Haptic Interface for a Microrobot Cell

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Abstract. This paper presents the design of the HIMiC haptic device, which was constructed for the teleoperation of microrobots. The requirements for a haptic device which is to be used for the teleoperation of microrobots are discussed. A force-to-sound transformation technique implemented to increase the force dynamic range of the developed haptic device is described. The design of the microrobot cell, which is teleoperated by HIMiC, is presented together with the results of the evaluation of the developed haptic device.

1 Introduction

Nanohandling robots or microrobots are the result of increasing research activities at the border between microsystem technology and robotics. Today microrobots with the dimension of a few cubic centimetres can be realised. These microrobots can handle different microobjects with an accuracy down to several nanometres.

Many applications require nano- and micromanipulation, for example:

- Microassembly - hybrid microsystems require new micro assembling techniques.
- Quality control in semiconductor technology - nanomanipulators are useful in this field.
- Flexible nanomanipulation and nanopositioning devices are needed for research in the field of nanotechnology.
- Microrobots can be used in microbiology, cell biology and medicine, for instance for in-vitro fertilization or for genetic research.

Most of the existent microrobots use piezoelectric actuators. Such microrobots have a working volume of tens of cubic centimetres and an accuracy of several nm [1].

Most current concepts for the manipulation and assembly of tiny objects rely mainly on machine vision. The microassembly is usually carried out under a light microscope or in the vacuum chamber of a scanning electron microscope (SEM). In the first case, the light microscope and one or a few CCD camera(s) are used for visual feedback. In the second case, visual feedback is implemented by transmitting SEM images to the robot's control system [2]. However, force and tactile feedback are required for reliable and non-destructive manipulation of microobjects because microobjects are more fragile and, thus, more easily deformed or destroyed during manipulations, than macro-objects. Very small gripping and contact forces in the range of 0,1µN up to 200µN and above have to be measured [3].

Different haptic devices are currently used for the force feedback teleoperation of robots, e.g. Phantom, Delta or force feedback joysticks [4,5,6,7]. However, these haptic interfaces don't enable simple and intuitive teleoperation of nanohandling robots. There are a number of reasons for that. First of all, the mentioned haptic devices have mechanical interfaces that don't provide comfortable and intuitive control of microrobots. The existing haptic interfaces have a limited force dynamic range and bandwidth that limits their application in microrobotics.

A microrobot is usually a complex system with a few actuators for coarse and fine positioning that cannot be controlled only by moving the handle of a haptic device. Therefore a haptic device for controlling a microrobot should have a number of integrated buttons, allowing different modes of control. It is impractical to use a computer keyboard for this since it is usually necessary to use two haptic devices for the simultaneous teleoperation of two microrobots. Using the keyboard would considerably slow down the teleoperation.

There is also a number of other factors which prevent the application of existing haptic devices for the teleoperation of microrobots; these will be presented below. To solve this problem, the Haptic Interface for a Microrobot Cell (HIMiC) described in this paper has been developed for the teleoperation of nanohandling robots inside an SEM and under a light microscope.

The HIMiC haptic device introduces a unique mechanical design, which was specially developed for the comfortable teleoperation of microrobots. A number of buttons and light indicators were integrated. HIMiC allows the teleoperation of microrobots using its own microcontroller without the need of an additional PC. When designing the HIMiC haptic device a low price was taken into consideration. HIMiC is designed primarily from off-the-shelf components. The total price of the HIMiC device is around 1000 USD, 60% of this is the price for motors and digital encoders.

In this paper, first, the required features for a haptic device suitable for microrobotics are discussed. After that the mechanical design and control system of the HIMiC is described. At the end of the paper an application of the HIMiC for the force-feedback teleoperation of microrobots in an SEM chamber is presented and the results are evaluated.

2 Design of the HIMiC Haptic Device

Before developing the HIMiC haptic device the requirements for a haptic device for the teleoperation of microrobots were compiled. These are presented below.

