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From Telerobotic towards Nanorobotic Applications

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1. Introduction

During the technical evolution, telerobotic systems (see fig. 1) have lost their simple mechanical links between master and remote sites in order to operate over a greater distance and, thus, the effects of long communication delays have occurred. The telerobotics projects presented in (Goldberg et al., 1995; Telegarden, 2009; Telelabs, 2009) rely on cameras to locate and distribute the robot's position and current environment to the user, via the internet. It is clear that such an approach needs a high-speed network to achieve on-line control of the robotic arm. Of course, when using the public network, the delays become unpredictable and unusably large in the case of long distance communication (space probes).

However, as the delay becomes larger, the efficiency with which operators can work decreases dramatically. This is the reason why long-range telerobotic applications also require predictive displays on the master-site and a low-level autonomy on the remote-site, in order to overcome communication delay problems (see fig. 2). Control using predictive display (Sayers, 1999) improves the teleoperational system in such a way that it provides the operator with an immediate feedback force; not with sensed force from the remote-environment, but from the model on the master-site, as shown in fig. 2 (Sayers, 1999).

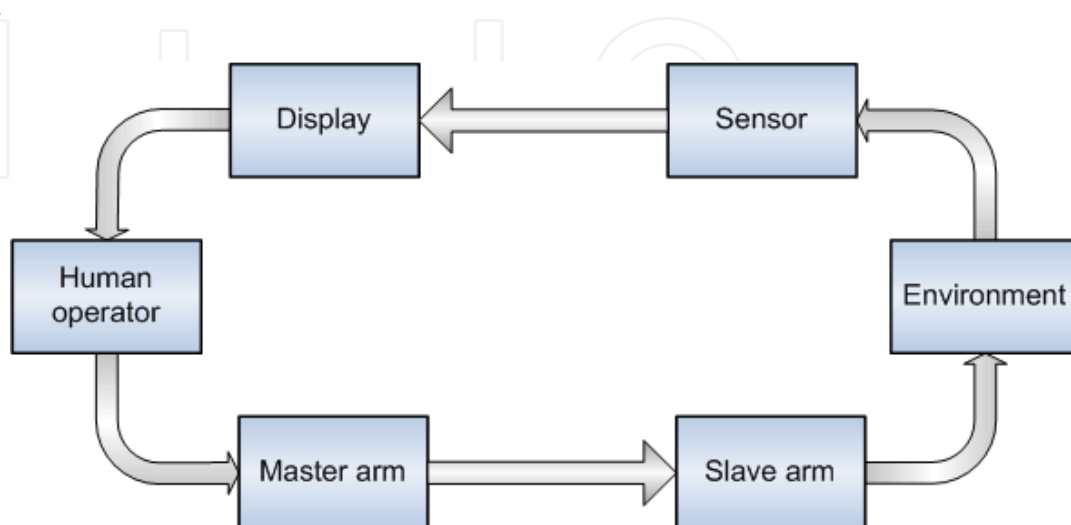


Fig. 1. Teleoperation system with a human operator in the closed feedback loop

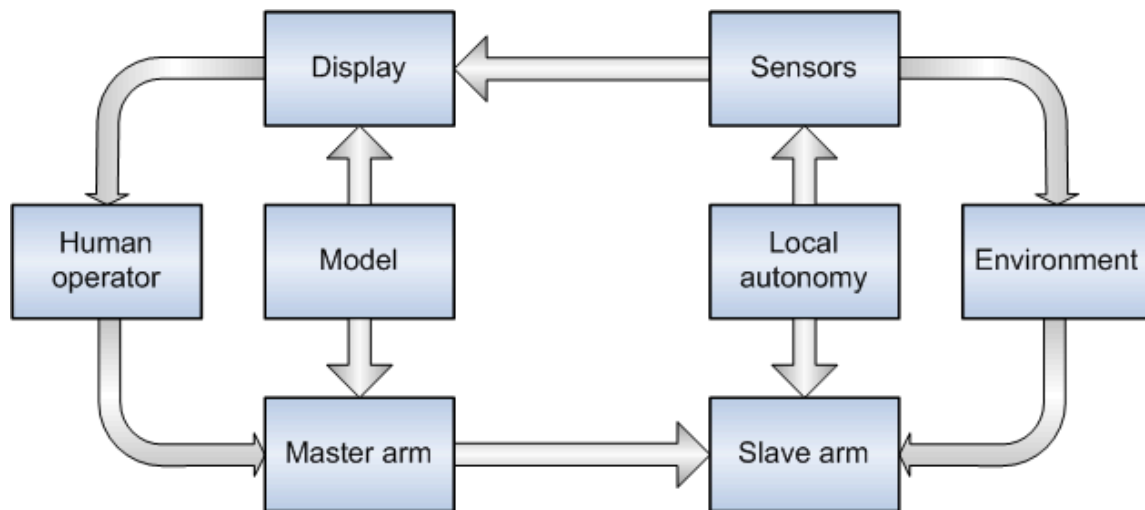


Fig. 2. Predictive display on the master side with added local autonomy on the remote site

Introducing local autonomy or increasing remote intelligence for further improvement when controlling with only a predictive display, is no longer sufficient. Of course, the goal is to ensure the remote system is able to recognize and react correctly for a few low-level problems at the remote-site. These systems allow the operator to use a more supervisory role. Added local autonomy can solve problems such as (Sayers, 1999): collision avoidance on the slave-site and, in the case of collision between the robot and environment on the slave-site, stopping the system and feeding information back to the operator in order to resolve the problem, by automatically tuning the remote robot position-controller's parameters (Čas et al., 2007)...

The aim of this paper is to present research work for developing a predictive display for telerobotic or micro/nanorobotic applications using a robotic or micro/nanorobotic arm. The remote robotic local autonomy is less precisely presented, as it is out of this paper's scope.

