Telepresence as a Solution to Manual Micro-Assembly

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Abstract

The progressive miniaturization and customization of today's products has lead to increased demand for manual micro-assembly systems. Telepresence technologies provide a promising solution to manual micro-assembly through overcoming scaling barriers and achieving high accuracies, while offering flexibility and an intuitive human-controlled working environment. Guaranteeing such 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.

Keywords

Assembly, Man-Machine System, Telepresence

1. INTRODUCTION

Microsystems technology (MST) has been forecast to double its world market volume to an anticipated US$68 billion in the years 2000 till 2005 [1]. Once largely confined to automotive and printer-cartridge applications, "MST has expanded to include some functions once believed to be impossible" [2]. Aside from low-cost high-volume silicon-based MST products, numerous miniaturized mechatronic products are emerging. Typical examples include biomedical applications such as fingerprint sensors, optical MEMS and radio frequency MEMS.

Micro-assembly is a key technology within MST, accounting for up to 70% of product costs for small lot sizes [3]. Examples of small lot micro-assembly applications include prototypes, initial batch productions, and specialized or custom made components. For such applications, telepresence technologies present an ideal solution through encouraging efficient and accurate assembly in an ergonomic, intuitive and flexible environment.

2. TELEPRESENCE SYSTEMS

Telepresence systems offer a promising approach to manual micro-assembly through achieving the required accuracy in an ergonomic manner.

Telepresence scenarios consist of a robotic teleoperator controlled by a remotely located human operator. The human operator is provided with input devices, usually haptic, to control the teleoperator. A communication framework exists between the operator and teleoperator to enable efficient transmission of all necessary data. Figure 1 depicts a typical telepresence scenario.

The remote nature of the operator is a key factor in telepresence situations. Typical telepresence scenarios possess some kind of "barrier" between the teleoperator and operator. For example, telepresence in the nuclear industry is adopted due to a "danger" barrier. Instead of having a human present at the nuclear site, a human-controlled teleoperator is present to carry out the required handling, inspection or maintenance tasks. The human is not physically present in the nuclear environment, but rather "telepresent".

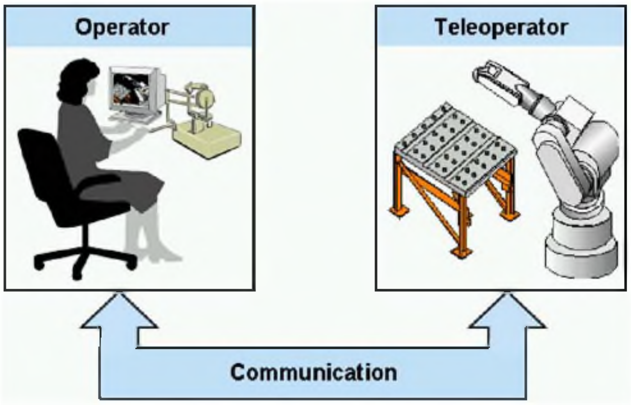

Figure 1: Typical telepresence scenario

In a similar manner, "telesurgery" overcomes a distance (and accuracy) barrier between patient and surgeon. For example, a surgical teleoperator could be set up in a military battlefield, where patients are treated while the surgeon remains in a safe remote location, such as in another land. Similar arguments can be used to explain the benefits of telepresence in outer space and planetary work, deep sea exploration and remote surveillance. In micro-assembly, telepresence is adopted to overcome scaling barriers as well as distance barriers. The latter is beneficial because micro-assembly teleoperators are often located in clean rooms, where human presence would only encourage contamination. Removal of direct human contact helps maintain a sterile environment.

What separates telepresence from the more loosely defined "remote control", is the goal of providing an *intuitive* and *ergonomic* operating environment. This is achieved through a suitable choice of input devices (e.g. various joysticks, PHANToM haptic devices, wearable gloves and foot pedals), and an optimal mixture of feedback information in the forms of haptic, visual and audio feedback. Such feedback information is often realized in the form of high-tech haptic input devices and elaborate virtual reality environments.

