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Johannes Schilp, Michael F. Zäh

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Collaborating agents in agile teleoperated and automated micro-assembly systems

Johannes Schilp, Michael F. Zaeh

Institute for Machine Tools and Industrial Management (*iwb*), Technische Universitaet Muenchen

ABSTRACT

Globalization and miniaturization – these trends in production technology cause R&D activities, focused on agile micro-assembly systems with autonomous subcomponents. Besides product and processes flexibility, agility in small production volumes can be mainly achieved by controlling the system in different operational modes and switching between those in an efficient way. Therefore an agile micro-assembly structure is presented, which can be controlled both in manual mode by teleoperation and in semi-automatic mode. To assure a highly efficient use of production resources in all operational modes, several cooperating sensor components have been developed. Thus a human operator can focus on the main processes, while secondary processes like adjusting and calibrating of sensor-modules are controlled by autonomous functions. In automatically controlled systems the same agents can speed up the main production processes and minimize set up times. In order to switch simply between manual and automatic mode, a smart teaching procedure is integrated into the control framework.

Keywords: Micro-assembly; teleoperation; agile micro-assembly systems; smart sensors

1. INTRODUCTION

1. About agile micro-assembly

The progressive miniaturization and customization of today's products has lead to increased requirements and demand for agile production technology. In particular these trends are dominating microsystems technology with its wide variety of innovations. Due to very short product life cycles and very high technical developments between two life cycles of hybrid microsystems [1], there is a special need for agile micro-assembly. Micro-assembly typically deals with product dimensions below 1 mm, and positioning accuracies down to the single micron. Typical examples of hybrid Microsystems, which are based on unique micro-assembly processes, are biomedical applications like fingerprint sensors, optical MEMS and RF-MEMS components.

Most of these more complex products exist only as prototypes because of a lack in agile micro-assembly systems [2]. One issue is the need for scalable systems which means switching easily between manually driven processes for producing prototypes and automated processes for small-lot production without any changes of the system itself. The other issue is flexibility provided by standardized setups and components in order to assemble a multitude of customized product on one system. The main goal is the reduction of proportional assembly costs of currently 70% of the product costs [3].

The main barrier in changing the production mode from manuality to automation is saving and transferring knowledge, gathered in assembling by hand, into automated systems. Like the decision-making procedures of humans, the micro-assembly system itself has to provide autonomous and case-dependent functionalities in order to assure high quality processes in a wide range of applications. Therefore process data has to be monitored and stored during manual processes in an appropriate manner.

An agile micro-assembly solution is presented in this paper. Its control technology is based on telepresence and teleaction technology for manual mode and smart sensor integration for automatic mode. In terms of flexibility a set of collaborating actor and sensor modules are presented, which mainly enable an ergonomic manual use of the micro-assembly system by autonomous sub-functions like calibration and parametrization and an efficient switch to automation hardly without any additional set-up times.

2. Telepresence and teleaction technology as a solution for manual micro-assembly

Manual micro-assembly faces several issues like the barrier between the macro-world of the operator and the micro-world of the process environment [4] and so-called scaling effects, which describe the dominance of surface forces compared to volume forces in the micro-world [5]. Telepresence and teleaction technologies provide a promising solution to manual micro-assembly processes through overcoming these issues, while offering flexibility, high accuracies and an intuitive human-controlled working environment.

Telepresence and Teleaction enable an operator to feel physically present and to carry out manipulations in an inaccessible environment through the use of suitable tools. The inaccessibility in MST is caused both by the clean environment and by the size of the objects to be manipulated. Thus the operator triggers the smart and precise assembly tools by haptic input devices and a graphic user interface, visualizing the assembly scenario. Guaranteeing an intuitive environment involves the provision of adequate feedback information. Various physical sensor arrangements at the micro-assembly site are used to generate haptic feedback in the human-controlled environment. Non-physical or "virtual" sensors, although artificially generated, can also remarkably improve user intuition. For precise controlling and high fidelity feedback, telepresence environments also require a flexible communication platform between the human operator and the assembly site.

For piece production with a lot size up to 50 per day a tele-operated manual micro-assembly system was designed and set up, which is more ergonomical and more efficient compared to conventional working environments with microscope and manually triggered tools. The know-how, collected in developing this platform, is used for setting up the agile micro-assembly approach described in this paper.

3. Flexible solutions for automated micro-assembly

Current automated micro-assembly solutions are mostly specialized for particular processes and mass production, mainly because of the required high positioning accuracy. Flexible and cost effective solutions for producing microsystems in small to medium batch sizes hardly can be found. Thus reducing the costs per unit can only be achieved by increasing the number of produced units. Therefore a micro-assembly tool system with standard end-effectors in combination with a standard SCARA-robot has been developed [6]. The tool is designed for flexibility, high accuracy and absolute or relative positioning strategies. Therefore it can be used for a multitude of assembly scenarios by coarse-positioning being done by the robot and fine-positioning being done by special piezoelectric micro-positioners. The specialized effectors can be attached at the tool base manually. This means, that different processes require always an intervention by the user for set-up, programming and teaching procedures. Because of long set-up times the system is only suitable for automated series production, but not for single piece production. [7] describes the development of a miniaturized factory consisting of assembly modules situated around a planar system. The planar system is the core of the concept. The control system is modularized, so each module has a special Java-controller. This concept, based on the regional separation of the effectors, has disadvantages concerning the accuracy. The planar system has a position accuracy of 20 μm . In this environment relative positioning is hard to implement because of the decentralized effectors each one requiring the same sensorical equipment. [8] describes an agile assembly architecture, which is based on intelligent, cooperating assembly agents. This assembly system can be easily adapted to changes in products or product types. However, this architecture uses non-standardized components.

For lot sizes over 50 per day a flexible configurable and automated assembly system is designed with exchangeable components [2]. Different assembly strategies are provided by a sensor-based assembly tool. The system allows short set-up times between product changes by an automated micro-tool changing system and smart sensor modules. Therefore various types of microsystems can be produced economically due to the high capacity of the automated production system. Nevertheless the complexity in setting up the automated mode for different assembly scenarios is not easy.

