Smart sensor application in teleoperated micro-assembly systems

Johannes Schilp, Michael Ehrenstrasser, Stella Clarke, Bernd Petzold, Michael F. Zäh

Angaben zur Veröffentlichung / Publication details:

Schilp, Johannes, Michael Ehrenstrasser, Stella Clarke, Bernd Petzold, and Michael F. Zäh. 2004. "Smart sensor application in teleoperated micro-assembly systems." In *Intelligent Manufacturing, 29-30 October 2003, Providence, Rhode Island, USA*, edited by Bhaskaran Gopalakrishnan, Angappa Gunasekaran, and Peter E. Orban, 38–49. Bellingham, WA: SPIE. https://doi.org/10.1117/12.516105.

Smart sensor application in teleoperated micro-assembly systems

Johannes Schilp, Michael Ehrenstrasser, Stella Clarke, Bernd Petzold, Michael F. Zaeh
Institute for Machine Tools and Industrial Management (*iwb*),
Technische Universitaet Muenchen, Boltzmannstrasse 15, 85748 Garching, Germany

ABSTRACT

Micro-production is meeting new challenges due to the continuing miniaturization of modern products and the increasing variety of emerging hybrid microsystems, which are mainly produced manually. For small lot production, teleoperated micro-assembly systems offer new perspectives in improving manual assembly processes. By using smart sensor information, teleoperated systems enable an operator to feel physically present in a distant environment. In contrast to conventional sensor applications, smart sensors are encapsulated and intelligent sensor modules with integrated functions for data processing, status monitoring and autonomous dynamic parameter adaptation. To investigate the correlation between smart sensor data and immersion, a teleoperated micro-assembly system has been developed [1]. To achieve a close-to-reality impression and to improve the dexterity of the operator, several smart sensor modules, including virtual sensors and shared sensor components, are integrated into the system. If required, sensor signals are enhanced and transformed into other modalities in order to control the micro-assembly system more intuitively. Due to flexibility requirements, all sensors are adaptable to new environments. Visual supervision is achieved through a precise optical system. All sensor components have been tested within an international teleoperation scenario consisting of a local operator in Munich, Germany, and a distant operator in Pittsburgh, USA.

Keywords: teleoperation, telepresence and teleaction, enhanced tele-X technology, smart sensors, agile micro-assembly

1. POTENTIALS OF TELEOPERATION IN MICROSYSTEM TECHNOLOGY

Teleoperation, a new tele-X technology, can be used for controlling micro-assembly processes. Based on smart sensor applications providing multi-sensory information for a close-to-reality impression, teleoperation enables both telepresence and real-time teleaction between distant environments. This is a new approach compared to known tele-X applications in the fields of tele-maintenance, tele-diagnostics and telecommuting. Users of these tele-X services can nowadays merely control distant environments without any feedback information. Tele-services often confine themselves to exchanging data or information, such as process parameters or control data, which have to be available from anywhere on the world. This simple user-interaction and data transmission hits the main goal of common tele-X applications, which is to optimize non value adding procedures in time and costs, and to enable flexible working environments.

In order to extend tele-X application to value adding processes, teleoperation shows additional potentials concerning multimodal feedback and close-to-reality interaction. According to the definition of telepresence and teleaction technology (also called "enhanced telepresence"), a human operator can feel physically present in an inaccessible environment (or "remote site", abbreviated to RS) and can carry out manipulations intuitively at the RS by using suitable tools [2]. In detail, inaccessibility of the RS may be caused by hazardous environments, local distance or the size of the objects to be manipulated. Due to the mentioned intuitive interaction at the RS and the immersion into the RS, teleoperated operations can be more ergonomic and efficient than manually performed processes. Teleoperation is therefore a promising approach in the field of production engineering, particularly with regards to simplifying manual, value adding operations like assembly processes and to coping with trends like globalization, flexible and customized production strategies and shorter time-to-market [3].

Intelligent Manufacturing, edited by Bhaskaran Gopalakrishnan, Angappa Gunasekaran, Peter E. Orban,
Proc. of SPIE Vol. 5263 (SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.516105

Manual assembly operations in microsystem technology (MST) are a promising field of teleoperation both from a technical and economic point of view. First, human intervention in clean production environments must be prevented in order to avoid damages of sensitive surfaces of micro-products. Therefore, a teleoperated remote control of assembly system must bridge the physical distance between the human operator and the sealed production equipment, or so-called teleoperator. This local separation also enhances safety issues. Besides these environmental requirements, the inaccessibility of the RS in MST is mainly caused by scaling barriers between the human environment and the micro-world. Due to the small dimensions of the micro-parts, which have to be manipulated, surface forces such as adhesive forces are eminent parameters in the micro-world. To overcome the scaling barrier and to realize a high fidelity impression, these minimal contact forces have to be monitored, adjusted and scaled to common dimensions of the human operator. Finally, precise positioning at accuracies down to the single micron and less is a crucial process in micro-assembly. Due to the insufficient human tactile sense and the resulting unsatisfactory hand-eye coordination, alignment tasks, which are performed manually with the help of auxiliary devices like magnifying glasses and tweezers, are inadequate for the required accuracy. Through the processing of motion commands and highly precise actuator and sensor components, which are integrated into the teleoperator side, teleoperation ensures long term process quality and highly precise movements.