Rather than allowing users to interact with the laboratory resources directly, as in many of the previous examples (Goldberg et al., 1995; Telegarden, 2009; Telelabs, 2009), the reported approach requires users to configure the experiments using a simulated representation of the real-world apparatus. This configuration data is then downloaded to the real laboratory application, for verification and execution on the real device, before returning the results to the user once the experiment is complete. A virtual robot or micro/nanorobotic arm and an environment model are used instead of cameras and microscopes, in order to minimise data transmission time through the network. This means that the network speed is no longer a critical issue for the telerobotics experiment in the case of telerobotics, or in the case of micro/nanorobotic experiments when a virtual model of a micro/nanorobotic arm and its environment is used to improve 3D visualisation, instead of a microscope.

2. Telerobotic experiment

2.1 A basic description of the telerobotics virtual model approach

The telerobotics virtual model approach is based on the concept that it provides a working facility for hands-on training whilst reducing the need for actual high-cost multiple devices. It is desirable that virtual robot model simulation should be capable of execution through any standard WWW browser application (Wang et al., 2004). Standard browsers for the

VRML 2.0 language don't incorporate collision detection between shapes in the virtual world (Hudson et al., 1997). Because the adopted control strategy does not provide the remote user with immediate feedback from the actual work-cell, it is desirable that some kind of collision detection between the virtual robot and the virtual environment is created to prevent, or predict, robot collisions in the real world. This problem may be solved by building JAVA oriented collision detection software or, as decided, to use finished libraries of the complete browser and collision detection software (Fukuda et al., 2000) in the C++ language.

The telerobotic laboratory equipment includes (see fig. 4):

- a WWW network server,
- a network layer,
- a robot workcell,
- remote user personal computers, and
- a haptic device.

The WWW network server is responsible for processing requests for information by an external WWW browser, installed on the user's remote personal computer, delivering on-line documents and providing access to the robotic and control hardware. The server is implemented by currently using a personal computer, running the Windows XP operating system, and a WWW server application program.

Training operatives for working with the expensive equipment, needed for carrying out profitable work tasks (e.g. production line robots) or when the work is of a complex and safety critical nature (e.g. nuclear environments, explosive placement, surgery), has long proved problematical. The method used in some instances is that of immersive telepresence (Mair, 1999), but different approaches are needed for different sectors (Mantovani & Riva, 1999) and the equipment is often expensive and does not release high-cost capital equipment for production line usage (Bambang, 2007). In all cases, the feedback of rich data from the physical hardware site to the operator site, via the Internet or Mobile Communication links is bandwidth limited and contains uncertain delays.

2.2 The remote robotic arm and its environment

An approach that may bear much fruit is to use Virtual Environments for achieving a simulated hands on experience by only connecting to physical hardware for short periods of time. Engineers can use animated robotic cell activity to conduct feasibility studies on their manufacturing processes, whilst their product is still being designed. The experiences of companies with robotized production lines show that they may save up to 85 % of downtime when the robot has to be reprogrammed, and up to 50 % of programming time (Dobrovodsky et al., 2000).

The presented telerobotic experiment has many predecessors – but mostly only laboratory experiments, which have culminated in this industrial telerobotics experiment (Šafarič et al., 2001, a; Šafarič et al., 2001, b; Šafarič et al., 2003; Šafarič et al., 2005; Pačnik & Klobučar, 2006). The robotic cell of the teleoperated robotic arm cell application (an industrial welding robotic cell) is presented in Fig. 3. The Almaga AX-V4 robotic arm from the OTC Daihen company was used in the presented workcell.

2.3 The remote robotic arm and its environment

A copy of the virtual environment has to be installed on the home client's computer. This configuration was chosen to allow various interfacing strategies to be investigated, whilst maintaining an open architecture for the future development of the project.



Fig. 3. Remote welding robotic arm

The user must first download and install the complete Robot Simulation application software (the teach pendant). Communication between the virtual robot model of the robotic manipulator, which is viewed by the remote user, and the control system which positions the joints of the actual laboratory-based manipulator, is achieved as follows (see also fig. 4):

