CONTROL ARCHITECTURE OF A FLEXIBLE MICROROBOT-BASED MICROASSEMBLY STATION

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Abstract: The assembly of complex microsystems consisting of several single components (i.e. hybrid microsystems) is a task which has to be solved to make mass production of microsystems possible. Therefore, it is necessary to introduce flexible, highly precise and fast microassembly methods. In this paper, the control system of a microrobot-based microassembly desktop station that has been developed at the University of Karlsruhe, will be presented from the lower to the planning levels. This comprises vision-based closed-loop control, user interfaces, a re-configurable computer-array, execution planning and assembly planning algorithms tailored to the needs of the microassembly station.

I. INTRODUCTION

There are particular problems with the mass-production of microsystems which can today be produced with structural dimensions in the micrometer range. Such systems usually consist of several microcomponents made of different materials and manufactured by different microfabrication techniques. These components must be very exactly assembled in one or more steps to form the desired microsystem. Often it is necessary to combine conventional components and microcomponents, which requires very accurate positioning and high flexibility on the part of the assembly system. The microassembly facilities which exist today are rather large, are usually tailored to a specific task and depend on the manual skill of the operator. In conventional systems there are drives with mechanical transfer elements, which are subject to frequent mechanical wear and maintenance, making the systems expensive. Direct-driven few cm^3 small robots are likely to help solving this problem (i.e. Breguet et al., 1996; Hesselbach et al., 1997; Kasaya, T. et al., 1998).

For this reason, we are currently working on an automated microrobot-based microassembly desktop station (Fatikow, 1996). Within this station, it is possible to carry out an assembly process under a light microscope by flexible microrobots. We have developed several piezoelectric microrobots that can perform high-precision manipulations with an accuracy of up to 10-20 nm and the transport of very small objects at a speed of up to 2-3 cm/sec (Fatikow et al., 1995). Automatically controlled with the help of visual and force sensors, these robots may free humans from the tedious task of having to manipulate very small objects directly.

Figure 1 shows an overview of the microrobot-based microassembly station (MMS). The robots work on an XY-stage mounted under a light microscope. The microscope, the table and the microrobots are controlled by a lower-level control computer equipped with several interface cards, power electronics and AD-converters. A higher-level computer hands down commands to the control computer.

The development of assembly facilities for microsystems is still in its infancy. The productivity of a microassembly system is low for manual operation; it improves by using teleoperation and further on to a fully automated assembly, like in conventional macro-robotics. An automated microrobot-based

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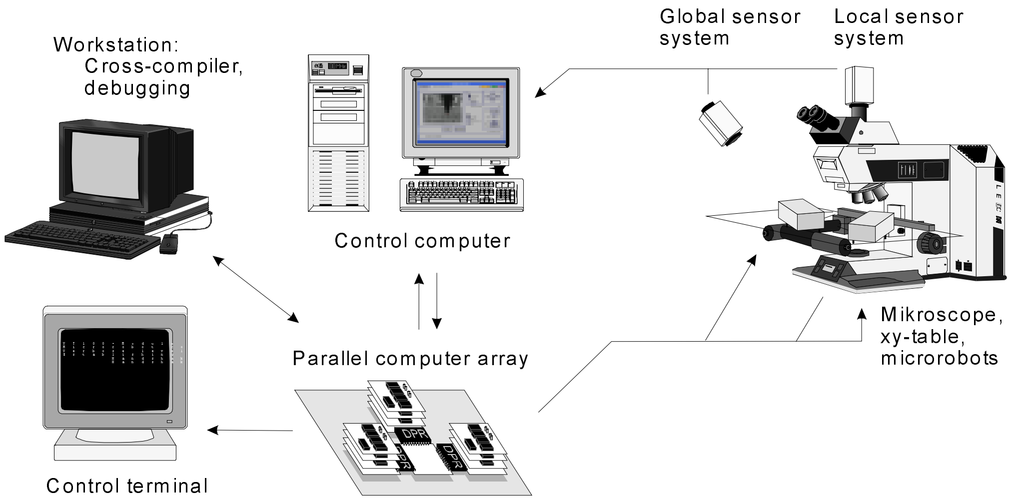

Figure 1: Overview of the microrobot-based microassembly station (MMS)

station can take over precise assembly tasks and thereby encourage the growth of microsystem technology. The spectrum of tasks in microassembly ranges from simple preparatory operations like applying adhesives, drawing adjustment marks, cleaning objects, etc. to the performance of the final assembly of the microsystem, including grasping, transportation, positioning and fixing of parts. A well conceived microassembly station must be able to automatically accomplish all these steps. In this paper, a control architecture of an automated microassembly desktop station (Figure 1) is described.