2.1 Design Rationale

– Microrobots manipulate objects of different materials and sizes. For this, gripping forces can range from several mN down to tens of nN. This means that the estimated ratio of maximal force to minimal force used in microrobotics is around

10^5:1. Therefore an ideal haptic device should provide force-feedback in the same wide range of forces.

- Existing mobile microrobots have a motion resolution around several nanometres. At the same time they have practically unlimited working area. Usually, when working under a light microscope or in an SEM chamber, the working area of microrobots is limited to tens of centimetres. This means that the ratio between working area and motion resolution is 10^8:1. Therefore an ideal haptic device should be able to control the microrobot over large distances as well as with high resolution.
- Signals from a force microsensor integrated into the gripper of a microrobot consist of not only constant force components but also low and high frequency force components which carry information about the working state of the microrobot, the state of a grasped object or a microhandling process. The bandwidth of a force signal can range up to several kHz. Therefore an ideal haptic device should be able to represent high frequency force components.
- An ideal haptic device should have a mechanical interface which allows comfortable and intuitive teleoperation of microrobots.
- The complex control of a microrobot combines human teleoperation and automatic control. A haptic device should be the central control element of the whole microrobot's control system. That is why an ideal haptic device should have integrated control elements (buttons and light indicators).
- It is seldom necessary to move microrobots (by humans in teleoperated mode) simultaneously in three or more DOF, because such a complex motion doesn't provide fast and precise positioning. On the other hand, it is often required to move a microrobot only in one predefined direction, and to prevent motions in other directions. Also, it is often required to position microrobots on a surface (motion in two DOF), and to prevent other motions. That is why an ideal haptic interface should provide the ability to decouple the motions in different axes on a user request and to assign each DOF of the haptic device to a different DOF of the microrobot. The ideal haptic device should also provide the ability to switch on and off different DOF on a user's request, so that when a user performs a motion in these DOF, the microrobot doesn't also perform the corresponding motions.
- For complex microhandling and microassembly tasks it is often necessary to control two microrobots simultaneously with two haptic devices. Therefore an ideal haptic device should be useable with only one hand.
- In many cases it is required to perform simple teleoperation of a microrobot under a light microscope, complex automatic control and coordination of many microrobots is not required. In such cases there is no need to use a PC for the control of a microrobot. In this case the performance of the system will be improved if the delay in the haptic-microrobot control loop is minimized. This can be achieved by running the software for the teleoperation of the microrobot directly in the real-time operating system of the haptic device and thus connecting the microrobot directly to the haptic device. So an ideal haptic device should preferably have an integrated microcontroller capable of the teleoperation of microrobots.
- The mechanical structure of a haptic device should have the following properties: high structural stiffness which is necessary to realistically feel rigid surfaces which a tip of a microrobot can touch; zero (or very low) backlash which is necessary for

precise micro manipulations; no mechanical singularities; backdriveability - necessary because during micromanipulations the operator should often move a haptic's handle in the direction opposite to the acting force; great dynamic range and great force bandwidth which are necessary for precise micromanipulations; compactness and ergonomic mechanical design because an operator should be able to work with the haptic device for many hours without fatigue.

– Last but not least, price is a consideration. Typical microrobots made by Klocke Nanotechnik or Kleindiek Nanotechnik cost around USD 10,000.- to USD 20,000.-. Therefore an ideal haptic device should not cost more than several thousand USD, otherwise it is economically unreasonable to use it for the teleoperation of microrobots.

2.2 Mechanical Design

The HIMiC haptic device is being developed to meet the requirements presented above. The prototype of HIMiC and its kinematic structure is shown in Fig.1.
The device is constructed mostly from plastic and aluminium. The weight of the moving parts is around 2,1kg. The weight of the whole haptic device is around 7kg, the dimensions are 490x390x220mm.

The haptic device's mechanism is driven by four DC-motors. The mechanical structure provides very little backlash, the structural stiffness is more than 7N/mm, the backdrive friction force less than 0,2N and the force bandwidth exceeds 50Hz.