Besides these technical aspects, economic issues in MST can also be solved by teleoperated systems. Because MST-applications are rapidly penetrating common market shares such as household, automotive and telecommunication, many innovative products, for example optical telecommunication components, are emerging [4]. Based on hybrid technology, most of these emerging MST-products consist of diverse sub-components with specific functionalities. Diverse combinations of these components made from different materials and shapes enable highly customized micro-products with high functional densities, but require a multitude of highly accurate mounting and joining methods. According to small global production volumes of given microsystems with hybrid setup [5], a lot of these hybrid products are mainly manually produced. Due to the ongoing miniaturization of products, ergonomical issues arise, involving higher process times and costs. To increase efficiency and reduce assembly costs, teleoperation provides efficient, ergonomic and flexible strategies for manual micro-assembly. Therefore Tele-X applications in small-scale micro-assembly of MST can cope with the demands in accuracy, flexibility and ergonomics.

2. REQUIREMENTS FOR TELEOPERATED MICRO-ASSEMBLY PROCESSES

2.1 APPLICATION DEPENDENT REQUIREMENTS

Due to the specific nature of MST, certain requirements are to be met by the design of manual teleoperated micro-assembly systems. For instance, handling miniaturized objects is quite different to handling in the macro-world, because so-called "scaling effects" influence the interaction between handling equipment and micro-parts. During micro-manipulation surface forces such as electrostatic forces and van-der-Waals forces, are far more predominant than volume forces, mostly represented by gravitational forces [6]. For example, in the macro-world, an object always falls down when released from a set of grippers. But in the micro-world the object may stick to the gripper or jump away at random. Although gravitational forces are relatively insignificant in micro-worlds, they are nevertheless expected by the unknowing human operator, accustomed to living in macro-worlds. Therefore, to give the user 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 at the RS.

As a consequence of small component dimensions and sensitive surfaces of micro-parts, even the smallest forces, which appear in a micro-assembly process, can cause unacceptably high surface pressures and therefore damage the product. Hence, micro-assembly processes require highly accurate and uniform motions, which are based on actor components with high resolutions, highly precise force control algorithms, smart sensor components and suitable input devices.

Furthermore, many micro-assembly processes involve clean room conditions, because any pollution, such as dust particles, may affect the functionality of the micro-objects to be assembled. Uniform process environments at the teleoperator side are best provided in laminar flow, without any direct interference of the human operator within the process area. Therefore, only supplying tasks need to be manually accomplished at specific interfaces without teleoperation.

Since they are used for piece or small scale production, teleoperated micro-assembly systems must be customizable to changing assembly tasks with minimum additional effort. Therefore, exchangeable hardware and software modules are essential. In order to assure a wide range of application, sensor modules must also be easily exchangeable and adaptable to different tasks.

2.2 SENSOR-SPECIFIC REQUIREMENTS IN TELEOPERATED MICRO-ASSEMBLY

In teleoperated micro-assembly systems, sensors are a core component for acquiring, processing and transmitting process data to the operator. In the domain of operability, ergonomic requirements and physiological fundamentals of human perception are essential. Particularly for the haptic perception, the sampling rate of the used sensor components plays a crucial role for the achievable impression. Various scientific publications [7][8][9] report that the human hand has asymmetric haptic input/output capabilities. According to [7], 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.

Furthermore, the design of teleoperated micro-assembly systems has to provide intuitive operability. During micro-assembly the operator shall focus on the assembly task and must not be distracted by additional auxiliary operations such as changing sensor parameters and adjusting camera settings. Therefore, the teleoperated system has to provide smart sensor modules with autonomous and semi-autonomous calibration functions. After employing sensors into new processes, they have to recognize new environmental parameters and adjust themselves. For a high-fidelity interaction the operator must not notice this calibration process.

For visualization and intermodal presentation of process information, all sensor signals have to be continuously monitored and provided for further processing. Sensor signals have to be processed and presented in a customized manner due to individual sensomotoric skills and preferences of the operator. 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.

2.3 SAFTEY REQUIREMENTS FOR TELEOPERATION

Safety-issues are important for the design of teleoperated micro-assembly systems. Two groups of possible safety risks must be considered. The first group of safety risks 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 safety mechanisms 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. The second group describes the safety risks of possible operations errors by the human operator. This class of safety risks can be handled 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. Automatic danger recognition by the sensor system based on previous malfunctions can also be implemented as an extra safety precaution.

3. SETUP OF THE TELEOPERATED MICRO-ASSEMBLY SYSTEM

3.1 SETUP OF TELEOPERATOR SIDE

For piece and small volume production of prototypes and customized products, a teleoperated and flexible micro-assembly system was designed. The 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 and is therefore the basis for the smart control mechanism between the operator and teleoperator side.