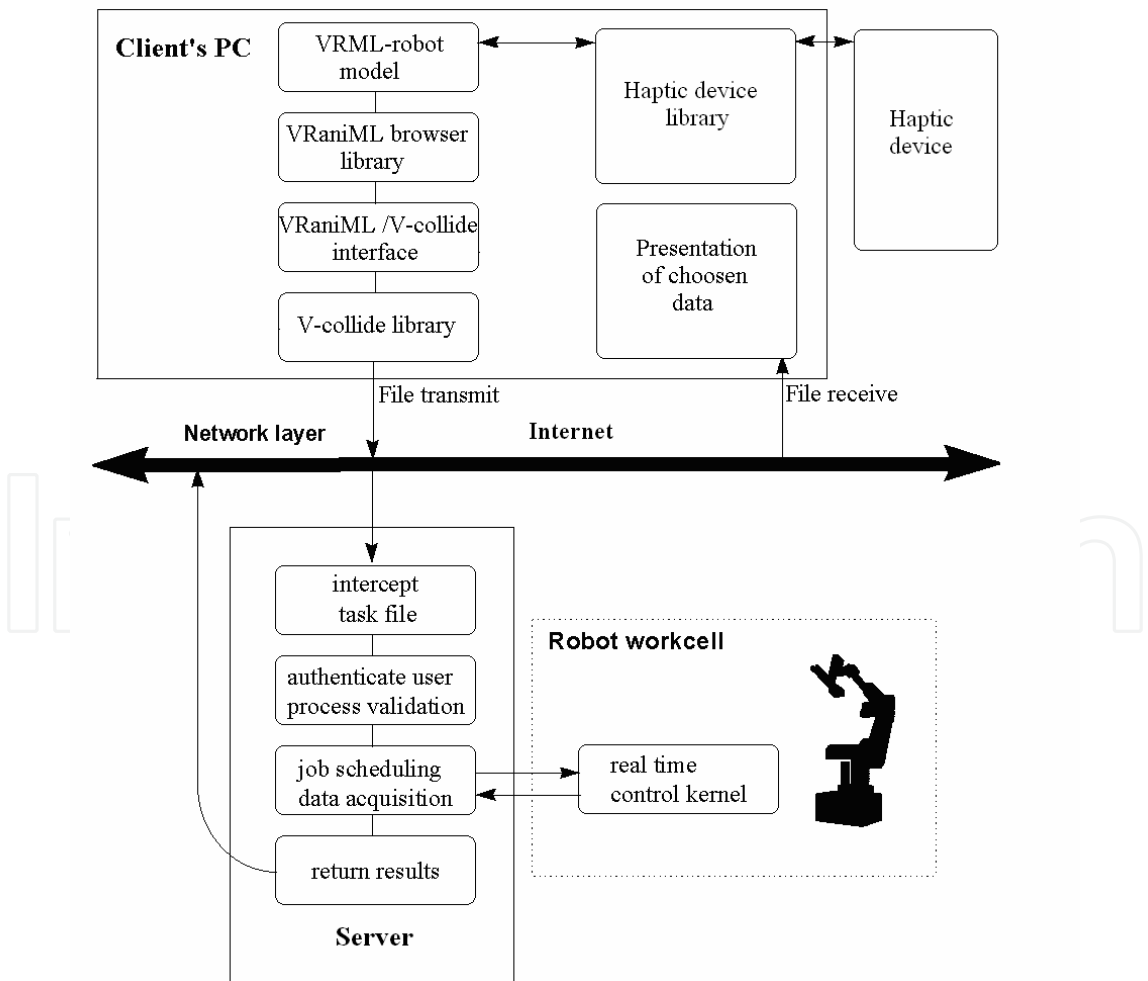


Fig. 4. The robot interface between a server and a client

- the user develops a robot task off-line within the virtual environment on the remote computer,
- collision detection checking on the remote computer; if there is collision between the virtual shapes in the virtual world of a teach pendant, then stop, otherwise proceed,
- transmission of the completed robot task file from the remote user to the laboratory server,
- authentication, error checking, and runtime scheduling of the received task file on the server,
- execution of the requested task within the laboratory workcell, and finally
- collation and return of the results to the remote user.

Of course, there were also further added improvements:

- the haptic device is introduced, so that communication between the remote user and robot is improved by the human sense of touch,
- the direct and inverse kinematic equations (Fu et al., 1987) are developed and included in the teach pendant, so that off-line programming is also possible in Cartesian coordinates and not only in joint coordinates,
- PTP movement, linear and circular interpolators are added, so off-line programming is even more accurate, especially the accuracy of its time component, and
- a set of industrial commands for the off-line programming of the Almaga AX-V4 robotic arm was added to the teach-pendant, so that developed off-line programs can also be executable on the real remote arm.

Descriptions of the VRaniML/V-collide interface and VRaniML browser library are presented in (Šafarič et al., 2001, b; Šafarič et al., 2003). The VRaniML library is used as an interface between the virtual models of the robot's workcell (written in VRML language) and a teach pendant (see Fig. 5) written in C++ language. The VraniML/V-collide interface serves as an intelligent interface to prevent collision in the virtual world.

Fig. 6 presents off-line programming using the haptic device. In fact, the haptic device provides the contra force only in cases where collisions between virtual shapes in the virtual model occur: between the virtual arm itself and between the virtual arm and its static environment in the robot's virtual workcell (Friconneau et al., 2002; Dong-Soo & Seung-Chan, 2007).

3. Micro/Nanorobotic experiment

The micro/nanorobotic experiment is the very last in a sequence of telerobotic experiments, done in our laboratory. It is not a real telerobotics experiment, because the distance between the client's computer and a nanorobot is less than 1 metre. But the experiment could be treated as a telerobotics experiment because it connects two different worlds, the macro world of the user and the micro/nano world of the micro/nanorobot. The focus of the presented micro/nanorobotic experiment is that the user cannot see the micro/nanorobotic object's movements etc (Fukuda & Arai, 2000; Cavalcanti et al., 2004). The 3D on-line image of the gripper and the object, even with powerful microscopic visual magnification, cannot be properly seen, due to the fact that the focused images of the objects and the nano-robotic tip tool can only be seen only within a narrow vicinity (few hundred μm) of the microscope's optical lens focus. So, the same techniques as for the previously-mentioned real telerobotics experiment were used in order to make a connection between the macro and micro/nano worlds. In fact, we used the telerobotics platform developed for the