In the haptic device an incomplete gravity compensation was implemented, so that a user feels approximately 3N force when moving the haptic handle in Z-axis. At the same time, if the haptic handle is in its lowest position and the user moves the handle only in the X and Y axes, the user doesn't feel the gravity force. This mechanical construction allows a more comfortable teleoperation of microrobots. At the same time, it should be pointed out that the active gravity compensation is possible whenever it is necessary.

The angular workspace of the HIMiC is 130°x60°x125° (for angles θ_1,θ_2 and

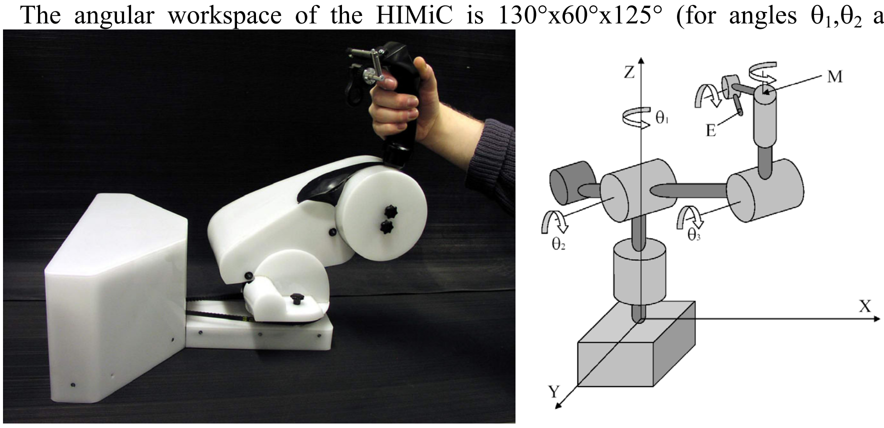

Fig. 1. HIMiC haptic device (left) and its kinematic structure (right)

θ_3 correspondingly). When moving the handle of the HIMiC, the point M at the tip of its handle describes an arc with the corresponding lengths of 820x370x480mm.

The end-effector (E) of the haptic device, which is realised in the form of a 1DOF active gripper handle, is used to sense motion of a forefinger and apply force to it. Usually the motion of this end-effector corresponds to the motion of the microrobot's gripper. The moving angle of the end-effector is 180°. During its motion the end-effector describes an arc with an approximate length of 80mm.

The torque of the actuators is provided by three 90W DC-motors by Maxon, which are used for the X,Y and Z DOF, and one 25W DC-motor, which is used for the end-effector. The torque transmission is realised by using belt and gear wheel transmission. Such a transmission provides zero backlash, high torque capability and high stiffness. The ratio of the transmission for all axes is 7.2:1. The force, which these motors apply on the haptic handle in the X,Y,Z axes, is about 15N (corresponding torque 1.7Nm), the maximum duration of this force is 4 minutes. The 24 hours maximal force is 7N (corresponding torque is 0,8Nm) for the X,Y and Z axes. The 4 minute maximal force applied to the end-effector is around 4N.

Digital MR encoders by Maxon, mounted on the motor shaft, measure the motion of the motors. Using these encoders it is possible to transmit 4096 counts per revolution resulting in an accuracy of 0,213 mrad when multiplied with the ratio of the transmission 7.2:1. That results in an average position resolution in the workspace 0,04mm.

The handle of the HIMiC haptic device contains two 8-way Hat switches, 4 buttons and one infrared touch sensor. In the housing of the unit 8 light diodes are integrated for visual feedback. The semitransparent white plastic housing covers the light diodes. The operator of the haptic device sees the light diodes only when they are lit. The base of the haptic device is made of massive plastic plate with rubber feet (Fig.1). On the rear part of this plate all indicators and all electronic components along with one of the dc motors are mounted.

2.3 Control System Design

To make the haptic device most suitable for the teleoperation of microrobots the computer control system should meet the following requirements:

- Real-time operating system for the real-time control of the haptic device and the teleoperation of microrobots;
- Fast DSP capable of simultaneously controlling the haptic device and a microrobot with an update rate up to 100Hz;
- RS-232 and Ethernet interfaces for the communication with a user PC and a microrobot controller;
- Simple development of applications for the control of the haptic device and for the teleoperation of microrobots;
- Low price of the computer control system.