3. TELEOPERATOR

The teleoperator side of a telepresence production system consists of all the required components to fulfil the desired task. Two important teleoperator requirements are:

1. The ability to provide feedback information to guarantee an intuitive *operator* environment.
2. Safety mechanisms to avoid harm to equipment.

The first requirement mostly involves the provision of high performance sensors, which are the core components for acquiring, processing and transmitting process data to the operator. In particular, sampling rates play a crucial role in guaranteeing adequate haptic feedback and the resuting "immersiveness" of the operating environment.

Physiological fundamentals of human perception are essential for providing a close-to-reality impression. According to [4], the human hand has asymmetric haptic input/output capabilities. Although the human is only capable of movement frequencies in the range 5 – 10 Hz, much higher haptic feedback rates are needed to ensure powerful haptic perception. For example, for meaningful kinesthetic perception, position and force sensors should provide sampling rates no less than 20 - 30 Hz. Even higher sampling rates (300 - 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 5 - 10 kHz.

Furthermore, intuitive operability requires the operator to be focused on the production task, and not be bothered by additional auxiliary operations such as changing sensor parameters and adjusting view-points during operation. Therefore, the teleoperated system must provide "smart" sensor modules which contain autonomous or semi-autonomous calibration functions. The sensors must recognize new environmental parameters and be able to adjust themselves. Additionally, for high-fidelity interaction, the operator must not notice this calibration process.

For visualization and multimodal presentation of process information, all sensor signals must be continuously monitored, processed and presented in a customized manner which is dependent on the individual sensomotoric skills and preferences of the operator.

The second requirement is that of safety in the teleoperator environment. There are two main groups of safety risks. The first group concerns possible malfunctions of the teleoperated assembly system itself. To minimize these risks, the status of all components is continuously monitored and appropriate safety mechanisms are implemented in order to decide whether this failure is safety-critical or not. The second group describes the safety risks from possible operations errors. This class of safety risks can be handled by continuously monitoring the current process conditions. In the case of irregular process conditions, such as when predefined force limits are exceeded, the system must react to the situation and 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.

Specific to manual micro-assembly tasks, additional requirements of the teleoperator side exist. The prime requirement is that of accuracy, which the sensor and actor components of the teleoperator must provide for highly precise positioning and assembly processes. Even very small forces which appear in the micro-assembly process can cause unacceptably high surface pressures, therefore risking product damage.

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 teleoperated micro-assembly systems are applicable to piece or small scale production, they must be customizable to changing assembly tasks with minimum additional effort. Therefore, exchangeable hardware and software modules of the teleoperator are essential. In order to assure a wide range of application, sensor modules must also be easily exchangeable and adaptable to different tasks. This flexibility also helps the goal of reducing production costs per part.

4. OPERATOR

The operator side is the "man-machine-interface" of a telepresence system. As previously discussed, to gain all the advantages of a telepresence system, the operator must be supported with high fidelity information to guarantee intuitive and ergonomic task completion. Visualization is the most important sense for humans. The simplest way to obtain a view of the scene is through a video camera at the teleoperator side which sends the image to the user. Particularly in micro-assembly, achieving a high-quality video stream of the environment is difficult, because of the small dimensions involved. High resolution cameras are mainly available in greyscale, and with many metallic surfaces, reflections can lead to a poor image. Remedy can be achieved by using a virtual environment for displaying the scene. Because the teleoperator environment in micro-assembly tasks is known, all objects can be modelled. This stands in contrast to teleoperation tasks in unfamiliar environments such as teleoperated planetary exploration or surgery. In most cases, three-dimensional CAD data is already available and can be used. The advantage of virtual reality visualization is the range of vision, which is only limited to the quality of the CAD data. Today's graphics cards are capable of visualizing more than one million triangles with a framerate of approximately 20. In addition, the viewpoint of a virtual environment can be easily changed. To solve the problem of missing depth of focus information in 2D images, several windows with different views can be displayed. If the workspace is very complex it is useful to have an immersive stereo vision system, which allows a three dimensional view on the scene. Active stereo with shutter glasses can be relatively easily implemented with a monitor. For larger displays, passive stereo with polarized beamers are fitting.