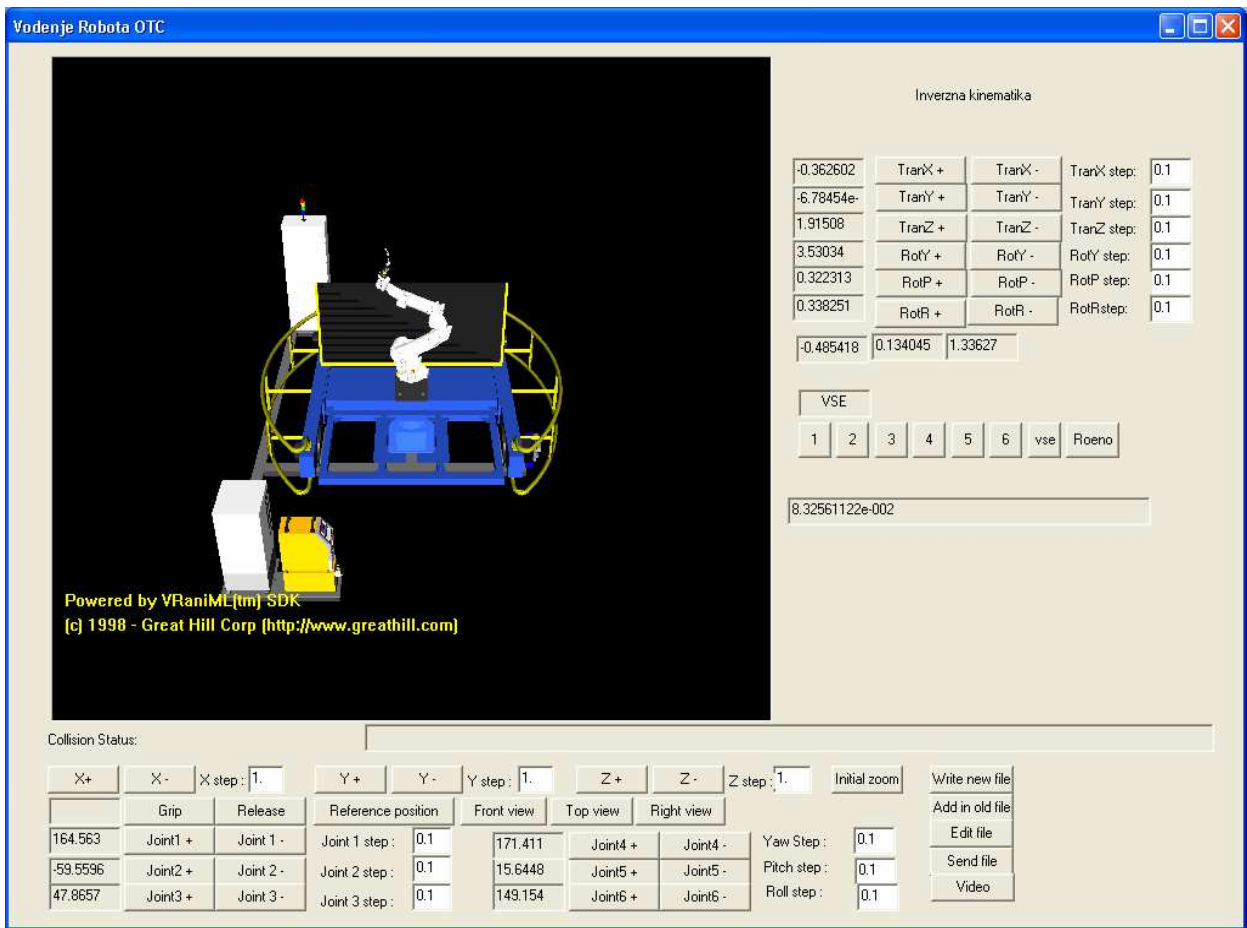


Fig. 5. Teach pendant of the telerobotic application using a haptic device



Fig. 6. Off-line programming of the telerobot using a haptic device

previously presented telerobotics experiment using a haptic device. The reason we used the haptic device is that we also like to include a sense of touch in the virtual teach pendant, in order to make communication between the human and the nanorobot easier and more user-friendly. Of course, the produced force from the haptic device is inadequate as a force produced during a collision in the micro/nano world, but it is magnified several times, so the human sense of touch can detect any collision within the micro/nano world (Dong-Soo & Seung-Chan, 2008; Cavalcanti et al., 2006). The hardware of the nanorobotic application is presented in Fig. 7.



Fig. 7. The whole micro/nanorobotic application

The micro/nanorobotic system is divided into two parts (see Fig. 8). The upper part of the figure consists of a real-time target application with a micro/nanorobotic cell: a development computer machine marked as 1, a real-time controller computer card marked as 2, and a target computer application marked as 3.

The usual notebook computer marked as 1 is used as the development computer for control algorithms and user interfaces with an installed Windows XP operating system and a LabView 8.5 software package.

The PC computer, marked as 2, executes real time control algorithms using so-called Real Time Desktop Target software. This PC runs a LabView Real Time operating system, which is independent of all the other operating systems already installed on the PC. Our real-time target PC is supported by a 7356 PCI motion-controller card from the National Instruments Company. This card is used as an interface between the control algorithm and the piezoelectric motor-power drivers. Its output has a separate reference signal for piezoelectric motor drive in regard to each axis of the controlled system for all 5 axes and is calculated by signals from the position of feedback and desired position inputs using the control algorithm. The execution time of the control algorithm is about 3 ms (National Instruments, 2009).