To meet these requirements the IPC@CHIP SC12 microcontroller (BECK) was chosen for the core of the computer control system. This microcontroller's feature list made it the ideal solution for the haptic device:

– 20MHz, 16 bit 186 CPU, 512KB RAM, 512KB Flash, 10BaseT Ethernet interface, two RS-232 interfaces, 2 programmable timers, watchdog and power failure detection integrated into one chip;
– The IPC@CHIP SC12 is a combination of hardware and preinstalled software. The software consists of a Real Time Operating System (RTOS) with file system, TCP/IP stack and hardware interface layer.

The architecture of the computer control system and electronic circuit of the HIMiC is shown in figure 2.

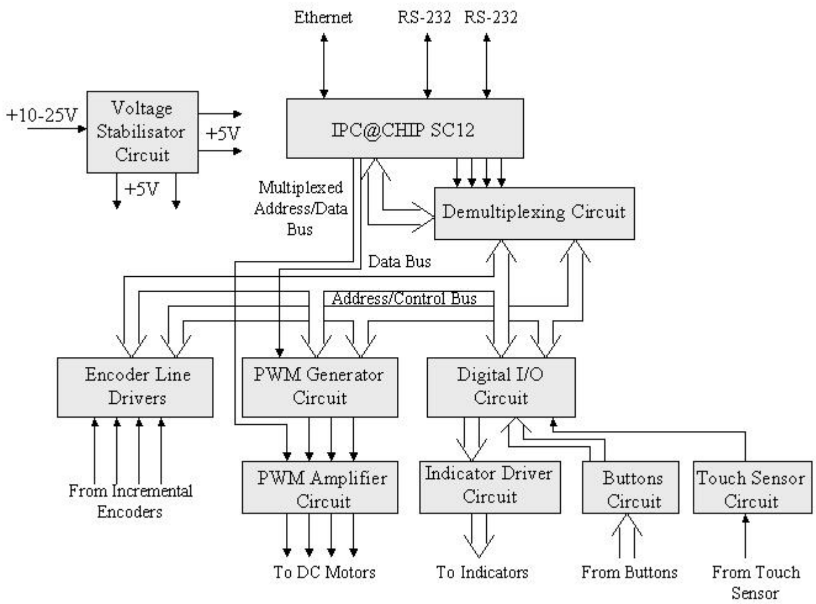

Fig. 2. Architecture of electronic circuits of the HIMiC

Two quadruple differential line receiver chips MC3486 are used to read the state of the incremental encoders, which is necessary to calculate the current position of the haptic handle. It can be implemented by using either a special chip, e.g. HCTL-2020, or a microcontroller. The latter solution has been implemented because of the following reasons:

– The speed of motion of the handle of the haptic device is rather slow and the calculation of the encoder position by software gives good results.
– The software solution reduces the price of the haptic device.

The encoder position is calculated with an update rate of 7 KHz.

Three channels of the PWM generator circuit are based on the programmable timer chip CP82C54 that communicates directly with the microcontroller via the address/data bus. One of the microcontroller's timers is used as a 2.5MHz clock frequency generator which supplies clock to the timer chip CP82C54. The PWM amplifiers are based on four full bridge motor drivers with a maximum peak current of 5A for each channel and a maximum output voltage of 40V. These PWM amplifiers drive the DC-motors. The HIMiC haptic device uses open-loop force control.

The control system of HIMiC is capable of running the overall control loop (microrobot + haptic) with an update rate up to 100Hz.

The control software can be developed on a user PC and then downloaded via FTP to the flash memory of the HIMiC haptic device.

2.4 Force-to-Sound Transformation

The forces which should be sensed in the microworld range from tens of nN up to several mN, which makes the dynamic range of forces 10^5:1. Such dynamic range of forces can not be represented only by force feedback. To be able to represent the whole range of forces, which should be sensed in the microworld, the authors propose the following force-to-sound transformation technique, which allows not only to feel, but also to hear the forces.