II. CONTROL ARCHITECTURE

The full system architecture of the MMS is shown in Figure 2. An assembly problem can be specified in a parts description language or a CAD model to the station. Then, the microassembly station has to perform task planning, generate a motion sequence and control the execution of this sequence.

The main problems of the practical realization of an MMS are the intelligent assembly planning on the uppermost control level and the task-specific distribution of the necessary robots and tools, which should allow the assembly process to run error- and collision-free. Assembly planning is often hard because of the large number of assembly sequences that must be considered, multiplied by the difficulty of dealing with the geometry and physics of each operation. In an MMS, there are some specific problems caused by the microscopic dimensions of the parts to be assembled. There have been considerable research efforts in computer aided assembly planning, because it provides a systematic way to search for an optimal solution.

At the first step of assembly planning, a formal description of the assembly process –assembly model– is proposed. In a mostly common case, an assembly model contains information of parts, their configurations, their geometry, their interconnection mechanisms, etc. With the help of this model, different feasible assembly sequences for a given product can be selected. An AND/OR graph is a compact representation of all possible assembly plans. The choice of which plan to follow in the assembly process is done on the second planning step and based on the chosen optimization criteria for assessing the quality of each solution.

The microassembly planning system of the MMS, which is currently being developed (Fatikow et al., 1998), consists of three main modules: system interface, assembly task planner and assembly execution planner. The modules are supported by a knowledge base which includes knowledge on the task specification, an assembly model of the microsystem, the specification of existing microrobots and their tools, a world model (micro and macro) and the current station state obtained by the sensor system. The integration of the planning system into the MMS is shown in Figure 2.