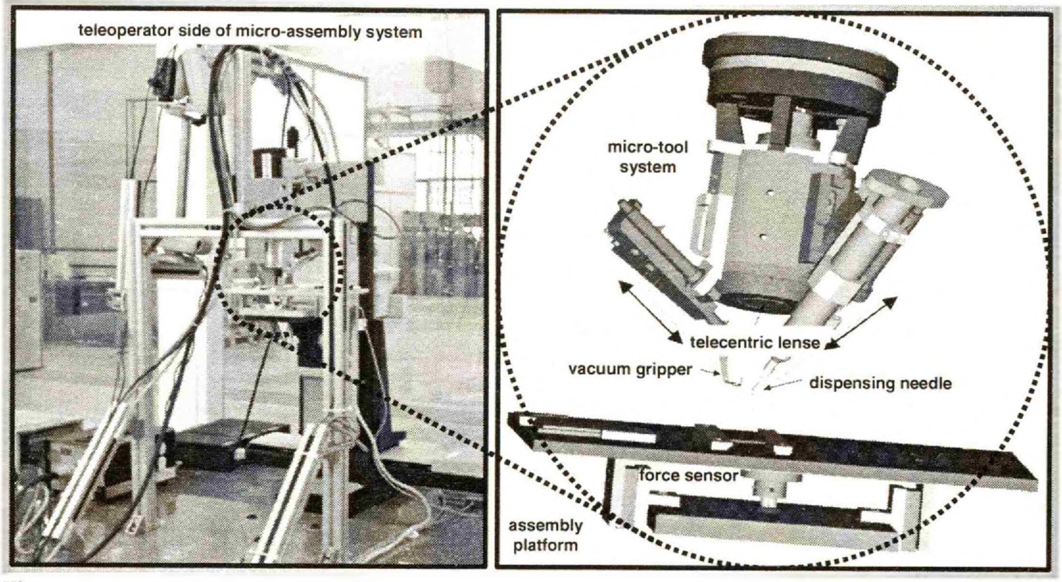

Figure 1: Setup of teleoperator side

The teleoperator for high-precision micro-assembly tasks consists of two core components (see Fig. 1). The first component represents an assembly platform, which is attached to a Cartesian coordinate axes system with three precision linear tables. With a positioning resolution of 0.1 µm and a total workspace of 204 mm x 204 mm x 204 mm, it ensures high accuracy, which is the basis for a multitude of assembly tasks. To achieve sensitive handling of microsystems, mounting forces of up to ±50 N at a maximum force resolution of ±0.024 N in the z-direction can be acquired through a uniaxial precision force sensor in conjunction with a 12 bit data acquisition card. The assembly platform provides fixtures for substrates which the parts are assembled to and fixtures for chip-trays or magazines, which supply the micro-parts.

The second core component, a micro-assembly tool system designed for teleoperation, is based on a flexible and modular micro-assembly tool head, which was developed at the *iwb* for automated micro-assembly tasks [10]. The tool system consists of a central tool head, which integrates all necessary sensor components, and up to four process specific assembly tools. These end effectors are flexibly attached to the tool head at provided interfaces, which are arranged equally around the cylinder-shaped tool head. The tool head includes a coaxial optical system for birds eye view purposes, which consists of a CCD-camera, a highly precise telecentric lens and coaxial illumination. The field of view of the birds eye view system amounts to 1.9 mm x 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. Designed for manually performed tasks, the whole optical system can be moved within a range of ±5 mm in the vertical direction, in order to adjust the optical focus. This optical system can be used for both visual monitoring by a human operator and for precise image processing measurement tasks. The sensor-based tool head can rotate 360° with an angular resolution of 0.005°. The process specific tools, such as grippers and dispense units, can be extended into the focus plane of the camera by pneumatic cylinders. In summary, the teleoperated assembly tool system provides a total number of four degrees of freedom and a total number of four end effectors, which is sufficient for a multitude of micro-assembly tasks. In addition to the precise optical system, which is integrated into the tool system, an overview of the assembly station is achieved by two side-view cameras for observation purposes.

3.2 SETUP OF OPERATOR SIDE

The teleoperated micro-assembly station can currently be controlled by one haptic and one non-haptic input device (see Fig 2). Therefore the operator can concentrate on the assembly task and does not need to grip other input devices such as keyboards or mice for auxiliary processes. This leads to an ergonomic interaction and a non-exhausting operation mode.

A force-feedback joystick (from Immersion) is used for controlling 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. Other haptic input devices such as Phantom® sticks are also possible for controlling the assembly system. In conjunction with the mentioned high-resolution force sensor and the data-processing on the teleoperator side a close-to-reality interaction during the manual micro-assembly process can be achieved.