Although visualization is the most important human sense, humans also benefit from other senses such as acoustic and haptic. The haptic sense is particularly useful in part assembly scenarios. The importance of haptic feedback during telepresent assembly was proven in an experiment at the *iwb* [5]. Because the haptic sense is more complex than the visual sense, haptic input/output-devices, also called force feedback devices, vary extremely in functionality and cost. The main differences are the types of the devices (e.g. wearable vs. non-wearable), the supported degrees of freedom, and the maximum forces that can be exerted. The required tasks help to determine the necessary device/s. For some tasks it is useful to support both hands. These bimanual tasks can achieve more efficient work, but should be handled with care, because the second input device can lead to a cognitive overload for some people (for more information see [6]). In contrast to the visual sense, which can detect 24 pictures per second, the haptic sense can resolve a frequency of 1000 Hz.

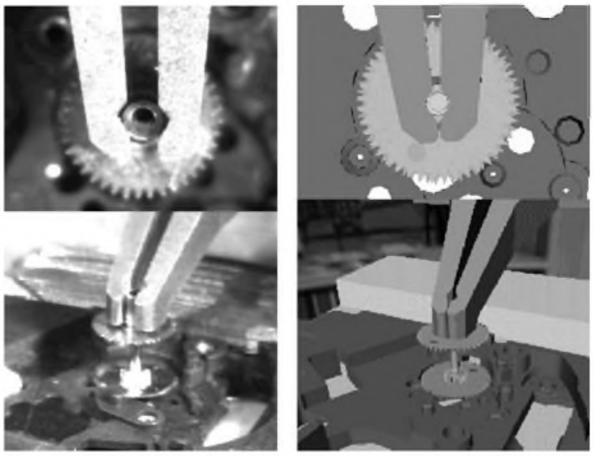

Figure 2: Camera image and virtual reality image of a micro-assembly scenario

5. COMMUNICATON

Ethernet-based networks provide an optimal communication mechanism for telepresence-based micro-assembly through offering high bandwidth and flexibility. However, the remote nature of telepresence systems introduces additional barriers which need to be overcome within the communication infrastructure. Two main obstacles include:

1. Inability to directly access the teleoperator and its corresponding processes.
2. Delay times introduced by distances and network traffic between the teleoperator and operator.

The first obstacle hinders the ability to directly manipulate or even start and stop any process on the teleoperator-side. The second obstacle can greatly reduce assembly performance.

The first problem has been solved through the creation of a “startup service” which enables the operator to remotely start up and control the state of any application within the entire telepresence system (see Figure 3). Each computer in a distributed telepresence system contains a “startup client”, which continuously listens for commands from the “startup master”, which may be located on any computer within or external to the telepresence system. The components within the distributed startup service communicate through a UDP-protocol based layer.

The most basic function of the startup service is to execute and terminate applications within the entire telepresence system from one single location. A more advanced feature is the ability to continuously monitor the status of each application in order to detect failures within any of the processes. In the event of a failure, the entire system is shut down (i.e. every process is terminated).

The second problem is unavoidable in all telepresence systems, and can pose serious problems in any circumstance where high network delays are produced. For example, the distance-factor alone can produce round-trip delay times of up to one second between two remote countries. A side-effect of this could be unwanted collisions, due to the fact that the operator is relying on visual feedback which is actually one second in the past.