2. REQUIREMENTS

1. Common requirements for micro-assembly

Agile solutions both for tele-operated and automated micro-assembly processes have to fulfill various requirements for industrial applicability. In particular handling and mounting tasks of micro-objects differ fundamentally from the ones in the macro world: Due to the specific nature of MST, scaling effects play a decisive role during micro-assembly processes by influencing the interaction between handling equipment and micro-parts [5]. Hence surface forces such as

adhesive, electrostatic or van-der-Waals forces are superordinate to gravity forces. E. g. sticking parts to grippers cause major problems in micro-assembly. Also due to the small geometric dimensions small contact forces of grippers can actually exceed the maximum allowed surface pressures of parts. In order to give the user, particularly in the manual mode, a “close-to-reality” feeling of the scenario, where “reality” refers to that of our macro-world, smart sensors have to be integrated into the micro-assembly system in order to virtually simulate gravitational forces. Hence the user is accustomed with force feedback more intuitively than simply by scaling the existing forces of the process. In automated mode highly precise force control algorithms have to be provided by the same sensor modules.

Also the very sensitive surfaces of micro-parts, e. g. due to surface coatings, require special process environments. So micro-assembly must be performed in clean rooms without human interference and micro-objects have to be handled with a maximum of care. In addition micro-assembly processes require a high positioning accuracy and reliability. Therefore highly precise kinematical systems and sensor components for precise online-monitoring of forces and positions are required. Also economic requirements have to be considered for small scale micro-production.

The hardware and software setup has to consist of flexible and exchangeable modules. Accordingly the reconfiguration time and costs for customizing the production system to different products will be reduced. This ensures a high availability of the production system, an essential precondition for industrial applicability.

2. Micro-assembly by teleoperation

Additional requirements have to be considered for teleoperation in micro-assembly. As a main topic, ergonomic aspects, especially physiological fundamentals of human perception, are important. In order to ensure an optimal operability of the system and to achieve a high-fidelity impression of the assembly scenario, every component of the tele-operated micro-assembly system has to be chosen with care in respect to the corresponding visual, kinesthetic and tactile bandwidth of the human perception. Especially for choosing the appropriate haptic input device at the operator-end and choosing smart sensor-components for the teleoperator, the sampling rate of kinesthetic data transmission plays a decisive role, because the human hand has asymmetric input and output capabilities [9]. According to [10], the maximum frequency with which the human hand can apply force and motion commands lies between 5 Hz and 10 Hz. Contrary to the human haptic output capabilities, much higher demands have to be fulfilled for powerful haptic perception. For meaningful kinesthetic perception, position and force input signals should be no less than 20 Hz to 30 Hz. Even higher sampling rates between 300 Hz and 500 Hz are required for feeling high frequency forces with low amplitude, such as chatter. For the perception of vibrations during skillful manipulative tasks, required bandwidths may exceed to 5 kHz to 10 kHz. Due to the small dimensions and to the discussed resolution of human haptic senses, sensor data from the teleoperator often has to be processed in order to simplify the operator’s work.

A second important aspect is the intuitive operability during the micro-assembly process. By using autonomous and self-adapting components with integrated functions for automatic calibration and parametrization during operation, the worker can focus on necessary assembly tasks and is not distracted by additional auxiliary operations like changing parameters and setting of system components. For visualization and intermodal presentation of process information, all sensor signals have to be continuously provided for further processing. Thus sensor signals have to be processed and presented in a customized manner due to individual sensomotoric skills and preferences of the operator [11]. For quality management purposes, both sensor signals and actor signals have to be continuously monitored and saved at given times, e. g. at predefined limits of the force sensor signal. The saving procedure has to start and stop autonomously without interrupting the plain assembly process by specific algorithms in the control software.

The usually unrestricted human interaction in a tele-operated micro-assembly system requires specific fail-safe features, caused by possible operations errors by the human operator. These safety features prevent collisions and damage to the work-pieces and the components of the assembly system itself by continuously monitoring the current process conditions. In the case of irregular process conditions, e. g. when predefined force limits are exceeded, the system has to react to the situation and should support the human operator in an appropriate manner. Suitable system responses include blocking further movements, retreating movements, an emergency stop reaction and visual or acoustic user warning. To further improve system reliability, fail-safe reactions such as reduced speed areas are important. By monitoring the status of all components and the exchanged data, the system has to be shut down instantly to a safe status in case of any irregular process condition.

3. Flexible and automated micro-assembly

High accuracies, needed in the assembly of microsystems, in combination with economic aspects induce relative positioning strategies. Most kinematic systems have a step size in the micrometer area, but position accuracy of these

systems is much lower. Especially for small and medium batches, highly specialized positioning systems are not practical due to their inflexibility and costs. A solution is the implementation of relative positioning by image processing or by comparing sensor signals. Accordingly the positioning strategy combines coarse positioning with absolute positioning and fine positioning with relative positioning strategies. To enable further flexibility, an automated micro-tool changing system has to be integrated to use the wide field of processes in micro-assembly. The small working area of high precision tools must be adapted to enable smart and ergonomic part feeding.

Similar to teleoperated micro-assembly systems possible safety risks in automated systems must be considered, which concerns possible malfunctions of the teleoperated assembly system itself.

To minimize these risks, the status of all components has to be monitored continuously. For example, the failure of a force sensor may result in exceeding the maximum allowable process-forces or in collisions and may cause damages to the micro-objects or to the micro-assembly system itself. Therefore, appropriate automatic danger recognition by smart sensor systems must be implemented in order to decide whether this failure is safety-critical and which reaction to take. In the case of severe safety-relevant malfunctions, the system has to be shut down to prevent further damage.

3. SYSTEM SETUP OF AN AGILE MICRO-ASSEMBLY SYSTEM

1. System overview

Besides product and processes flexibility, agility can be mainly achieved by controlling the system in different operational modes and switching between those in an efficient way (see fig. 1). In this way the system can be adopted to different productions scenarios and small and mid-sized production volumes.