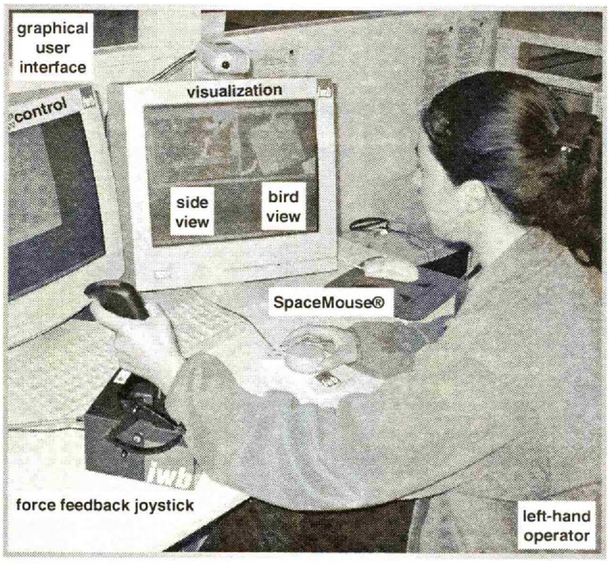

Figure 2: Setup of operator side

The micro-assembly tool system can be rotated by a SpaceMouse®, in order to adapt the view point and the tool position by revolution. This non-haptic, 6-DoF input device also drives the motorized axis of the optical system for adjustment purposes of the focus plane. By pushing certain keys, the adapted end-effectors of the tool system can be extended or retracted, and specific tool functions such as opening and closing of a gripper, can be activated.

As mentioned above, visual supervision of the assembly scenario is achieved through two side-cameras with different viewpoints and zoom factors and the bird eye view camera in the tool system. The top-view camera mostly is used for the accurate positioning process and the side-views for coarse-positioning.

3.3 SOFTWARE ARCHITECTURE

To ensure the same flexibility as the hardware components of the teleoperated micro-assembly system, the software architecture also consists of a modular setup (see Fig. 3). 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. 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 (**manager**) has access to all DEO's 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 (**GUI**).

All process data which is displayed on the GUI, must be continuously refreshed. Additionally, all operator inputs have to be processed and forwarded. Therefore, the user interface thread (**user interface**) reads all process data from the user interface output DEO (**UIOutput**) and refreshes all user input data in the user interface input DEO (**UIInput**).

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

The actuator manager thread (**actuator manager**) 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 (**server**) continuously receives or sends data from or to a client application. The client application itself requests data from the different user input devices, e. g. haptic or non-haptic devices. Communication between the client and the server is realized through a UDP/IP 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 (**clientoutput**) and transmits them to the server application. Received data from the client application is stored into the client input DEO (**clientinput**). The client application can be either an external application or the system can be controlled on-site by a client thread (**client**), which is integrated into the software framework.

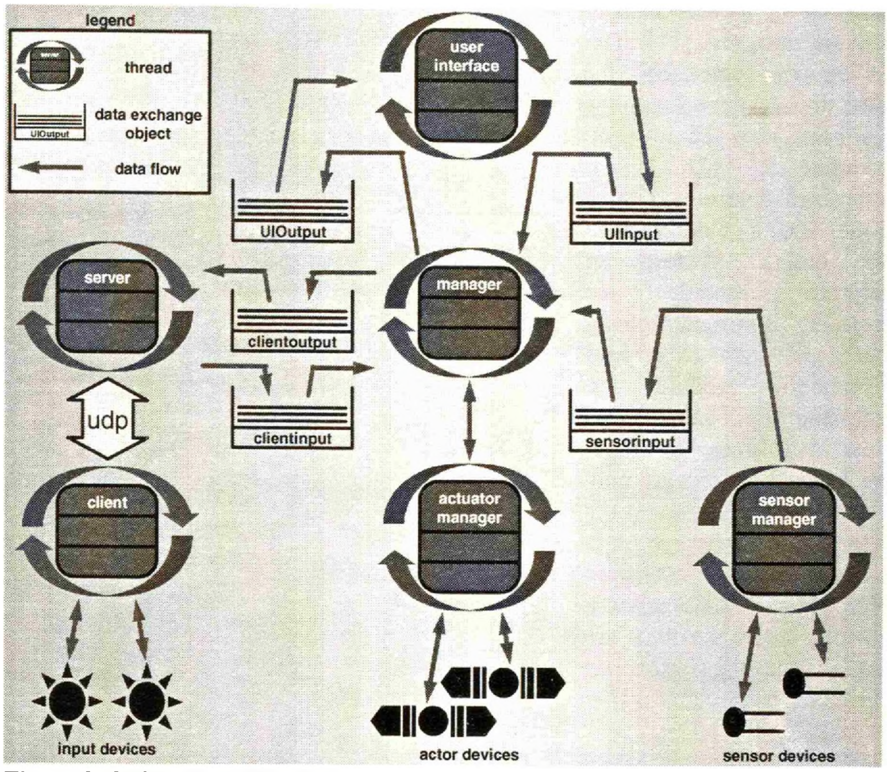

Figure 3: Software architecture

4. SMART SENSOR APPLICATIONS

Today's industrial automated micro-assembly systems usually use simple sensor applications, so-called "dumb sensors", with limited capabilities. Such sensors are passive objects with only unidirectional data flow capabilities and predetermined parameter settings. All sensor data are interpreted by an external centralized controller. Aside from sensor data processing, this controller must also provide the full functionality for process data monitoring, fail status supervision and parameter setting. Hence, integrating new assembly tools with tool-specific sensors, as well as system adaptations to new products and processes, requires substantial changes to the central controller software. In order to cope with the above postulated requirements for teleoperated systems, a conceptual approach based on "smart sensors" has been chosen. Smart sensors can be seen as encapsulated intelligent sensor modules with integrated functions for data processing, status monitoring, decision making and autonomous dynamic parameter adaptation. For this purpose, smart sensors are able to communicate with other smart sensors through predefined and standardized input/output interfaces. In addition, several smart sensors can be combined and grouped into new, task-specific virtual sensor modules. Thus, through the use of smart sensors, the structure of the control software of TPTA systems can be managed in an orderly fashion. New sensor components can also be easily integrated and adapted to process-specific requirements.