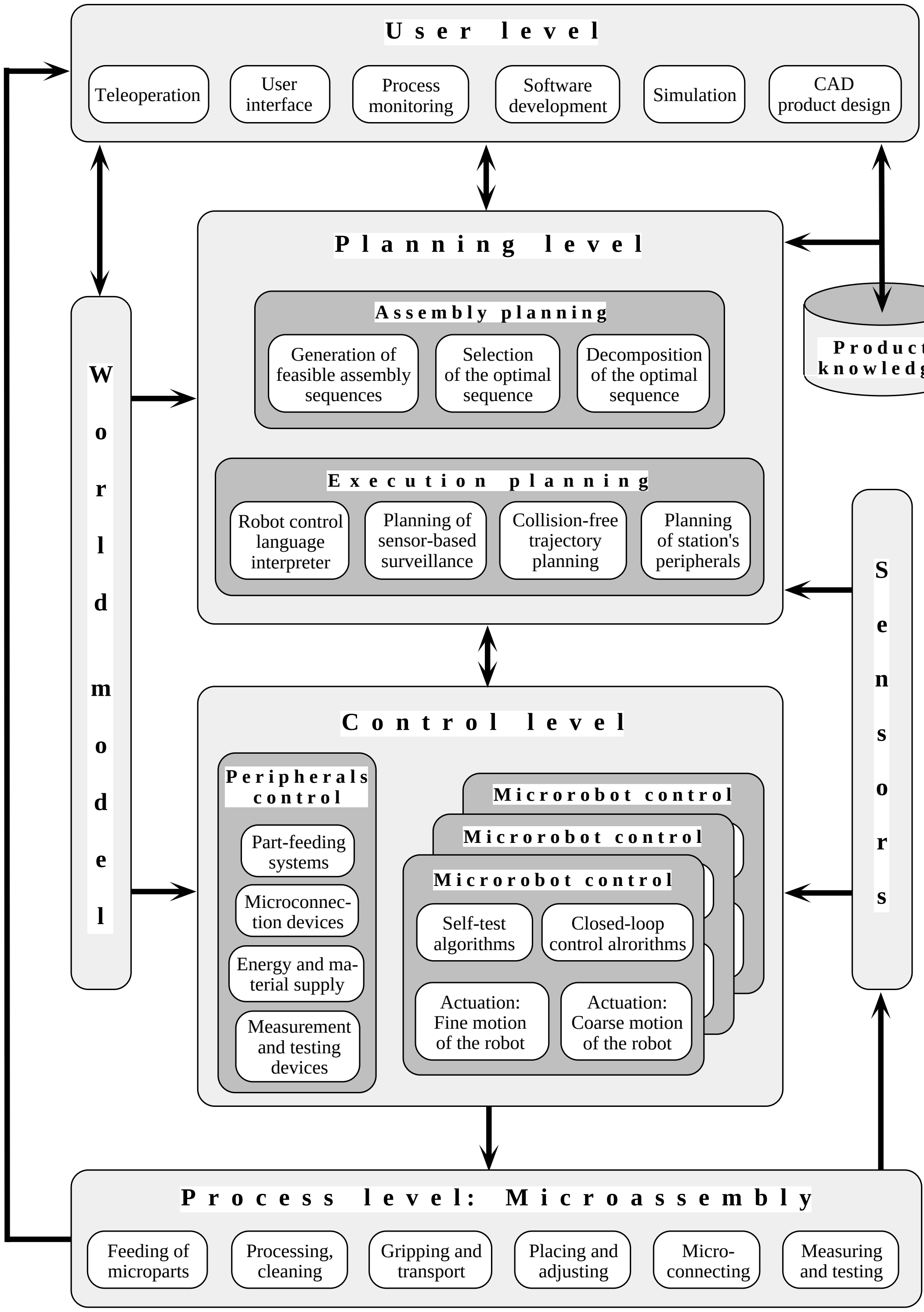

Figure 2: Control architecture of the MMS

The user interface module is designed to allow the user to define a multi-robot environment and help the user in building the domain knowledge and specifying the initial and desired final states of the world in terms of the objects to be assembled, microrobots, tools and their relationships.

The planning process is based on the assembly model of the microsystem to be built. It is performed in three planning levels: assembly graph generation, action sequence planning and task decomposition. In the first step, an assembly graph, here in form of an AND/OR graph, is generated. At the next level, a sequence of executable assembly operations (like operations for pick and place, push, turn etc.) is selected while considering the order restrictions of the assembly graph. The chosen operation sequence must fulfil the given optimization criteria. The geometry of the working area and the resources available such as microrobots and their tools must be taken into account during this planning step. After obtaining the action sequence, a task decomposition has to be done. The action sequence is decomposed into sub-plans for microrobots based on their operational capabilities.

The execution planning done by all microrobots' sub-planners must be supervised to ensure the consistency of the plans. The sub-plans will be decomposed into single operations by the execution planner, which produces robot control language code used by the interpreter. The interpreter rearranges particular commands to corresponding procedures and functions of the control algorithms.

III. CONTROL SOFTWARE

1. Closed-loop robot control

The motion control of the robots is based on their geometric description (Santa et al., 1997). The aim is to control the robot movements in a such way that, first, the tip of the manipulator is moved from the initial (actual) point to the aspired end-point and, second, the defined orientation of the robot in the final state is achieved. One can distinguish between transportation (coarse motion) and micromanipulation tasks (fine motion). Figures 3 and 4 give an example for platform movements when performing a transportation and a manipulation task, respectively. There are several methods to move the robot: 1) First turn the platform by an angle q, then move it by a distance S in the direction up to the aspired point B (Fig. 3a and 4a); 2) First execute the linear motion by a distance S in the direction up to the point OB and then turn by an angle q toward the aspired point B (Fig.3b and 4b); 3) Turn by an angle q and execute the linear motion by a distance S, simultaneously (co-ordinated motion, Fig. 3c and 4c).

When solving a transportation task, the robot operation time, which corresponds to the route length of each robot leg, must be minimized. To achieve that by the methods shown in Figure 3a and 3b, the robot must rotate around the point 0A or point 0B, correspondingly, along the periphery of the triangle formed by the piezolegs. When performing a micromanipulation task, the manipulator tip must stay under the microscope objective. In this case, the center of rotation of the robot is the point A or B, correspondingly, on the endeffector tip (Fig. 4a and 4b).

However, both the linear and the rotational motion phase are performed sequentially by using these two methods so that the whole operation time of the robot is generally not optimal. When performing a transportation task by the third method, the center of rotation is point 0A (Fig. 3c). In this case, the route length between points OA and OB is minimized. When performing a micromanipulation task, the center of rotation is the tip of its manipulator (in the initial state - point A, Fig. 4c). In the latter case, the route length between points A and B is minimized to keep the endeffector tip under the microscope objective. An advantage of the third method is the possibility to move along an optimal trajectory in minimal time. Its disadvantage is that the actual direction of the linear robot motion is determined by its current orientation and, therefore must be continuously corrected.