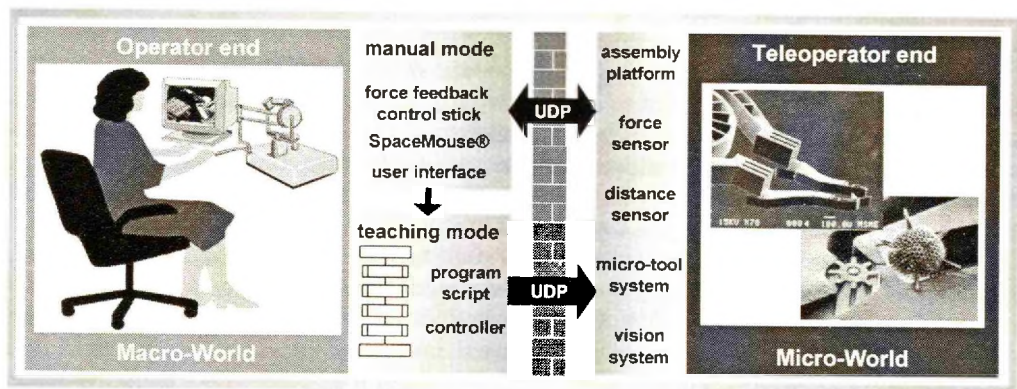


Figure 1: System overview of an agile micro-assembly structure

The agile assembly system consists of three main parts: (1) the teleoperator side, which represents the actual micro-assembly station, (2) the operator side, providing all input devices, control interfaces and visualization system, and (3) the software architecture, which includes all control algorithms. It is therefore the basis for the smart control mechanism between the operator and teleoperator side or the teleoperator itself. For prototype production of customized products, the teleoperation mode can be used. For small and mid-sized productions lots of similar products the automatic mode is suitable. The barrier between manual prototype assembly and automated small-lot production can be overcome by a new, intuitive teaching mode of the assembly system. During operation in the manual mode, the system is teaching itself by an autonomous program script algorithm.

2. Teleoperator side

The teleoperator for high-precision micro-assembly tasks consists of several core components (see fig. 2): In first, assembly platforms are attached onto two couriers of a planar table system, which can be controlled both manually and automatically. With a positioning resolution of $1\text{ }\mu\text{m}$ and a total workspace of $600\text{ mm} \times 1000\text{ mm}$, it ensures a sufficient accuracy in x-, y-direction, which is the basis for a multitude of assembly tasks. This platform is used for fixing the substrates and supplying the parts in chip-trays or bluetape magazines for the assembly operation (fig. 2). To ensure a sensitive handling of the microsystems, mounting forces with a maximum force resolution of $\pm 0.024\text{ N}$ in z-direction can be acquired by a uniaxial precision force sensor in conjunction with a 12 bit data acquisition card. In additional two flexible and modular micro-assembly tool systems for teleoperated and automated tasks are attached to precision linear stages, providing an accurate motion in z-direction (resolution $0.1\text{ }\mu\text{m}$, work space 204 mm). This third

axis is used to place the parts with a defined joining force, e. g. in a joining process with glue. Therefore the joining force is monitored by a high-resolution force sensor.

The micro-assembly tool system is based on a sensor-based tool concept [12], which enables a multitude of different assembly tasks like handling, positioning, dispensing of glue and solderpaste respectively and laser joining processes by one tool system. According to specific assembly tasks suitable function modules like individual grippers for different components, dispensers, stamps or fibre coupled diode laser optics, can be attached automatically to the tool-base by a micro-tool-changing system. This micro-tool-changing system is based on a tapered interface. Lead-throughs are realized e. g. for air pressure. In this way up to four process-specific tools, like grippers, dispense units etc., can be arranged equally around the tool head. The specific tools can be extended into the focus plane of the vision-system on demand by pneumatic cylinders. Because of the rotation ability of the tool system by 360° with an angular resolution of 0.005° , the assembly tool system in conjunction with the couriers of the planar provide a total number of four degrees of freedom, which is sufficient for a multitude of micro-assembly tasks. Using two similar tool systems, one for normal, one for bimanual interaction in the agile assembly system, this setup ensures a higher availability of the production system.

The heart of both assembly tools are bird-view cameras which are integrated into each tool head. By the optical system, consisting of a CCD-camera and a highly precise telecentric lense with a coaxial illumination, the field of view of the first tool system amounts to 1.9×2.5 mm and the depth of focus is ± 0.5 mm at a working distance of 34.9 mm and a magnification scale of 2:1. The system for bimanual interaction provides a larger field of view due to the larger workspace of the endeffectors. For adjusting the optical focus plane, the whole optical system can be moved within a range of ± 5 mm in the vertical direction.

The camera takes pictures of the parts, tools or substrates. By simply visualizing or online image processing the deviation path can be calculated and controlled both by the operator or the system itself. In any way this closed loop control strategy allows position accuracies down to the single micron in the automated mode. Because the endeffectors tools are also controlled with this strategy, it is not necessary that the micro-tool changing system itself reproduces high accuracies during tool changing processes.

To assemble flip-chip components, which have to be placed face-down onto the substrate, a special optic module, developed in first for automated processes, is used. During the positioning process it is moved between the gripped part and the substrate, by hand or automatically. A picture of the component and the substrate is taken and the positioning path is calculated as above. After matching the part to the substrate, the optic module is drawn back and the component is placed onto the substrate with a position accuracy of less than $3 \mu\text{m}$. With this strategy, long lateral movements between the capture of a picture with the vision control and the positioning of a part, as it is usual state of the art for flip-chip assembly, are avoided.

In summary, the agile setup of two couriers of a planar system and two assembly tool systems provides each a total number of four degrees of freedom and each a total number of four end effectors, which is sufficient for a multitude of micro-assembly tasks. In addition to the precise optical systems, which are integrated into the tool system, an overview of the assembly station is achieved by two side-view cameras for manual observation purposes.