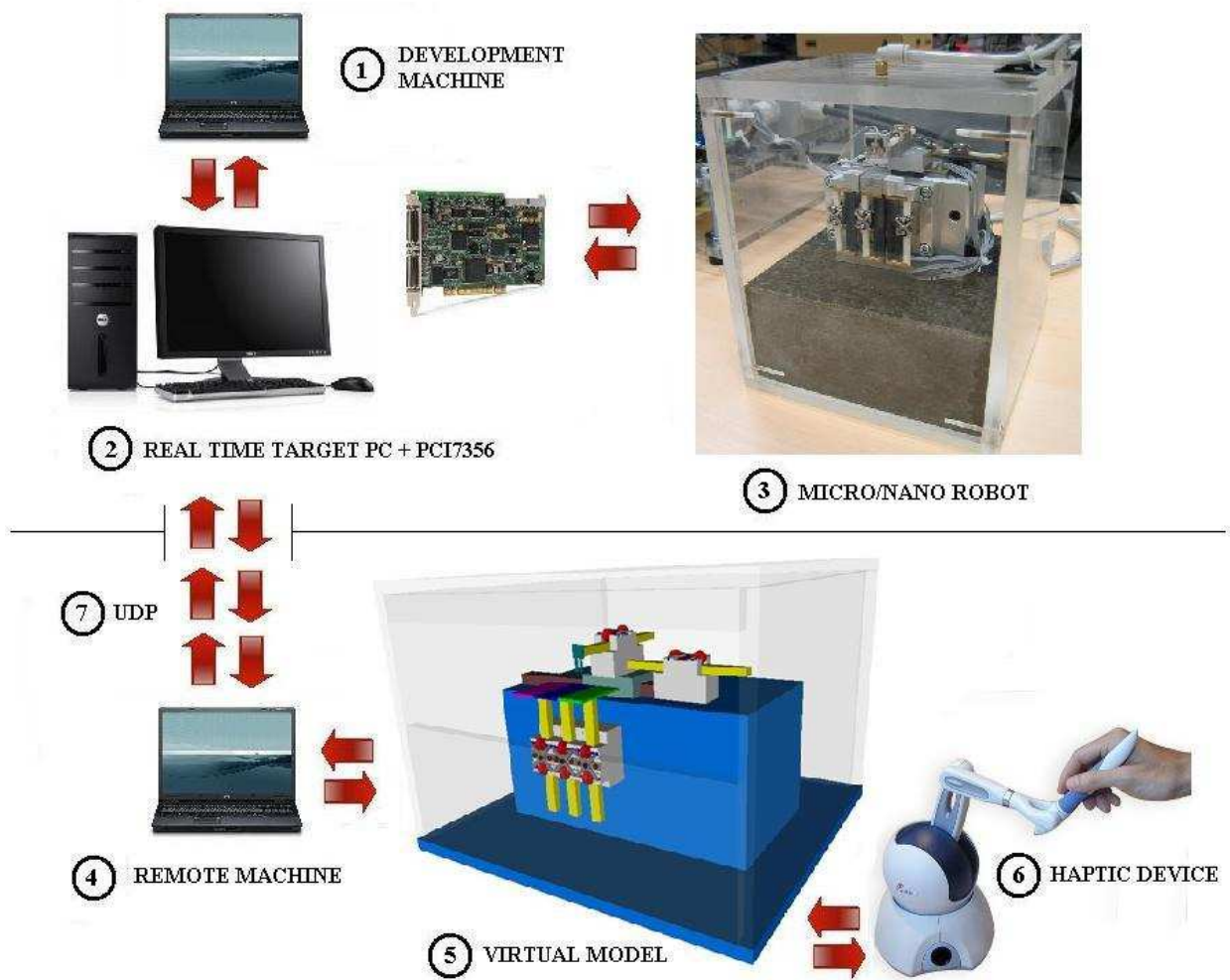


Fig. 8. Micro/nanorobot system components

The micro/nanorobotic cell, presented as 3 (fig. 8), is actuated by five linear piezo-motors produced by the PiezoMotor Upsala AB Company, where the motor movement steps can have lengths from 2 nm to 8 μm and can achieve speeds of up to 12.5 mm/s using factory-delivered demo-drive electronics (Piezomotor Upsala, 2003). The construction of the nanorobotic cell is done in such a way that two of the piezo-motors act as X/Y manipulators, and the other three are used as motion drivers for three separate serving tables within the Z axis. Positional feedback values for all axes are achieved using electromagnetic linear encoders produced by the NANOS Instruments Company. Each encoder-set's electronics are built using magnetic scale and sensor electronics. The linear position instrument has a resolution of 61 nm with precision of $\pm 0.15\%$ (Nanos instruments, 2009). The micro/nanorobotic cell allows implementation of different micro and nanorobotic tip tools. A special two finger gripper is used temporarily for gripping objects of micro-scale sizes (100 μm to 200 μm). It is placed at the top of the Y axis (Keoschkerjan & Wurmus, 2002). The second part of the application, as presented in the lower part of fig. 8, shows a man-machine interface. It consists of a "remote computer" marked as 4, where a virtual model of the micro/nanorobotic cell, marked as 5 and a haptic-device (Phantom Omni by Sensable Technologies Company), marked as 6, have been installed. The "remote computer" is a notebook, based on the Windows XP operating system, supported by a Microsoft Visual

C++ software package and OpenHaptics software package from the Sensable Technologies Company. Both packages with the PC hardware are used for developing and executing the micro/nanorobot application. A UDP protocol, marked as 7, is used to ensure the fastest and reliable enough communication between the user and the machine.

A virtual VRML model of the micro/nanorobotic cell, marked as 5, is also included in the application, because the user does not see the target application - manipulation of the micro sized objects on all three serving tables with the naked eyes. The user doesn't have a real feeling of what is exactly happening within the target application. The virtual model gives a user 3D magnification and visualisation of the objects, including a robotic tip-tool within the target application. The virtual model of the micro/nanorobotic cell with its static macro/nanorobotic environment is updated with the on-line positional data acquired from the real micro/nanorobotic cell application. So, the user can visualise a 3D on-line image of the object's current positional situation and macro/nanorobotic tip-tool movements from different viewing points. This is needed, because otherwise we would need to use a microscope which could provide focused images of the objects and the micro/nanorobotic-tip only within a narrow vicinity (less than 500 μm if we use an optical magnification factor between 10 and 25) of the microscope's optical lens focus. The micro/nanorobot's workspace is a little less than 3 cm^3 . The second reason for using a virtual model of the micro/nano robotic cell is for an off-line programming of it, which gives the user the possibility studying the target application program, to improve it, to test it and, after that, to send it for execution in the real-world.

The micro/nano robotic cell system uses a Phantom Omni haptic device in order to provide the user with a more realistic feeling about the situation inside the micro/nano-robot workspace. The user can control the haptic device by moving the its arm along 6 degrees of freedom (X, Y, Z, roll, pitch and yaw). Three motors are built onto the X, Y and Z axes to give the user force-feedback information as a virtual presentation of friction or space limits or collision between micro/nanorobot axes or between the micro/nanorobot tip tool with the object in the virtual world. The chassis of the haptic device has two free programmable built-in buttons which are used to grab, move, create different viewing points etc, of a single axis of the micro/nanorobotic cell's virtual model.

Fig 9 takes a close look of the current real micro/nano robotic tip gripper. It is made of so called structural glass (Keoschkerjan & Wurmus, 2002; Škorc et al., 2009) driven by a piezoelectric motor, which is situated horizontally to the vertical fingers of the gripper. The piezoelectric actuator allows the fingers to be moved approximately 100 μm . So, the gripping distance between fingers is between 100 μm and 200 μm . It was specially designed to grip and move optic fibre glass-cables with diameters between 100 μm and 125 μm .

Fig. 10 presents a screenshot of the so-called Control teach pendant or man-machine interface. This interface is divided into 7 sections:

1. The implemented VRML model of the micro/nanorobotic cell can be seen in the upper left corner of fig. 10.
2. The viewing section (right upper corner of fig. 10) is used for selecting the most appropriate viewing point for the VRML model of the micro/nanorobotic cell. Integrated virtual buttons allow the user to translate or rotate the view. A zoom function is also available within this section.
3. Manual control section (beneath the viewing section) is used for moving each axis using two virtual buttons. The first one is used for moving the axis one step forward and the other for moving one step backwards. The lengths of motor steps can be set

individually by typing the length number in millimetres in the small windows near the virtual buttons.

