenging effort if we compare to other systems:

- conventional robot: 1 m / 100 µm = 80 dB
- human arm: 0.5 m / 0.5 mm = 60 dB
- high quality NC-milling machine: 0.5 m / 1 µm ≈ 114 dB

Two different solutions have been investigated for solving the range problem. Firstly, one could try to cascade two actuators for the same direction in a **redundant configuration**. The first one is used for the large movements and has a range from 10 mm to a resolution of 1 µm while the second one for the fine positioning operates from 10 µm down to 10 nm (Fig.2). It is important to give the system an overlap of at least a factor of 10 in order to achieve a reliable, smooth and fast operation. The control strategy has to deal with this redundancy and if implemented carefully, this configuration can be seen as a single actuator, easing the robot's main control.

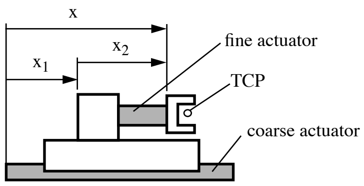

Fig.2: Redundant Drive

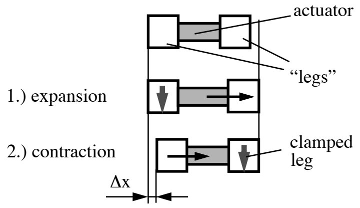

Fig.3: Stepping Mechanism

The second principle is a copy of the nature: basically, animals operate in a local area with the limited range of their legs. They can however travel big distances by **walking**, using, again, their legs (Fig.3). The Inchworm® is a direct inspiration of this idea. The Inertial Drive relying on the inertia of a mass and the non linearity of friction adopts also somehow the idea of a walking mechanism. Moving step by step has the big disadvantage that controlling a force during the movement, for instance for cutting a cell or inserting a peg into a hole is almost impossible due to non continuous displacement operation. Inserting a compliance softens the force peaks but decreases the system's bandwidth and probably its accuracy. A much better way is the usage of a second, local and redundant actuator to compensate for the discontinuities. The control is not obvious but will lead to a good behavior.

The behavior of a shrunk system can be analyzed by the mean of scaling laws. It is not the purpose of this paper to discuss this subject, but it is worth noting that an homothetic reduction of an object does not affect the angles. In other words, this means that if a very high precision is required for linear actuators in the nanoworld, rotations do not require much precision than in macro-scaled machines. The problem with rotations is rather to find a very small actuator which can be placed close to the TCP, avoiding too much travel of the linear axes to compensate for the drift caused by non centered rotations.

A problem occurring when using a stereo microscope is also the limited field of view. This can be solved either by moving the microscope or a table carrying the objects and the robot. Because of the size and weight of microscopes, the first solution is impracticable, especially for the SEM. Thus we propose to split the degrees of freedom in two parts, one for the table and the other for the robot itself. The table will be used to bring the area of interest into the field of view of the microscope. The robot itself will have a workspace limited to the field of view of the microscope and will bring the high resolution. This solution is proposed and called two arms robot by [Sato 93] and [Morishita 93]. A redundancy in the total number of dof will help designing a simpler robot structures. This higher demand in dof is paid off by a more complicated electronic hardware and an increase of control power. However this higher costs are worth being; they will lead to more flexible and smoother systems.