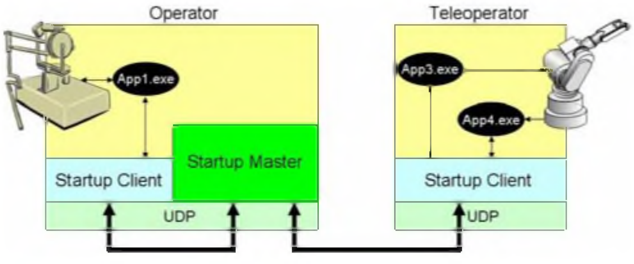

Figure 3: Startup service

To overcome this delay problem, prediction of position data from the haptic input device can be implemented. This means that instead of sending position data directly from the input device to the teleoperator, the position data is first sent through a prediction algorithm which predicts the future position of the input device based on past position data, and sends this “guessed position” to the teleoperator. If the prediction time is equal to the network delay time in the telepresence scenario, the network delay will be compensated for; that is, assuming an accurate prediction. There are a number of possible prediction algorithms which can be implemented in telepresence scenarios. For further details, see [7], which uses the support vector regression algorithm to analyze the predictability of data from a PHANToM 6 degree of freedom haptic input device.

6. TELEPRESENCE SETUP

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 the 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.

The teleoperator for high-precision micro-assembly tasks consists of two core components (see Figure 4). 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. 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 a birds eye view image, which consists of a CCD-camera, a highly precise telecentric lens, and coaxial illumination. The field of view of the optical 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 of four degrees of freedom and 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 through two side-view cameras for observation purposes.

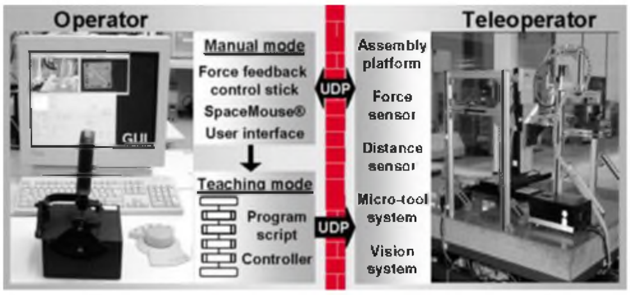

Figure 4: Telepresence Setup

The teleoperated micro-assembly station is currently controlled at the operator side by one haptic and one non-haptic input device (see Figure 4). The operator can concentrate on the assembly task and does not need to adjust system parameters or carry out other such auxiliary processes with input devices such as keyboards or mice. This leads to ergonomic interaction and a non-exhausting operation mode.

A force-feedback joystick (from Immersion) is used to control the motion of the three axes of the precise Cartesian kinematic system. Three-dimensional motion through a “two-dimensional” input device is achieved with different press combinations of the joystick's two buttons. Pressing the front joystick button moves the axes in the x-y plane, while pushing two buttons enables only the z-axis. Three dimensional haptic input devices such as the PHANToM® 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 is achieved.

Rotation of the micro-assembly tool system and motion of the optical system axes are controlled at the operator side through a 6 degree of freedom SpaceMouse®. In addition, through pushing certain buttons of the SpaceMouse®, the end effectors of the tool system can be extended or retracted, and specific tool functions such as opening and closing of grippers can be activated.

Visual supervision of the assembly scenario is achieved through the two side-cameras, which each have controllable zoom factors and are used for coarse positioning. The optical birds eye view camera located within the tool system is mainly used for accurate positioning.

7. CONCLUSION

This paper described the many benefits of implementing telepresence within micro-assembly systems, and outlined key issues in the development of the three key telepresence components: the teleoperator side, the operator side and the communication framework. For each of these components, many considerations must be made to fulfil the goal of an intuitive and ergonomic operating environment. This is achieved through an adequate sensor infrastructure on the teleoperator side, optimal visual and haptic feedback settings on the operator side, and an efficient communication structure between both sides.

The telepresence system at the *iwb* is continuously being improved to achieve the level of efficiency, flexibility, ease of use, and cost effectiveness required in industry. For example, new force feedback devices are being developed to enable more intuitive and ergonomic manipulation abilities, and the prediction algorithm is being optimized to allow almost delay free communication over the internet. New methods will also extend the abilities of the telepresence system beyond that of manual micro-assembly to areas such as teaching processes, wherein telepresent environments are used to train the teleoperator in automated tasks. This “teleoperated teaching” is useful in small-scale production tasks, such as micro-assembly prototype production.

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