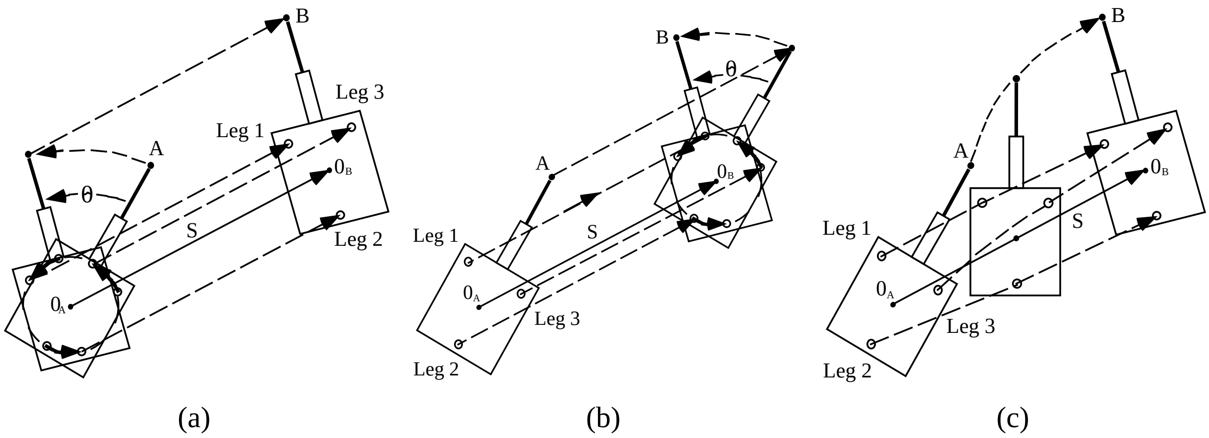

Figure 3: Robot motion during transportation

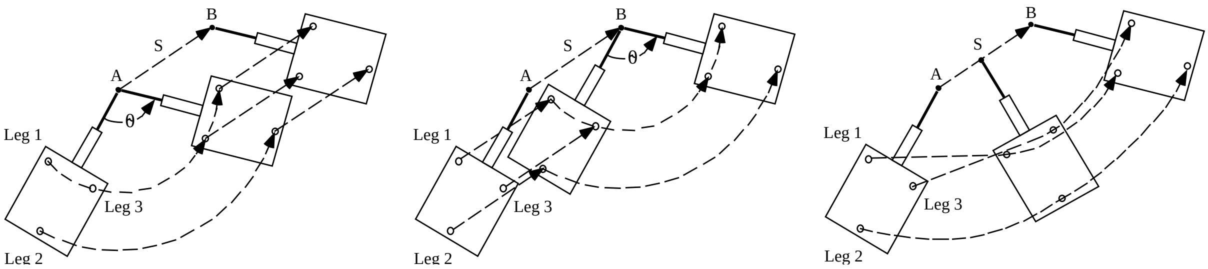

Figure 4: Robot motion during micromanipulation

Figure 5: Dialog windows of the graphical user interface

2. User interface

A robot system with a complexity like the presented micromanipulation system has to offer an intuitive way to operate the robots and enter commands. Otherwise, the number of parameters the user can adjust would make the system too complex to control for a human. Therefore, a graphical user interface has been developed to perform telemanipulation (Seyfried et al., 1997). It offers an intuitive point-and-click interface to control the robot; the user can specify the desired robot position and orientation onscreen and perform experiments with several available closed-loop control methods (e.g. Fuzzy Logic, neural nets). This interface is being extended to give more complex commands which involve automatic or semi-automatic assembly sequences; this combination offers a convenient way to resort to telemanipulation in the case of an error condition.

The development was done with the Khoros[1] system. Figure 5 shows an overview of the dialog windows for telemanipulation. The higher-level layers of the control software also incorporate CAD components with which the specifications and geometric data of the microparts can be determined.

IV. CONTROL HARDWARE

The control computer of a complex MMS has to perform numerous tasks. Namely, it has to perform processing of the camera images, assembly planning, execution planning and a closed-loop control of the robots' motions to generate the appropriate driving voltages for the actuators as well as to control the peripherals (microscope, XY-stage, terminal, etc.). This set of tasks is clearly too much for a single computer, if one demands feasible response times and real-time constraints. The real-time constraints are quite strict: given the maximum velocity of a single robot, 2-3 cm/sec, and a maximum field of vision of 5×5 mm^2 (through the microscope), it is obvious that the control system should have response times explicitly below 1 second.

To get the necessary computational power, a parallel computer array is the cheapest solution which can also take advantage of the inherent parallelism of the control algorithms and the multi-robot system. The layout of the parallel computer can easily be changed, e.g. when an additional microrobot or another special piece of hardware is added to the system. The hardware layout, i.e., the arrangement of the processor modules next to each other, should take into account the amount of communication between the functional blocks, which is high for example between *control* and *I/O* and lower between *coordination* and *vision*.