4.1 COMMON SENSOR ARCHITECTURE

In order to enable agility and 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 [11]. The first known approaches for abstracting sensory functions have been reported in [12]. According to [12], 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.

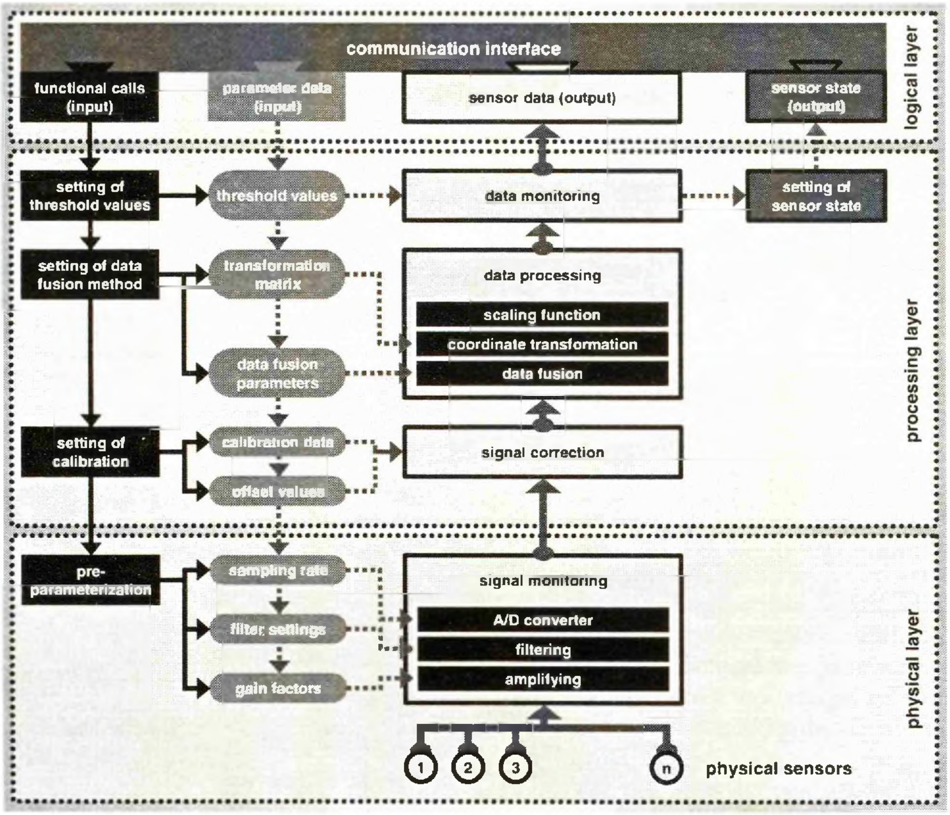

Figure 4: Common sensor architecture

Fig. 4 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 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 (see section 3.1). 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 teleoperated micro-assembly system and for avoiding safety critical situations. For this purpose, several standardized sensor states are available. For example, the state SENSOR_NORMAL represents the normal operation mode, whereas SENSOR_WARNING_LEVEL_1 and SENSOR_WARNING_LEVEL_2 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.

4.2 SENSOR COMPONENTS

The micro-assembly system described in this paper consists of the following physical sensors: a uniaxial force sensor, a fibre-optical distance sensor for measuring the distance between the dispensing needle and the substrate, and four position transducers for each of the translatory kinematic axes as well as a rotary transducer for the rotary axis of the assembly tool head. In the following sections, the implementation of the processing layer is discussed in detail.

4.2.1 INTEGRATION OF A FORCE SENSOR

As described in section 3.1, a uniaxial precision force sensor is integrated into the assembly platform. The force sensor must fulfil two important demands: First, the sensor must provide precise process force data to the force feedback input device, in order to support the operator during the assembly process. Second, the force sensor has to monitor the current force values, in order to prevent collisions and possible resulting damages.

Fig. 5 shows the software structure and the state diagram of the force sensor. The structure of the telepresent force sensor corresponds to the three-layer architecture described in section 4.1. The class CDAQBoard represents the physical layer. It includes the data acquisition board and provides functions for acquiring raw sensor signals. Within the class CForceSensor the functions for signal processing and signal conditioning are implemented.