3. Operator side and visualization

The agile micro-assembly station can be controlled manually with two haptic input devices, like PHANToM® devices or force-feedback joysticks. The micro-assembly processes are mainly controlled by two force-feedback joysticks (from Saitek), including all auxiliary operations. Thus the operator can concentrate on the assembly task and does not need to

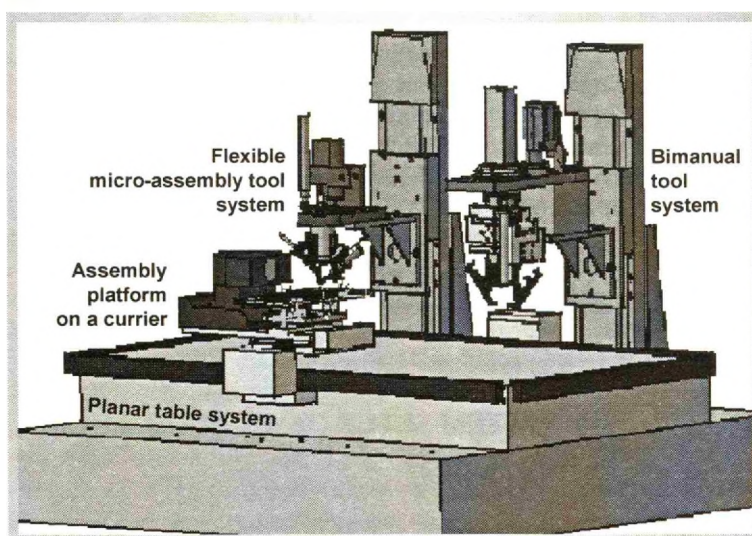


Figure 2: Setup (CAD-model) of the teleoperator side

grip other input devices such as keyboards or mice for auxiliary processes. This leads to an ergonomic interaction and to a close-to-reality-impression during manual micro-assembly.

One force-feedback joystick is used for controlling the motions of the three axis of the precise Cartesian kinematic system. By activating the joystick by pushing the front button, the kinematic system can be controlled in the x- and y-directions while the z-axis is blocked. Pushing both buttons on the joystick, the z-axis of the kinematic system can be activated while x- and y-axis are blocked. Using this 2DOF haptic input device in conjunction with the mentioned high-resolution force sensor and the data-processing on the teleoperator side, a close-to-reality impression can be achieved.

The second joystick is used for all auxiliary functions like adapting viewpoints, adjusting the focus plane of the vision system and changing the tool positions by rotation. By pushing its functional keys, the adapted end-effectors of the tool system can be extended or retracted and specific tool functions, e.g. opening and closing of a gripper, can be activated. In addition additional kinematic systems at the tool head can be triggered for bimanual interaction.

Visual supervision of the assembly scenario is achieved by two side-cameras with different viewpoints and zoom factors and the mentioned top-view camera in the tool system. Usually the video image of the top-view camera is used for the accurate positioning process both in manual or automatic mode and the side-views for manual coarse-positioning. The use of two haptic input devices increases the need for an ergonomic operating environment. For example, devices should not be placed in front of the monitor, in order to provide full sight of the visual display. However, placement of the devices to the left and the right side of the screen is not ergonomic. For this telepresence setup a new working environment was designed for the operator. The visualization is projected onto a screen that is fixed in front of the operator (see Fig. 3). With the use of stereo projectors and polarized glasses, an immersive three-dimensional view on the scene is possible. The input devices are located beneath the screen. The operator receives the impression, that he/she is reaching into the scene and interacting with the real parts, resulting in a more intuitive and consequently faster interaction.

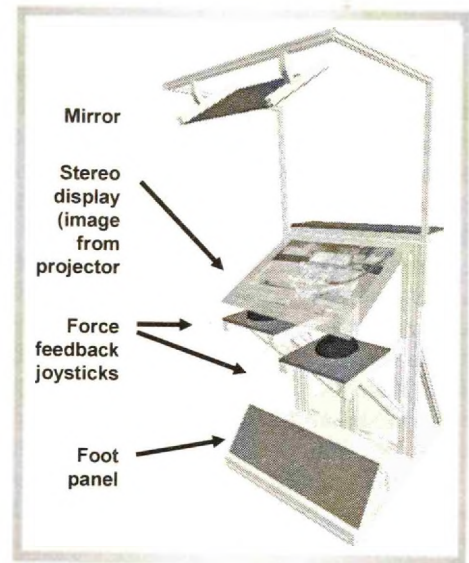


Figure 3: Working place of the operator

4. Communication and control system

To ensure the same flexibility as the hardware components of the agile micro-assembly system, the software architecture also consists of a modular setup (see Fig. 4). The software consists of several independent program threads which fulfil special functions of the control system. The data exchange between these program threads is realized through shared data exchange objects (DEOs). Similar to a filing folder, data is being generated by a data sender and stored into the shared DEO. Other program threads can read data out of these DEOs. The

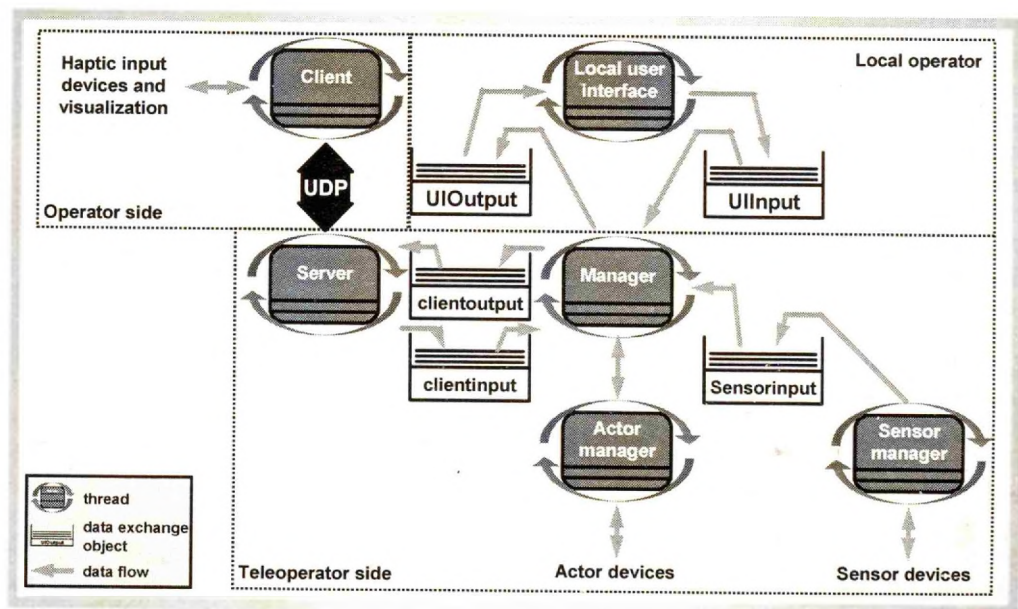


Figure 4: Control system architecture of an agile micro-assembly system

generated by a data sender and stored into the shared DEO. Other program threads can read data out of these DEOs. The

threads are divided in two parts of the agile assembly system: The teleoperator side including the local operator (local user interface) and the operator side, connected by a UDP communication. Overall, there is a total number of six program threads. In the following, the specific tasks of each program thread are explained.