The force information, which is received by the haptic device from the microrobot, is presented as a 16 Bit value, which ranges from 0 to 65534. This force information is periodically updated with update rate up to 100Hz. This force value is used to change the settings of the timer of the microcontroller. Its output is connected to the PWM amplifier, which supplies voltage to the DC-motors. When the value of force is small, the DC-motor generates low-pitched sound and doesn't produce any torque. When the value of force rises, the DC-motor generates sound with higher pitch, without producing torque. When the value of force reaches 65200 the user can both feel the force and can hear the high-pitched sound. When the value of force reaches 65300 the sound disappears and the user feels only force. When the value of force increases up to 65534, the force which acts at the user also increases to its maximal value. In this way, by using the force and sound feedback, it is possible to represent a higher range of forces than when using only force feedback.

Also the combination of force and sound feedback adds a flexibility to the system, because a user can not only feel, but can also hear the forces. If a user doesn't want higher forces to interfere the motion of his hand, he can reduce them up to the sound level. This can be sometimes necessary for high fidelity micromanipulations and is useful to the user. On the other hand, if the forces are too small and form a low frequency sound, a user can amplify them to the high frequency sound and forces with value up to 15N.

The auditory signal, which is generated by the haptic devices was analysed using a spectrum analyser software on a PC. The spectrum of a sound corresponding to the value of force 63000 presented on fig.3.

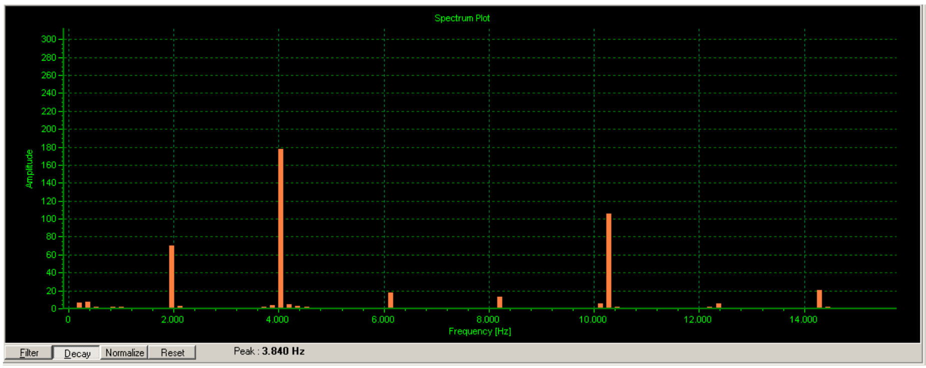

Fig. 3. The spectrum of a sound corresponding to the value of force 63000

When the value of force is low, the number of peaks is big and their amplitude is small. When the force grows, the number of peaks reduces, they become bigger in amplitude and shift in the direction of higher frequency. The amplitude of different peaks changes differently, depending on the value of force. The frequency of the generated sound, depending on the value of force, can change from several hundred Hz and up to 20KHz. The detailed analysis of the properties of the auditory signal is still to be performed.

3 Haptic Control of the Microrobot Cell

The HIMiC haptic device is currently being integrated into the control system of the microrobot cell which is being developed. The microrobot cell is realized on the basis of LEO-1450 scanning electron microscope. There is a positioning table inside the SEM chamber, on which a steel plate with smooth surface is mounted. On this steel plate two microrobots operate.

Figure 4 shows two microrobots, made by Kleindiek Nanotechnik (left) and Klocke Nanotechnik (right), operating under the vacuum from $9.0 \cdot 10^{-5}$ to $3.0 \cdot 10^{-6}$ mBar inside the SEM chamber.

Both Kleindiek and Klocke microrobots have piezoelectric actuators. The principle of operation of the piezoelectric actuators is the following: If the voltage is applied to the piezo elements, which are integrated in these actuators, they bend, allowing a precise positioning in the range of 3 µm with a motion resolution of 1 nm (fine positioning mode). If a bigger distance is to be bridged, the piezo elements are bent to the maximum stroke and then, a “step” is performed (coarse positioning mode). By repeating this sequence with a frequency of up to 10 kHz, speeds of up to 3 cm/s can be obtained (depending on the robot prototype, the base material and other factors of the surroundings, which have to be taken care of by the control system).