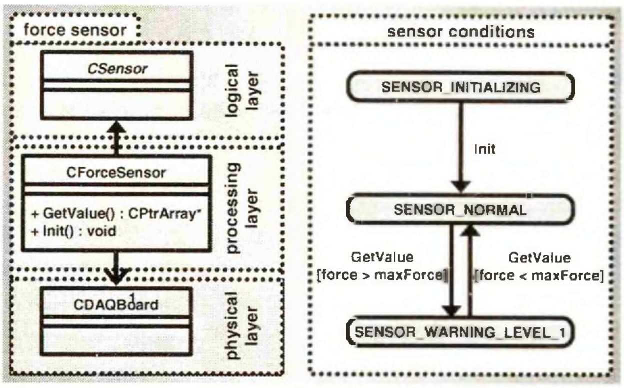

Figure 5: Implementation of force sensor

After the force sensor is initialized, it is in normal operation mode and provides sensor data to the sensor DEO. At each call of the function *GetValue*, the force sensor verifies the status. If the measured force exceeds the maximum force, the sensor changes to the state SENSOR_WARNING_LEVEL_1. This state indicates a safety-critical situation. Through the corresponding entry into the sensor DEO, other components of the framework can react to this event. For example, the actuator manager prevents further axis movements in the positive direction, which would result in an additional rising of the assembly force, whereas movements into the negative z-direction are still possible. As soon as the measured force value falls below the force limit, the sensor returns to the normal condition SENSOR_NORMAL.

4.2.2 INTEGRATION OF POSITION SENSORS

According to the above described three layer sensor architecture, the implementation of position sensors has been realized. Fig. 6 shows the software structure of the logical position sensor CPISensor. Each instance of this sensor class accesses the axis controller board and provides the actual position, the current velocity and the deviation between target position and the actual position of the corresponding axis. For safety reasons limit switches can be defined for each axis. If an axis exceeds the lower or upper limit switch, the sensor state changes from condition SENSOR_NORMAL to SENSOR_LOWER_LIMIT or SENSOR_UPPER_LIMIT. These sensor state signals are used by the integrated safety algorithms of the actuator manager in order to prevent possible collisions.

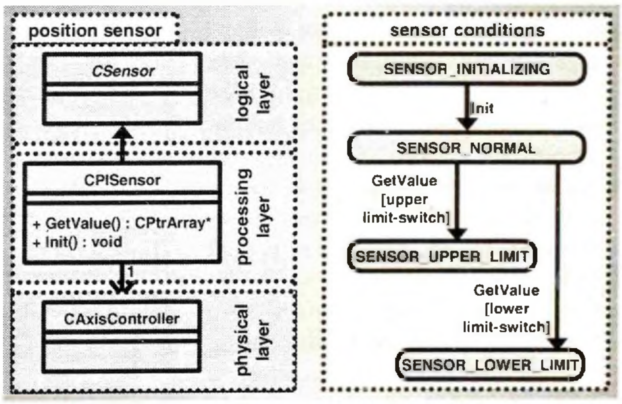

Figure 6: Implementation of position sensor

4.2.2 COOPERATING SENSORS - A SMART DISTANCE SENSOR

According to the concept of [12], several logical sensors can be combined in order to set up a new logical sensor. Because logical sensor modules can autonomously communicate with 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. 5 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.

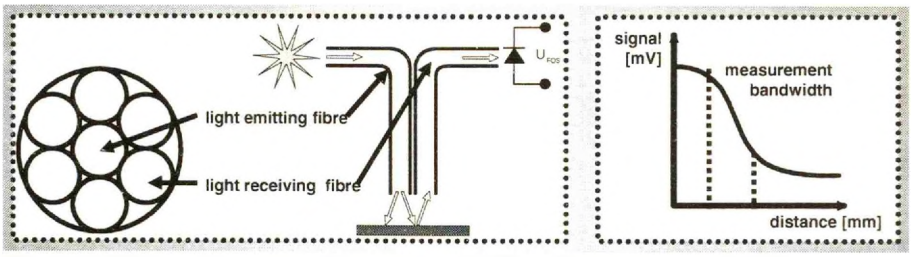

Figure 5: Fibre-optic sensor: Cross section (left); calibration curve (right)

Fig. 6 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.