The manager thread has access to all DEOs of the software framework. The manager thread is responsible for processing and forwarding data. For example, sensor data from the sensor data exchange object must be forwarded to the user interface data exchange object in order to be displayed on the developed user interface.

All process data which is displayed on the local user interface and the client user interface, must be continuously refreshed. Additionally, all operator inputs have to be processed and forwarded. Therefore, the local user interface thread reads all process data from the local user interface output DEO and refreshes all user input data in the local user interface input DEO. The same is done by the client user interface by the functionality of the server and its DEOs.

The sensor manager thread continuously monitors all sensor data and sensor states. For this purpose, it communicates with all sensors and with the sensor input DEO, which contains all current sensor signals and sensor states for later processing through other program threads.

The actuator manager thread provides all functions for controlling and driving the actuators of the micro-assembly system. It is also responsible for continuously monitoring the safety state of the system.

The server thread continuously receives or sends data from or to a client application. The client application itself requests data from the different user input devices and the client user interface. Communication between the client and the server is realized through a UDP connection. Hence, the system can be controlled over the internet. The server thread reads all current haptic data and process data from the client output DEO and transmits them to the server application. Received data from the client application is stored into the client input DEO. The client application can be either an external application or the system can be controlled on-site by a client thread, which is integrated into the software framework.

5. COLLABORATING SENSOR SYSTEMS

1. Sensor architecture

In order to enable changeability of sensor components, physical and application specific details of sensor data are required in an abstracted manner. In particular, the software implementation of sensors demands standardized interfaces, whereas the physical measuring principle of the sensor module is not relevant. Therefore a framework consisting of logical sensors has been designed [13]. The first known approaches for abstracting sensory functions have been reported in [14]. According to [14], logical sensors are determined by a unique ID, a characteristic data output vector, an interpreter module for processing information from other logical devices as well as function modules for processing the characteristic output data from the input data. Logical sensors are only determined by the characteristic interface data output type. It is irrelevant which physical measurement principles and algorithms are used to obtain the sensor-data output.

Fig. 5 shows the common sensor architecture used for the implementation. It can be divided into three layers: physical layer, processing layer and communication layer. In the following, the three layers and their functions are discussed in detail. Within the physical layer, raw sensor data is obtained from physical sensors. For this purpose, device specific functions are implemented by hardware specific drivers. The processing layer provides advanced signal-processing functions, e.g. functions for signal correction or coordinate transformation. Also, dynamic sensor adjustments to changing environmental conditions as well as signal processing parameters and calibration data can be

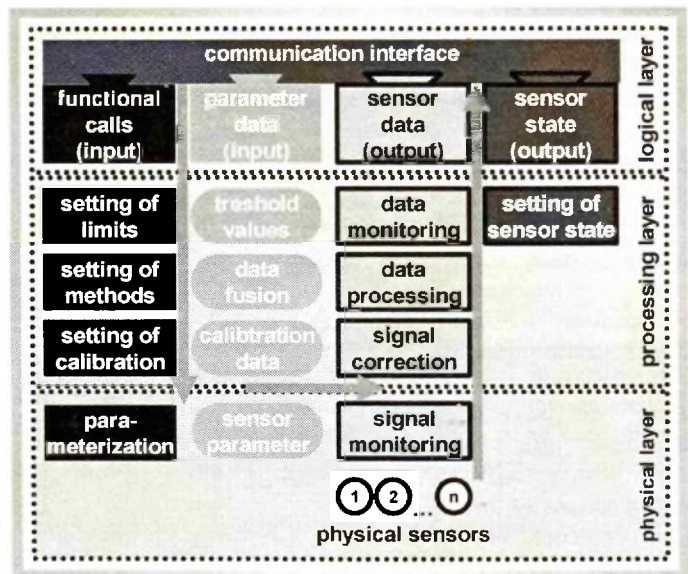


Figure 5: Agile sensor architecture

modified during operation. Through the logical layer the sensor module can communicate with other components of the TPTA system through predefined and unified interfaces.

The implementation is realized by the use of object-oriented methods in order to create modular, flexible and reusable software modules. The logical layer is realized by an abstract upper class *CSensor*. This class contains all properties and functions which are common for all types of sensors. Each instance of this sensor class provides a unique sensor ID and a corresponding sensor state. The sensor manager thread requests each sensor and stores the sensor values and the sensor state into the sensor DEO. Each sensor object is registered to the sensor manager thread and can be accessed by other framework components by its unique sensor ID. Sensor components can be easily added to or removed from the data exchange object.

The sensor state is used for correct operation of the agile micro-assembly system and for avoiding safety critical situations. For this purpose, several standardized sensor states are available. For example, the normal state represents the normal operation mode, whereas two sensor warning states indicate safety critical situations which require an immediate reaction of the system. Which events trigger a transition from one state to another, depends on the implementation of the specific sensor class and must be implemented within data processing functions of specialized sensor classes. These specialized sensor classes must be derived from the upper class *CSensor* and represent the processing layer of the framework. The upper class *CSensor* contains only virtual signal processing functions, which must be overloaded. The physical layer must be realized by hardware specific objects.