The picture of Kleindiek Nanotechnik and Klocke Nanotechnik microrobots has been made by an infrared camera that is integrated into the front wall of the SEM

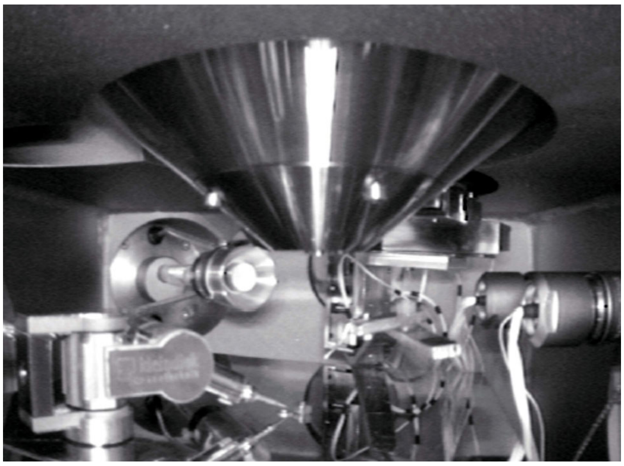

Fig. 4. Two microrobots operating in the SEM chamber

chamber. Each of the microrobots has three DOF driven by three piezoelectric actuators and is operated with an accuracy of up to a few nanometers. The SEM provides visual information from the working place of the robots, with a resolution of up to 3-4 nm.

The control structure of the microrobot cell utilizing a haptic interface is depicted in Figure 5.

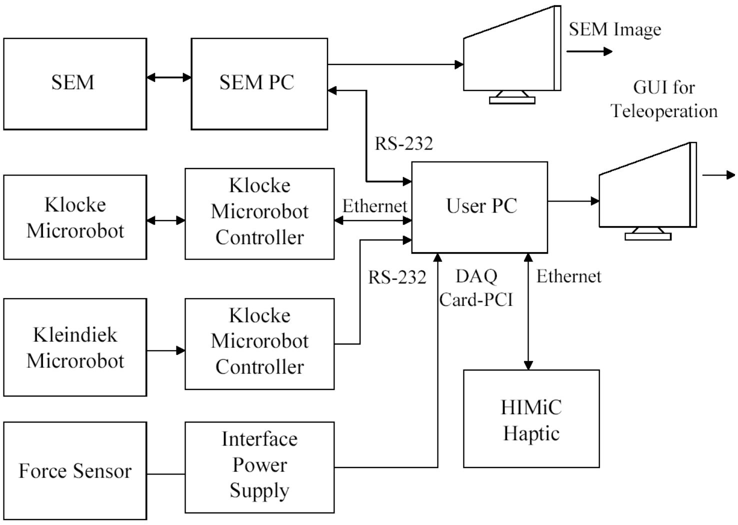

Fig. 5. Control structure of the microrobot cell with a haptic interface

The SEM is controlled by an SEM PC, which calculates SEM images and sends them to its monitor. The SEM is additionally controlled by the user PC through a RS-232 computer port.

The user PC has a Pentium III-1GHz processor and 256MB RAM and runs on a Windows 2000 operating system. The high-level control software that is responsible for the overall microrobot cell was written in Labview 6.0 programming language and runs on the user PC.

The movements of the SEM positioning table, the magnification, focus and position of electron rays can be controlled by means of the user PC. The actuators and position measuring system of the cell's microrobots are connected directly to the microrobot controllers, which communicate with the user PC through RS-232 and Ethernet interfaces.

The 6-axis force/torque sensor Nano17 F/T by ATI Industrial Automation is being used in the developing system. The upper force range of this sensor is 12N, the force resolution is 1mN. This force sensor is connected to the Interface/Power Supply 9105-IFPS-1, which is in turn connected to the NI DAQ PCI-6034E card. The force information from the Nano 17 F/T force sensor is filtered and amplified in the user PC and then sent to the haptic device. The force in the developed system is linearly scaled with the force scaling factor 100.