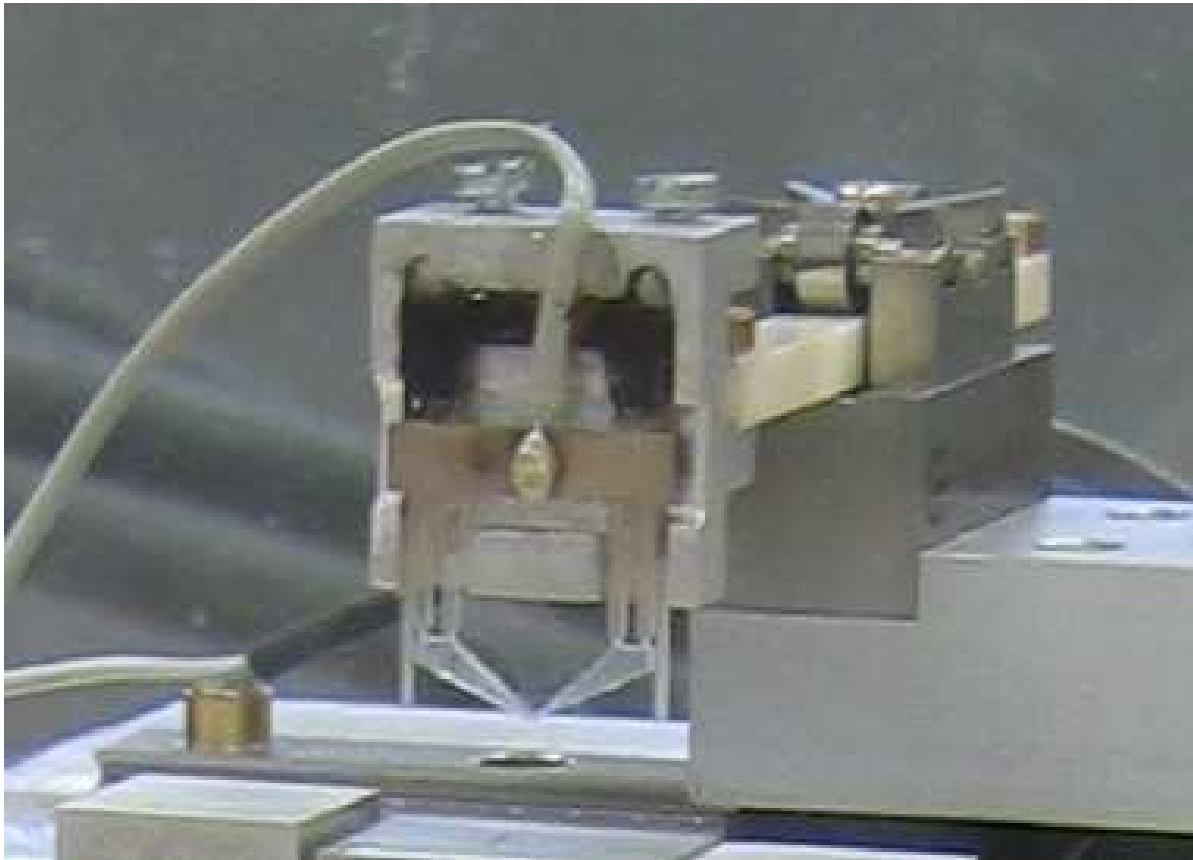


Fig. 9. Close look of a real micro/nano-robot tip gripper

4. Control of the haptic-device section (beneath the manual control section) is used for selecting the axis, which will be controlled using the haptic-device. This function is also available on the haptic-device by using one of the buttons integrated on the haptic-device's chassis. The number of the selected axis is shown within this section.
5. PTP regime control section (lower right corner of fig. 10) allows the user to load a file within the given micro/nano robotic cell program using PTP trajectory coordinates. Movements are executed sequentially, step by step, as they are programmed and written in the file. Any positional changes of any axis within the described control sections are animated in the virtual model of the micro/nanorobotic cell.
6. On-line/off-line section gives the user the possibility of simulating programmed micro/nanorobotic cell target applications before they are sent to the real micro/nanorobotic cell. Of course, this option is only provided if the off-line virtual button is selected. Here, any changes within any control-section are executed as a simulation of the micro/nanorobotic cell's virtual model. When the user enacts the on-line regime, the given changes are executed on the real machine, immediately. This off-line function is very helpful when the user programs and tests certain new trajectories in the micro/nanorobotic cell's workspace, and when it is unsure what consequences some newly-programmed movements would have (collision inside workcell space, movements outside workcell space etc).
7. The last section is the reference position section, where the user can set axis reference positions in certain specific cases, where the default given references are unacceptable.