2. Collaboration between a distance and a position sensor

According to the concept of [14], several logical sensors can be combined in order to set up a new logical sensor. Because logical sensor modules can autonomously communicate with

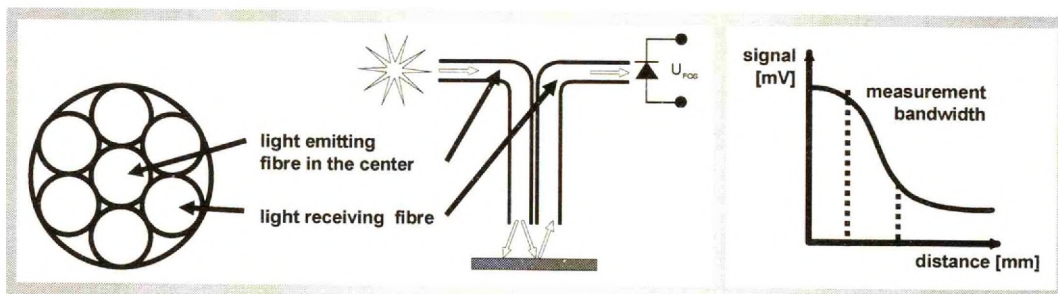


Figure 6: Fibre-optic sensor: Cross section (left); calibration curve (right)

other logical sensor components through pre-defined and standardized interfaces, this results in a hierarchical process of sensor data processing. This technique was used for implementing a smart distance sensor, which is able to react to changing environmental conditions:

The fibre-optical sensor is an integral part of the dispensing tool, which is integrated into the teleoperator side. It is used for measuring the distance between the dispense needle and the substrate. Fig. 6 shows a cross section and the physical principle of the fibre optical sensor. The sensor consists of several glass fibres. In the center of the sensor there is a light emitting fibre. The light beam is reflected by the substrate. The reflected light is received by several fibres, which are arranged around the light emitting fibre in the center of the sensor. Depending on the distance between the sensor needle and the substrate, the sensor provides a corresponding output signal. Due to the small dimensions of the sensor and its high resolution the sensor is appropriate for non-contact distance measurements very close to the dispense needle. However, this sensor principle has three specific properties which need to be considered for sensor data processing. First, there is no linear correlation between the sensor output voltage and the distance between sensor tip and substrate. Second, only a limited band, in which the gradient of the calibration curve is high enough, can be used for precise measurements. Third, the calibration curve is dependent on the surface of the substrate. Therefore, for using this sensor type in the developed micro-assembly system, a smart sensor component is necessary. In order to guarantee intuitive operability, the sensor must enable autonomous selection of the correct calibration data, and has to verify if the sensor is within the tolerable working distance. Hence, the smart fibre optical distance sensor must consider additional information for data processing and therefore communicate with other sensor components of the framework.

Fig. 7 shows the principle of signal processing of the smart fibre optical sensor. First, the sensor output voltage is acquired by accessing the data acquisition board. Second, based on the x- and y-coordinates of the current sensor position above the substrate, the corresponding calibration curve has to be selected from a calibration database. For this purpose, the smart fibre optical sensor has to communicate with the position sensors of the actuators. In a third step, the correct dispensing distance is determined by loading a corresponding calibration data table and using interpolation.

For determining the actual substrate surface, a digital map of the substrate is used. This digital surface map contains three-dimensional data vectors consisting of the following parameters: x- and y-coordinates and an unambiguous ID-code for the surface type of the corresponding substrate point. A simple and effective way for storing this information is using a bitmap file. Each pixel of the bitmap corresponds to a point on the real substrate. The surface type of each single point is coded with different color values. Each color represents a certain surface of the substrate. The resolution of the digital map must be at least the diameter of the optical fibre. Hence, for the used test substrate (dimensions 50 mm x 50 mm) a bitmap consisting of 2000 x 2000 pixels is required (see Fig. 6). For industrial use, corresponding digital bitmaps can be easily generated by digital image processing. For aligning the digital bitmap with the position and orientation of the real substrate, a singular calibration cycle is necessary. It can be manually realized by visually aligning several reference points and storing the corresponding coordinates. Another possible method for autonomous aligning is the use of image processing techniques as described in [15].

The logical distance sensor can access the sensor data output of the logical position sensors. Hence, the x- and y-coordinates of the actual sensor tip position are available. After the digital bitmap is aligned with the real substrate, the position data provided by the position sensors of the system axes must be transformed into bitmap coordinates. After that, the smart distance sensor can look up the corresponding surface ID-code, the correct calibration table can be loaded and the corresponding distance can be calculated.

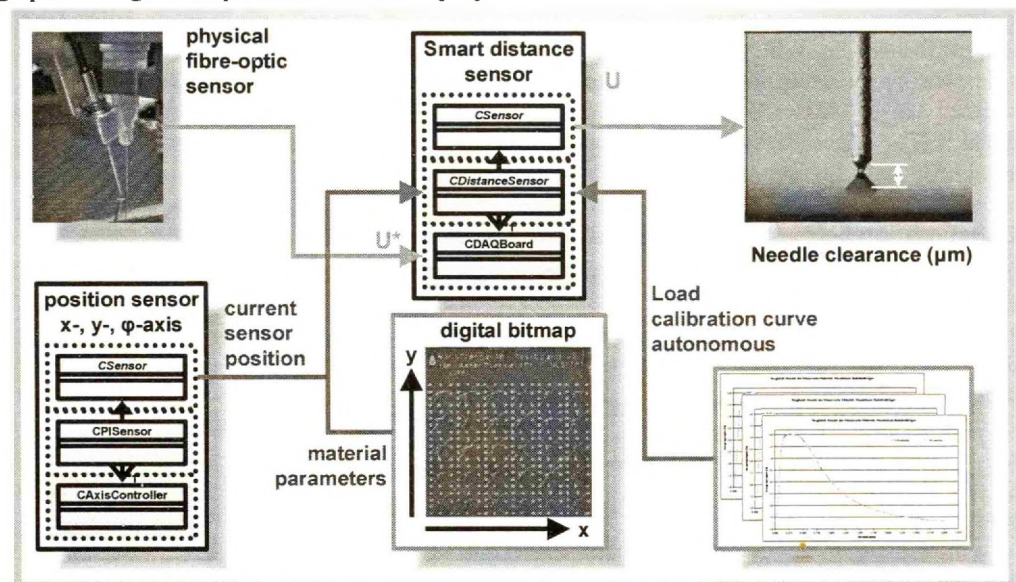


Figure 7: A smart distance sensor by collaboration of two different sensors

3. Collaborating collision detecting

Beneath the described logical sensors, so called virtual sensors have also been developed. Virtual sensors are logical sensors without a direct connection to physical sensors. They are therefore a consequent extension of logical sensors in terms of a hierarchical data