The haptic device communicates with the user PC through Ethernet. The operator uses the graphical user interface (GUI) of the user PC to teleoperate the SEM and the haptic device to teleoperate the microrobots.

By using the HIMiC haptic device the teleoperation of microrobots can be realised both in coarse positioning and fine positioning modes. Using buttons on the handle of HIMiC, the user can choose between coarse and fine positioning modes. Since only one haptic device is used for the teleoperation of two microrobots, the user can switch between the teleoperation of Kleindiek and Klocke microrobots using one of HIMiC's buttons. For the coarse positioning the user can choose between the following position scaling factors: 1:1, 10:1, 10^2:1, 10^3:1. In the fine positioning mode the user can choose between the following position scaling factors: 10^3:1, 10^4:1, 10^5:1 and 10^6:1. The transformation factor 10^6:1 means that 1mm of motion of HIMiC's handle corresponds to 1nm of motion of a microrobot.

To reduce the unwanted motions of a microrobot, the haptic device sends commands to a microrobot only when the activation button on the haptic's handle is pressed. The force feedback is activated only when the user grasps HIMiC's handle and the corresponding signal comes from the infrared touch sensor to the control system of HIMiC.

The haptic-microrobot control loop in the developed system runs with an update rate 20Hz.

Different objects were manipulated by using the developed system. In the experiments which were carried out the operator could perform dexterous manipulation of microobjects by using the HIMiC haptic device.

Experiments have shown that the quality of the teleoperation of microrobots was improved significantly compared with teleoperation using Wingman Strike Force 3D force-feedback joystick by Logitech.

Despite the relatively big number of independent control elements, it was easy for a person to learn to teleoperate microrobots. Several students, which before had not worked with the developed haptic device, were offered to teleoperate microrobots.

Practice has shown that a person needs approximately 5-10 minutes to learn to teleoperate microrobots without the visual control of his or her hand's position.

8 light diodes were programmed to represent the working mode (rate/position control, coarse/fine motion, speed/(position scaling factor)) of an active microrobot. By using this information after switching from one microrobot to another, an operator recalls in which mode the microrobot had operated.

The following improvements were achieved in comparison to previous solutions:

– The HIMiC haptic device has a number of control elements, which are integrated into its handle. By using these control elements, it is possible to control a microrobot in different operation modes by one hand without the need of a keyboard. It is also possible to simply switch HIMiC between several active microrobots. This allows dexterous teleoperation of the microrobot cell, which consists of the SEM and two microrobots, by one operator.

– The combination of auditory feedback and force feedback adds flexibility to the system, so that the user can choose how to represent microforces - as sounds or as feedback forces - and makes it possible to represent a large dynamic range of microforces.

– With the HIMiC haptic device it is possible to completely decouple the motion of different axes of microrobots. It is possible to set HIMiC such that it will move a microrobot only along one axis, and motions in other axes will be excluded. It is also possible to combine the motion of microrobots in different axes. The decoupling of axes is often necessary for fast and precise positioning of microobjects.

– The HIMiC haptic device doesn’t need an external PC for the teleoperation of microrobots. The HIMiC has an embedded processor, which can be programmed to control microrobots via RS-232 or Ethernet interfaces. This reduces delay in the microrobot control loop and reduces the price of the system.

4 Conclusion

The design of the HIMiC haptic device, which is used for the teleoperation of microrobots, has been presented. The requirements that a haptic device should meet have been introduced. On the basis of these requirements the mechanical and control structure of the HIMiC haptic device was developed. The HIMiC haptic device was successfully tested by means of the teleoperation of two commercially available microrobots. The integration of the haptic device into the overall control system of a nanohandling station that includes an SEM was discussed.

The research carried out shows that the teleoperation of nanohandling microrobots can be improved significantly by using a haptic device specially designed for this purpose.

Future work will include the improvement of sound feedback, which will be used to increase the bandwidth of the haptic system. It will also include the integration of

HIMiC into the multimodal control interface of a microrobot cell, which is currently being developed.

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