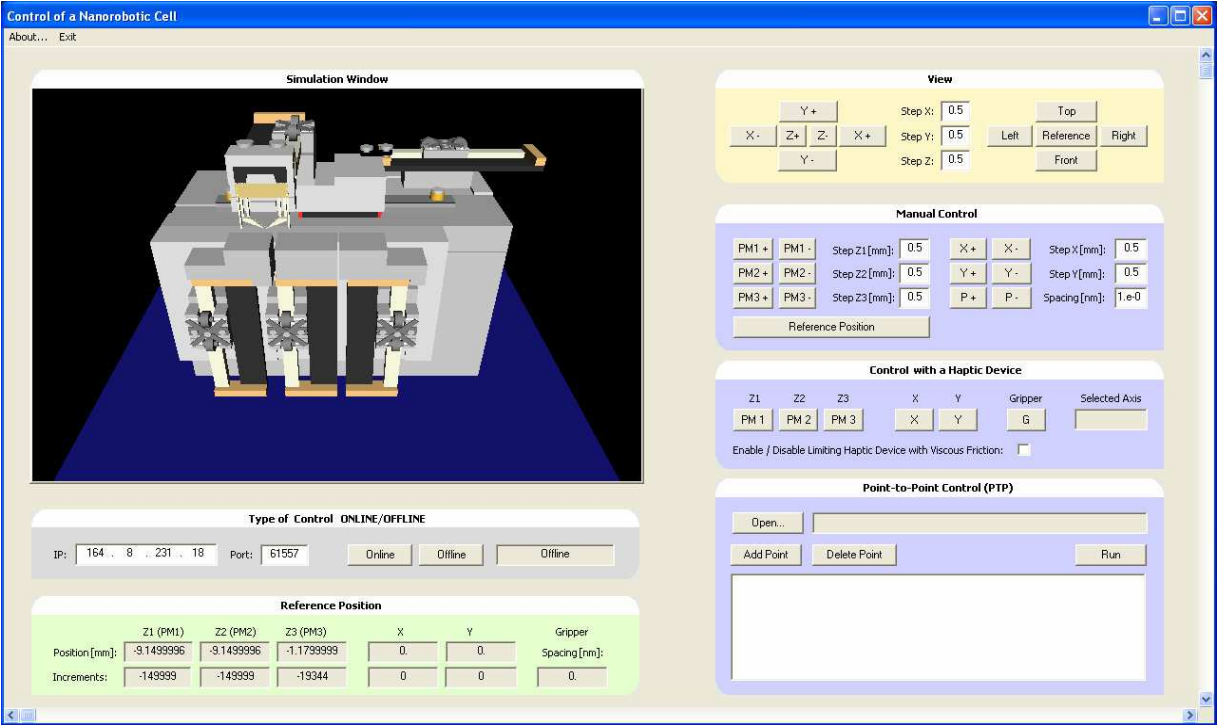


Fig. 10. The Control teach-pendant of the nano-robotic application

Another user interface, the so-called Monitoring teach pendant (see fig. 11) is built on the same basis as previously described. The control teach pendant can only provide a function for axes actual positional monitoring on an already executed target application. It also has a virtual model of the micro/nanorobotic cell, so the user can visualise the real

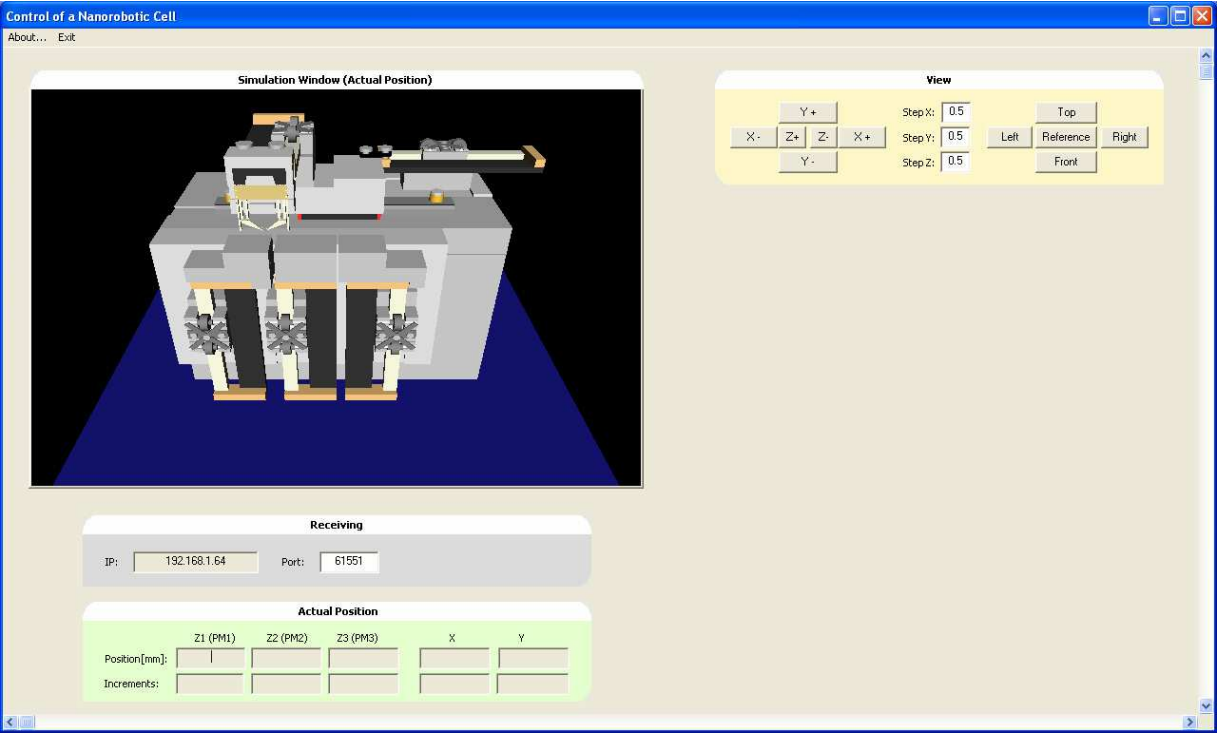


Fig. 11. The Monitoring teach-pendant of the micro/nanorobotic application

micro/nanorobotic axes, and tool movements. This interface uses a C++ built receiver to animate an implemented VRML model. The C++ receiver receives the actual positions of all five axes and the gripper from the real micro/nanorobotic cell, during the programmed target application execution, and delivers these positions to the VRML model, where they are animated. A viewing section is also available in the Monitoring teach pendant, where user can choose different angles for viewing and zooming. All other functions, which are available within Control teach pendant are disabled here.