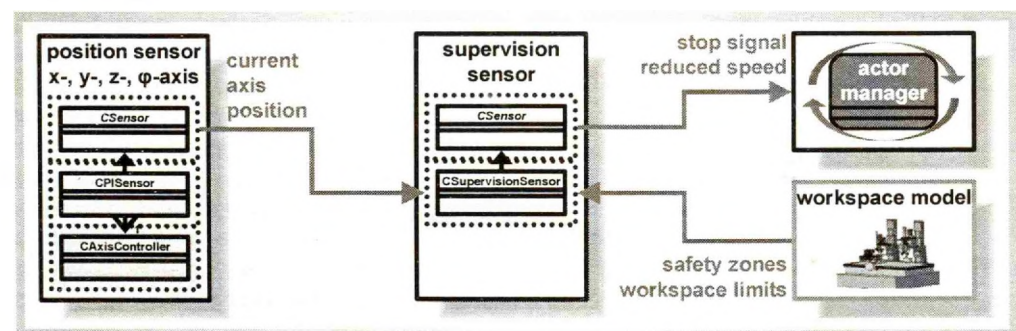


Figure 8: Collaborating collision sensor

processing flow. Virtual sensors do not have a physical layer, but rely solely on the data output vectors of other logical sensors. In agile micro-assembly systems, virtual sensors offer high potentials for improved intuitive system operability. In order to minimize the potential danger of collisions, a virtual sensor for workspace supervision and safety algorithms has been implemented. Fig. 8 shows the functional principle of the developed workspace supervision sensor. The virtual supervision sensor is connected with the logical position sensors of the x-, y- and z-axis and can detect possible

violations of the workspace limits. In the case of predefined workspace limit violations, a corresponding supervision flag will be set. These supervision flags can be interpreted by the actuator manager thread, so that further movements of the corresponding axis will be blocked. However, retreating movements for re-entering the workspace are still possible. Similar to the workspace supervision, safety zones can also be supervised. As soon as a predefined safety zone is entered, all axis velocities will be automatically reduced by the actuator manager thread, in order to minimize the danger of possible collisions.

6. EVALUATION

1. Experimental setup

For testing the manual mode, a simple pick-and-place task was chosen (see fig. 9). The objective of this experiment was defined as follows: a test die has to be picked up from a chip-tray and to move it to a test-circuit board. The dimensions of the integrated circuit were about $1.5 \text{ mm} \times 1.5 \text{ mm} \times 0.5 \text{ mm}$.

There the contours of the micro-part have to be aligned with reference marks on the

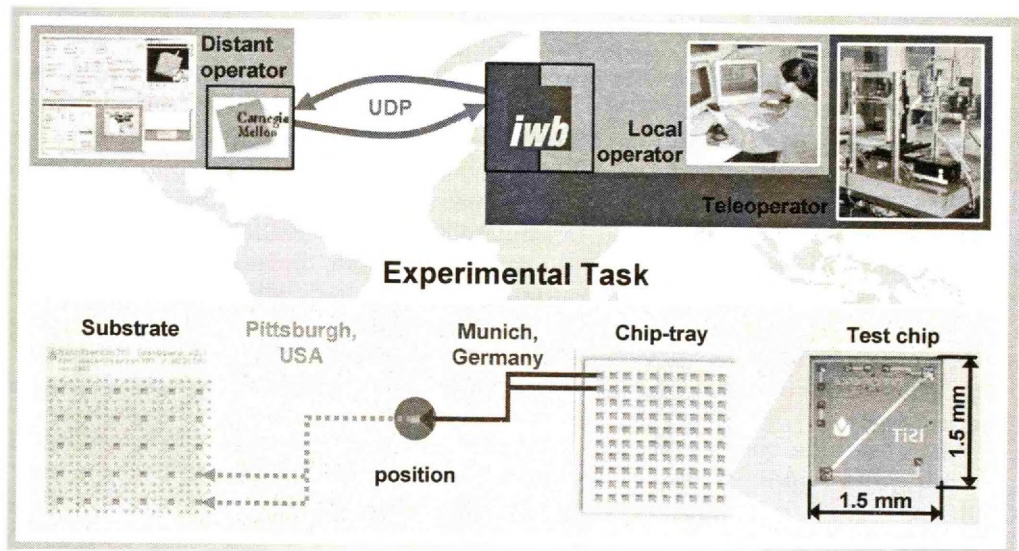


Figure 9: Experimental setup

substrate. Finally, the micro-part has to be set down with a defined amount of force and to be placed on the substrate. For executing this task, the micro-assembly tool head was equipped with a vacuum gripper.

The teleoperator side was located in a clean-room at the research laboratory of the iwb in Munich. It could be controlled from two different operator stations. The first operator station was located at the research laboratory of the iwb in Munich. The second operator station was located at the Microdynamic Systems Laboratory of the Robotics Institute at the Carnegie Mellon University in Pittsburgh, USA. To communicate verbally and visually, both operators were connected using a video conferencing application. To show the ability to switch the control between Munich and Pittsburgh during operation, the assembly task was divided in two sub-tasks.

The first sub-task was performed by the operator in Munich. The operator had to pick up the integrated circuit from the chip-tray and to move it into the middle between the chip-tray and the test circuit board. The second sub-task had to be accomplished by switching to the operator station in Pittsburgh. He then moved the gripper with the integrated circuit above the desired position on the test-circuit board, adjusted the orientation and placed it there. As the top-view video camera provided no information about the distance between the integrated circuit and the substrate, the operator had to rely on haptic information provided by the 1-DOF-force sensor, which was integrated into the teleoperator.

2. Manual mode

In manual operation mode, the micromanipulator can be positioned by use of the force-feedback joysticks. For facilitating assembly operations and speeding up transport operations, the operator can define and recall way points by pushing function buttons of one joysticks. Furthermore these positions can be inserted into the automated program sequence script for later use in automated mode.

3. Automated mode

The described task can be divided into several elementary operations. For creating program sequences for the automated mode, a distinction must be made between open-loop operations and closed-loop operations.

Open-loop operations are usually used for simple elementary operations which can be executed independently from any outside process influences, e. g. assembly tolerances. For instance, the automated execution of the elementary operation "Coarse positioning" only requires the coordinates x , y and z . These positions can be intuitively programmed during the manual teleoperation mode by moving the teleoperator to the desired target position and saving the coordinates along with the desired elementary operation into the program script file. In a similar manner, the other open-loop tasks "Grasp part", "Release part", "Extend gripper" and "Retract gripper" can be easily programmed. So far the developed system makes it possible to create open-loop program sequences and initial experiments have been successfully carried out.