- **Control**

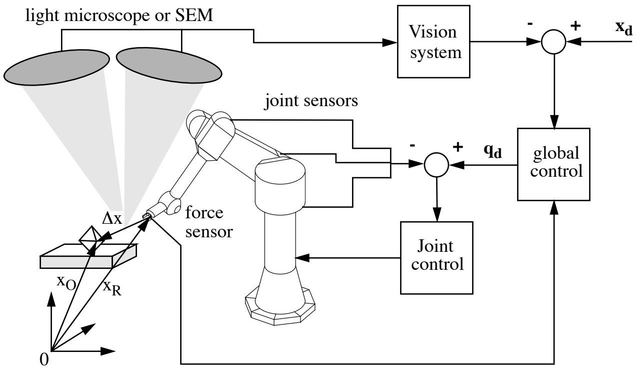

Fig.4: Control Strategy

It will not be possible to acquire the new position at a high rate with the vision system. In order to achieve an effective motion it is necessary to move “blind” while the vision is calculating the new data. To assure a proper operation and above all the stability of the arm, a fast joint position control is needed. The resolution of the joint sensors must be as good or even better as the wanted system’s resolution, but locally only. The control loop will thus be cascaded, like shown in figure 4.

5. The Micro Crawling Machine

The micro crawling machine we have built first can basically be assimilated to 3 DOF Inchworm. It consists of an inner and an outer platform which are connected by three symmetrically arranged piezo actuators between flexible joints (Fig.5). Each of the platforms is equipped with electromagnetic coil allowing them to clamp on a ferromagnetic base plate. The crawling sequence consists of two steps. Firstly while clamping down one platform to the ground the other one is moved using the piezo actuators until the desired displacement is reached. In the second period that platform is clamped while the first is released and the actuators perform the same movement as before to their resting position and so on (Fig.3). By controlling the actuators in an appropriate way, the mechanism allow any movement and rotation on the ground table with nanometer resolution. Due to the electromagnetic clamping, the crawler can not only move on the table, but also can push loads, climb up a wall or even crawl upside down. For fast movements it is controlled like a stepping motor using maximum displacement (about 5 μm at 150 V). In the fine positioning mode, the actuators are continuously controlled while clamping down the outer platform. The accuracy is controllable down to 10 nm. The prototype has dimensions of about 60 mm by 60 mm, but can easily be scaled down.

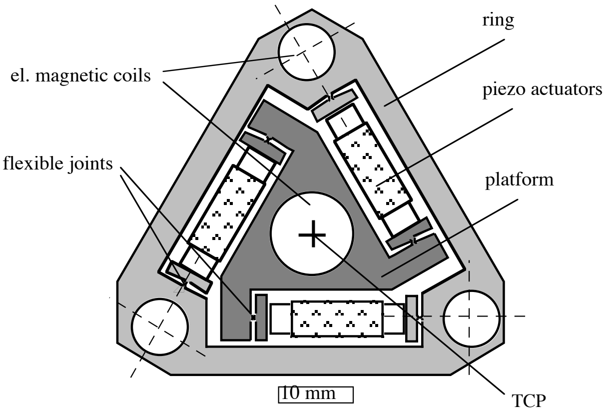

Fig.5: Micro Crawling Mechanism

Looking forward to a usage of the system under a SEM we decided to change the mechanism in a way, that no electromagnetic components are used, their magnetic emissions making accurate measurements in a SEM impossible. Therefore the principle of crawling was dropped in the second design an replaced by an inertial drive principle (Fig.6) arranged in the 3-symmetric structure described above. The basic principle is as follows: a mass (m_1) laying on the ground is connected to another mass (m_2) with a piezoelectric actuator.

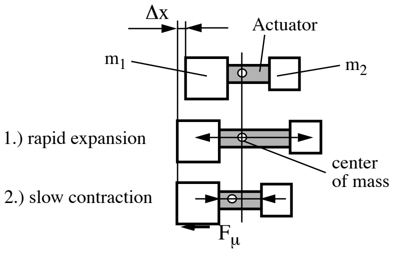

Fig.6: Impact Principle

In the first phase the actuator is elongated very rapidly, forcing both masses to move away from the center of mass. In the second step, the element is contracted slowly moving only m_2, $m_1$being held by the Coulomb friction. With this method it is possible to move on almost every surface since the speed becomes independent of the friction coefficient. To withstand the high dynamic loads the piezo elements have to be preloaded. This structure is currently being tested.