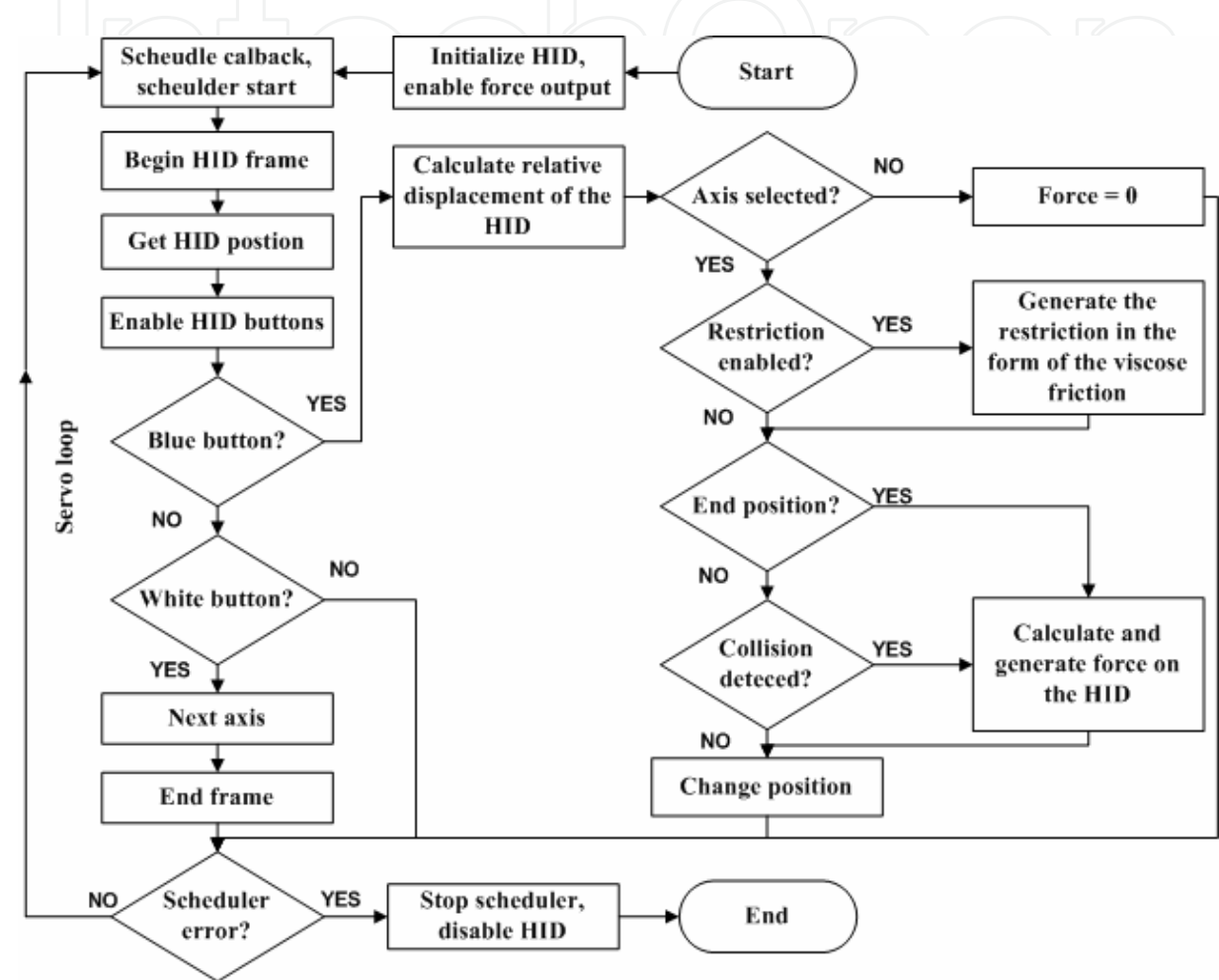


Fig. 12. An execution diagram of the remote application

A complete source code for both user interfaces is very voluminous therefore, we focused only on that part which includes code for the haptic-device. Figure 12 shows an execution diagram of our haptic-device interface program. The first program steps are initialization of the haptic-device, enabling the force generator, a schedule callback and the start of a scheduler. This is followed by initialization of the frame within which runs a so-called servo-loop. In order to ensure stable work of the control program loop, must this loop run with frequencies higher than 1 kHz. The first step within the servo-loop is acquiring position, which is followed by enabling integrated buttons. We check the state of the integrated positional button in continuation. When the positional button is pressed, a relative change of position is calculated. The servo-loop is closed by enabling a friction function and applying feedback force in case a collision has been detected. Finally we change the position of the nano-robot.

4. Conclusions

The chapter has presented the development of a telerobotic application using an implemented VRML virtual model. This virtual model is used for the visualisation of real-time actual or desired remote robot positional control data, and is used as a replacement for live camera pictures. The broadcasting of live camera picture over the Internet incurs long time-delays in spite of a good internet connection, which is often unavailable, for example, during rush hours.

The same “remote” techniques were also used for the next micro/nanorobotic application, where the human machine interface for connecting of macro and micro/nano worlds was presented and where a virtual model of the micro/nano robotic cell is used to improve 3D visualisation. The use of a haptic device remarkably improved the communication link between the user and the micro/nano-robot.

The main drawback of the presented methods is that they can prevent collision, or provides feeling of touch, only within predefined robotic cell and its environment, while it is very difficult or even impossible to sense or visualise so-called unknown dynamic objects (Matko & Šafarič, 2009), (Matko & Jezernik 2010).

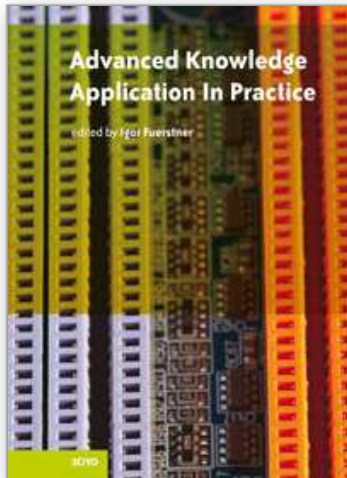
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The integration and interdependency of the world economy leads towards the creation of a global market that offers more opportunities, but is also more complex and competitive than ever before. Therefore widespread research activity is necessary if one is to remain successful on the market. This book is the result of research and development activities from a number of researchers worldwide, covering concrete fields of research.

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