However, closed-loop tasks are necessary for more complex assembly operations, e. g. for compensating assembly tolerances, or for monitoring critical process conditions, e.g. maximum allowable mounting forces. For this purpose, additional sensor data usually has to be processed during the automated program execution. For the elementary operations "Touch down gripper" and "Align gripper", the proposed system can be used for the intuitive programming of automation sequences:

The elementary operation "Touch down gripper" can be taught by moving the gripper toward the surface until there is contact. By haptic feedback and/or by observing the alphanumeric display of the acquired sensor data, the operator can intuitively define force limits for the specific assembly operation. For teaching the elementary operation "Fine positioning", an image pattern of the part to be grasped has to be generated and saved as an input parameter to the program sequence file. During the automated assembly execution, the image processing unit can process the relative distance between the object and the tool center point by comparing the actual video image with this image pattern. This also can be realized by the system by moving the micro-assembly tool and the top view camera to the specific target object. After making a snapshot of the target object, the operator only has to define reference edges and points within the image pattern. Both pieces of information, the image pattern along with the defined reference data, are saved to the program sequence file.

7. SUMMARY AND OUTLOOK

This paper presents a agile micro-assembly system providing both manual teleoperation mode for single-piece production and automated operation mode for series production of microsystems. During the manual operation mode, two force-feedback devices are used for controlling the position and orientation of the micromanipulator. The manual operation mode also includes features to create program sequences for the automated operation mode. During the automated operation mode, an automation controller replaces the human operator by executing the previously recorded program sequences.

The agile micro-assembly system is based on a smart sensor framework out of collaborating sensor modules. The developed logical sensor modules can access other sensor components of the framework. Thus, a smart sensor component with an autonomous calibration function could be developed in order to achieve intuitive and efficient operability. Furthermore, several logical sensors can be grouped and combined to build new collaborating sensors.

The paper concludes with a short description of a first experiment based on a simple pick-and-place operation for demonstrating the abilities of the developed system. So far, program scripts for open-loop operations, i. e. coarse positioning and gripper operations, can be generated. The integration of closed-loop operations, in particular aligning processes and force monitored placing operations by a robot vision system, will be the very next steps of future developments. Furthermore, a series of experiments for determining the capabilities of the described system as well as a comparison of manual and automated mode in respect to cycle time and process quality will follow.

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9. REFERENCES

1. Microsystems World Market Analysis 2000-2005 - NEXUS Task Force Market Analysis, Duesseldorf: VDI 2002.
2. Schilp, J.; Ehrenstrasser, M.; Harfensteller, M.; Jacob, D.; Zaeh, M. F.: Agile Micro-Assembly - Flexible Solutions by Tele-Operation and Automation. In: Reichl, H. (Ed.): Proc. of Micro System Technologies 2003, Munich. Poing: Franzis 2003, pp. 131-138.
3. Koelmeijer Chollet, S.; Jacot, J.: Cost Efficient Assembly of Microsystems. MST-News. Teltow: VDI/VDE Technologiezentrum Informationstechnik GmbH, 1999.
4. Reinhart, G.; Clarke, S.; Petzold, B.; Schilp, J.: Telepresence as a Solution to Manual Micro-Assembly. In CIRP Annals 53(1), 2004.
5. Fearing, R. S.: Survey of sticking effects for micro parts handling. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, August 5th – 9th 1995, Pittsburgh, Pennsylvania, USA. Los Alamos, Calif.: IEEE Computer Soc. Press 1995.
6. Jacob, D.; Höhn, M.: Assembly of semiconductor based microsystems with sensor guided tools. In: Reichl, H. (Ed.): System Integration in Micro Electronics, Nuremberg. Berlin: VDE 2000, pp.193 – 202.
7. Gaugel, T.: Minifabrik für Laserdioden und Biochips. In: Schraft, R. D.; Westkämper, E.; Sihn W. (Eds.): ProMikro 2002 Produktionstechnik für Mikrosysteme, Stuttgart. Stuttgart: Fraunhofer IRB
8. Rizz, A. A.; Hollis, R. L.: Opportunities for increased intelligence and autonomy systems for manufacturing. In: Robotics Research: The Eight International Symposium of Robotics Research, Hayama, Japan, October 3rd-7th 1997. London: Springer 1997, pp. 141-151.
9. Tan, H.; Pang, X.; Durlach, N.: Manual Resolution of Length, Force and Compliance. In: Advances in Robotics, DSC-Vol. 42, Proceedings of ASME-WAM, 1992, pp. 13-18.
10. Shimoga, K. B.: A survey of perceptual feedback issues in dexterous telemanipulation: part I. finger force feedback. In Proc. of IEEE International Symposium on Virtual Reality, Seattle, WA, USA, September 18th-22nd 1993, pp. 263-270.
11. Petzold, B.; Zaeh, M.F.; Faerber, B.; Deml, B.; Egermeier, H.; Schilp, J.; Clarke, S.: A Study on Visual, Auditory and Haptic Feedback for Assembly Tasks. In PRESENCE: Teleoperators and Virtual Environments, MIT Press, Cambridge, 13 (2004) 1, pp. 16-21.
12. Reinhart, G.; Jacob, D.: Positioning strategies and sensor integration in tools for assembly MOEMS. In: Motamedi, M.; Göring, R. (Eds.): MOEMS and Miniaturized Systems, Santa Clara, USA. Washington: Proceedings of SPIE Vol. 4178 (2000), pp. 395 – 402.
13. Schilp, J.; Ehrenstrasser, M.; Clarke, S.; Petzold, B.; Zaeh, M. F.: Smart Sensor application in teleoperated micro-assembly systems. In: Gopalakrishnan, B.; Gunasekaran, A.; Orban, P. E. (Eds.): Intelligent Manufacturing, Providence, RI, USA. Washington: Proc. of SPIE Vol. 5263 (2004), pp. 38-49.
14. Henderson, T.; Shilcrat E.: Logical Sensor Systems. Journal of Robotic Systems, 1 (1984).
15. Reinhart, G.; Anton, O.; Ehrenstrasser, M.; Patron, C.; Petzold, B.: Framework for teleoperated micro-assembly systems. In: Stein, M. R. (Ed.): Proceedings of SPIE, Vol. 4570, 2001, pp. 86-96.