6. Control with Real Time Vision Feedback

The 3 dof magnet-based micro-crawling machine described above has been controlled successfully under a light microscope. The control setup consists of a VME compatible 68020 microprocessor board and a vision board that collects the information of a CCD camera mounted on the microscope. A primitive user interface allows the operator to give commands to the system (Fig.7). The program is written in XOberon, a real-time kernel developed in our lab. The system supports two modes: firstly, the robot can be driven directly with a space mouse® (Logitech) used as a 3D joystick. During the motion the operator is supplied with the original image displayed on a video screen. and with the 3 coordinates of the calculated in 100ms by the low level vision system. This can be assimilated to a teleoperation like in [Sato 93] where the operator has direct access to the robot’s motion. No force feedback is however provided. The second mode is called semi-automatic. It allows the user to freely position a 3D cursor on the screen and then let the mechanism move toward this new goal. In this case, the control loop is closed by the computer and not by the operator who is just a supervisor. A new measured position is provided every 100ms by the vision process. In-between, the robot moves blindly. It is thus possible to control the mechanism inside the field of view of the microscope with an accuracy of 5 μm. The final accuracy is only limited by the resolution of the microscope in that experiment, the robot being controllable down to a couple of nanometers.

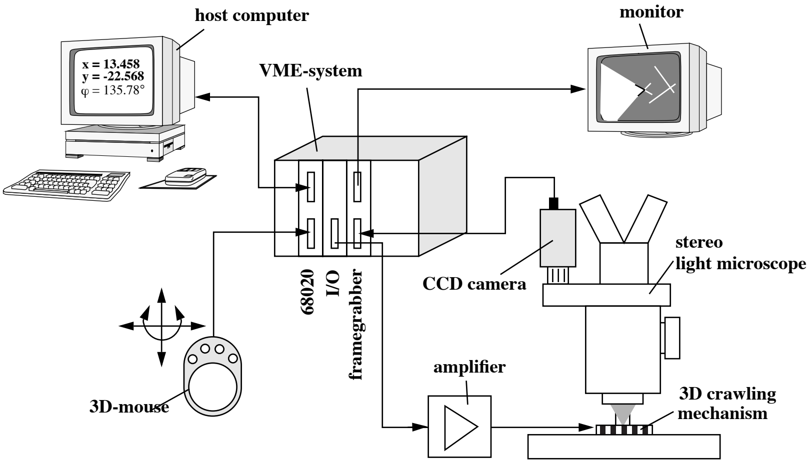

Fig.7: Nano control system

With this experiment, we noticed a bad behavior and non-predictable motion of the robot. By closing the loop with this global sensor, it was however possible to achieve a good accuracy. This validates our approach and the assumption that only a good resolution is required for the robot.

7. Conclusion

The ETHZ nano robotics project, which started in 1993 has been presented. Its goal is the building of a 6 dof nano-robot system for handling and manipulating micro-sized objects with a precision of 10 nm within a workspace of a 1 cm^3. To achieve precisions in the order of magnitude of the nanometer, new mechanical design must be elaborated, as well as new control strategies. It is furthermore shown that an increase of the number of dof will lead to less complicated mechanical structures and to better performances.

Two new robot designs were discussed, which, we hope, are starting points in the developments of microworld applications. Both of them are planar 3 dof mechanisms with a theoretically infinite work space and which should reach the desired resolution of 10 nm. The first one is a micro-crawling machine with electromagnetic clamps. It is based on an Inchworm-like principle and can move along, loads much bigger than its weight. The second one relies on an inertial principle that allows working in the cavity of a SEM.

Closing the loop with a vision system showed promising results. It was possible for the operator to move the robot in a light microscope’s field of view (0.9 x 0.7 mm) with an accuracy of 5 µm. It has even be possible to compensate for the bad behavior of the robot. Operating under a SEM should show much better results, since the achieved accuracy is primarily restricted by the resolution of the microscope/camera system.

8. References

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