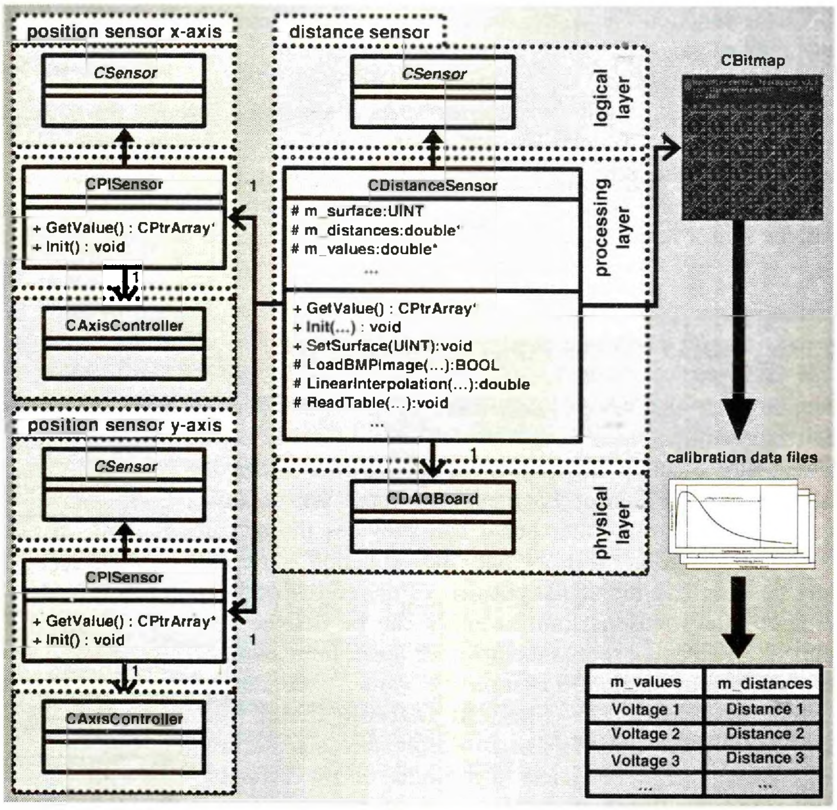

Figure 6: Implementation of smart distance sensor

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 computer aided circuit board layout programs. For aligning the digital bitmap with the position and orientation of the real substrate. a singular calibration cycle is necessary. In the experimental setup. this was 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 [11].

The logical sensor of the class CDistanceSensor can access the sensor data output of the logical position sensors of the class CPISensor. 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.

4.2.3 VIRTUAL SENSOR FOR WORKSPACE SUPERVISION

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 processing flow. Virtual sensors do not have a physical layer, but rely solely on the data output vectors of other logical sensors. In telepresent 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 has been implemented. Fig. 7 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. e. g. X_AXIS_UPPER_LIMIT. These supervision flags can be interpreted by the actuator manager thread (see section 3.3), so that further movements of the corresponding axis will be blocked. However, retreating movements for re-entering the workspace are still possible.

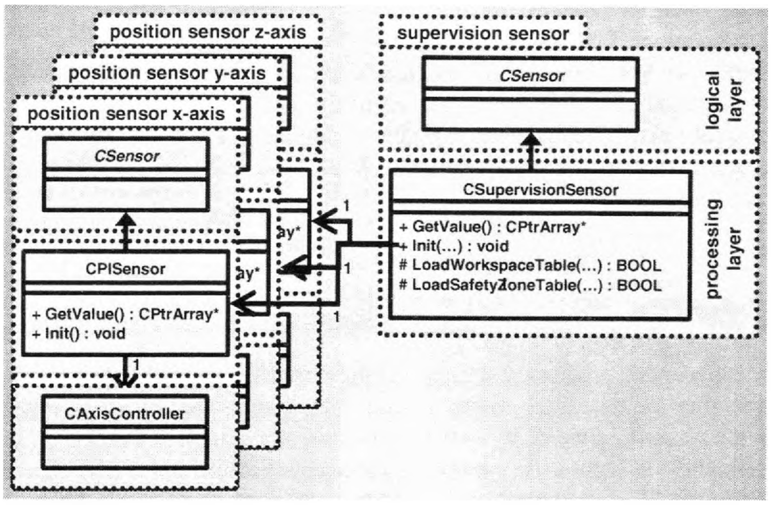

Figure 6: Implementation of supervision sensor

Similar to the workspace supervision, safety zones can also be supervised. As soon as a predefined safety zone is entered. which is indicated by the condition SAFETY_ZONE, all axis velocities will be automatically reduced by the actuator manager thread, in order to minimize the danger of possible collisions.

5. EXAMPLE OF USE

5.1 ASSEMBLY TASK

For verifying the work described in the previous sections, an international teleoperated micro-assembly experiment has been conducted (see Fig. 7). The task was to pick up an integrated circuit from a chip-tray and place it on a test circuit board. The dimensions of the integrated circuit were approximately 1.5 mm x 1.5 mm x 0.5 mm. The micro-assembly station was located in a clean-room at the research laboratory of the *iwb* in Munich. In order to demonstrate the ability to control the assembly system through the internet, the system could be teleoperated from two different locations.

First, an operator in Munich had to pick up the integrated circuit from the chip-tray and to move it to a specific position between the chip-tray and the test circuit board. For facilitating the navigation, a European 20-cent coin was placed to mark this point.