A hybrid parallel computer array is currently being implemented into the microassembly station (Figure 6). It consists of two types of computer modules: microcontroller modules incorporating the Siemens C167 microcontroller and PC104 modules equipped with Intel Pentium processors. As it can be seen in Figure 6, each computer in the parallel computer array can communicate with its neighbours[2] via a dual ported RAM (DPR). Each RAM can be accessed from both sides, providing a very fast communication channel; access times are in the range of 300 ns, as presented by (Woern et al., 1998). When robots are to be added or removed to the system, the control computer can be easily reconfigured by adding or removing computer modules. After booting, the parallel computer array initiates a detection algorithm to determine the current set-up of the parallel computer array and transmits a complete map of the array's topography (including the type of the module, i.e. PC104 or C167) to the host computer. Here, the user can experimentally assign the single modules different tasks (e.g.

[1] Registered trademark of Khoral Research Inc.

[2] Up to eight, depending on the layout and interconnection structure

vision, control, planning) to adjust to the given topography and the resulting message paths from module to module in order to obtain an optimal system performance. All modules incorporate real-time operating systems to guarantee a stable behavior and reasonable response times for critical tasks.

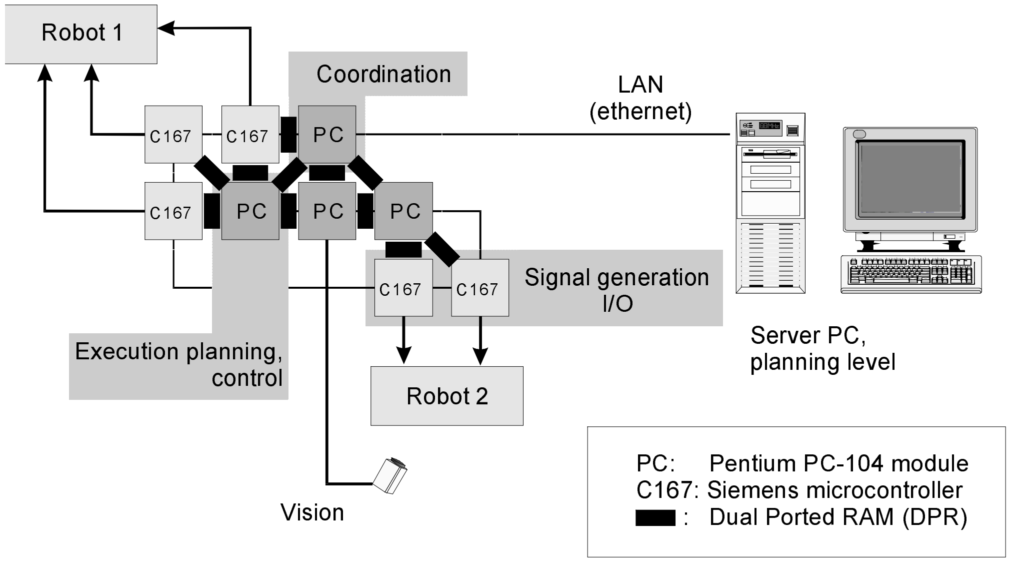

Figure 6: Parallel computer system

V. FUTURE WORK

Besides the continuous work which is done to improve the robots' hardware, including additional sensors, like micro-force sensors, several aspects of the control system software are being worked on and are still to be implemented. Control systems based on Fuzzy Logic and neural networks are currently being researched. The user interface is to be extended by a comfortable way to assign tasks to the processor modules, to monitor the system performance and automatic load and communication balancing algorithms are to be implemented. The assembly planning algorithms should be extended to take special micro-properties into account to minimize the effects of dominant forces of the micro-world (i.e. electrostatic and adhesive forces) by rearranging the assembly sequence in an appropriate way. Furthermore, to assemble complex microsystems consisting of many components, efforts must be taken to reduce calculation times for assembly planning, which is NP-complete (Kavraki and Kolountzakis, 1995; Kavraki et al., 1993) and therefore a problem that can be calculated only for small input sets if an exact deterministic calculation method is used.

VI. CONCLUSIONS

In this paper, the architecture of an automated microassembly cell, its control hardware and software system has been presented, the planning level and the user interface which makes easy experiments with several control methods possible. The microassembly station consists of several micromanipulation robots, a microscope, cameras and an xy-stage. This system is controlled by a multiprocessor array which can simultaneously control the components of the station and offers feasible computational power. This system is easily re-configurable due to the hardware and software design to account for changes in the set-up of the station. The control algorithms are based on the geometric description of the robots and use the processed camera images to determine the robots' positions. The planning level provides the execution planning module with the best assembly sequence of the microsystem to be assembled. The whole system offers a convenient graphical user interface to support the user in the microassembly process.

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