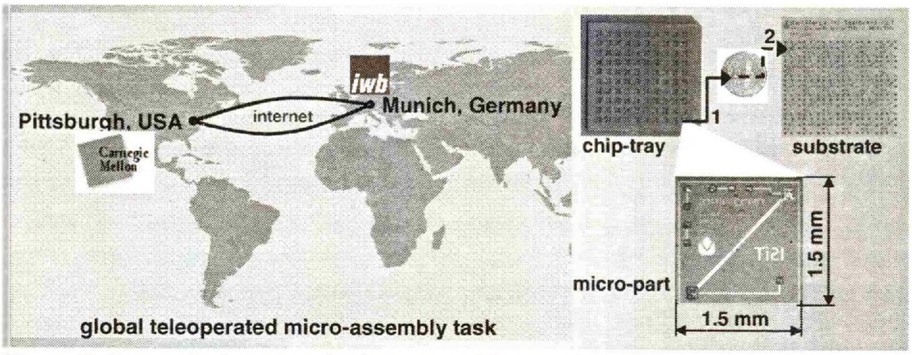

Figure 7: Setup of teleoperated micro-assembly experiment

Control was then switched to a second operator, located at the Microdynamic System Lab of the Robotics Institute at the Carnegie Mellon University in Pittsburgh. The operator in Pittsburgh moved the gripper with the integrated circuit above to the desired position on the test circuit board, adjusted the orientation and lowered the circuit into place. Because the top-view video camera provided no information about the distance between the integrated circuit and the substrate, the operators had to use haptic feedback from the uniaxial force feedback sensor for sensitive handling operations.

5.2 RESULTS

The experiment confirmed the capabilities of the developed telepresent micro-assembly system. The average time for performing the described micro-assembly task amounted to 3.5 minutes. During the experiment, the long distance and thus the resulting time delay between the operator station in Pittsburgh and the micro-assembly station in Munich did not significantly influence the system performance. For estimating the time delay between Munich and Pittsburgh, the round trip time (RTT) was measured in a 24 h measurement series. The average RTT was approximately 120 ms without any major deviations, and confirmed the positive subjective impression of the described experiment. The sensitive handling capabilities of the system could be demonstrated by stacking up to four circuits upon each other.

6. CONCLUSIONS AND OUTLOOK

In this paper, a teleoperated micro-assembly system based on a smart sensor framework has been reported. In this framework, logical and virtual sensors are used for achieving agility and changeability. In contrast to conventional, automated micro-assembly systems, the developed sensor components can be easily added to and removed from the framework.

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 operability. Furthermore, several logical sensors can be grouped and combined to build new, virtual sensors. This technique has been used for implementing virtual supervision sensors for monitoring safety-critical system conditions and avoiding possible collisions and damages.

In addition, the conducted global teleoperated micro-assembly experiment shows interesting possibilities for future industrial applications. Through using telepresent micro-assembly, the physical presence of an operator in a clean room is not necessary, which helps contribute to improved working conditions. In addition, the convenience and integrated safety of teleoperated micro-assembly systems helps facilitate the flexible interchange of operators (e. g. when one operator is unable to attend work for a variety of reasons). The international capabilities of such teleoperated systems also enables 24 hour per day production schedules without overtime premiums, by simply shifting to operators in different time-zones.

7. ACKNOWLEDGEMENTS

The work presented in this paper is funded within the "SFB 453" Collaborative Research Center "High-Fidelity Telepresence and Teleaction" of the DFG (Deutsche Forschungsgemeinschaft). The authors also thank Christian Schuberth, Matthias Doerfel and Mark Endress for their contributions to the concept and implementation. Special thanks goes to Dr. Ralph Hollis from Carnegie Mellon University in Pittsburgh, USA. With his friendly support an operator station could be set up in Pittsburgh.

REFERENCES

[1] Zaeh, M. F.; Jacob, D.; Ehrenstrasser, M.; Schilp, J.: Hybrid Micro-Assembly System for Teleoperated and Automated Micro-Manipulation. In: Ziegert, J.C.: Machines and Processes for Micro-scale and Meso-scale Fabrication, Metrology and Assembly, Florida. North Carolina: Proceedings of ASPE Vol. 28 (2003), pp. 119 - 124.

[2] Anton, O.; Cuiper, R.; Ehrenstrasser, M.; Patron, C.; Reinhart, G.: Telepresent Microassembly for Industrial Applications. In: Nair, S. (Ed.): Proceedings of the ASME Dynamic Systems. ASME 2000.

[3] Zäh, M. F.: Megatrends in der Produktionstechnik - Herausforderungen für Gesellschaft, Wissenschaft und Ausbildung. In Zäh, M. F.; Reinhart, G.; Hoffmann, H.; Milberg, J. (Eds.): Münchner Kolloquium 2003, Munich. Munich: Utz 2003, pp. 269-297.

[4] Microsystems World Market Analysis 2000-2005 - NEXUS Task Force Market Analysis, Duesseldorf: VDI 2002.

[5] Wicht, H.; Bouchaud, J.; Bahle, C.: Vergebene Liebesmueh oder Wachstumsmark? In IVAM NRW e.V (Ed.): inno Nr. 20, Dortmund 2001.

[6] 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.

[7] 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.

[8] 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.

[9] Burdea, G. C.: Force and touch feedback for virtual reality. New York:John Wiley & sons, 1996.

[10] Reinhart, G.; Jacob, D.: Automated assembly of holder chips to AFM probes. In: Nelson, B. J.; Breguet, J.-M. (Eds.): Microrobotics and Microassembly III, Boston, USA. Washington: Proceedings of SPIE Vol. 4568 (2001), pp. 310 - 317.

[11] 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.

[12] Henderson, T.; Shilcrat E.: Logical Sensor Systems. Journal of Robotic Systems, 1 (1984).