A Multimodal Training Platform for Minimally Invasive Robotic Surgery

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Abstract— **This paper gives an overview of a multimodal training platform developed for minimally invasive robotic surgery, based on the DLR MiroSurge system. It describes the technological components and integration of the hardware and software platform and presents the first integrated training tasks that enable surgeons to get familiar with the robotic system. The training platform shares the same surgical operator workstation as MiroSurge and simulates the behaviour of the telemanipulator arms and the surgical instruments. Like the real system the training platform provides haptic feedback and 3D-vision. However instead of the real telemanipulator itself, a virtual environment with abstracted tasks is connected to the operator workstation. This allows reduction in costs, to provide various levels of difficulty, and to focus on the skills to be taught. Thus a training platform is presented that aims at training a surgeon's skills in handling the robotic system MiroSurge rather than training surgery in general.**

I. INTRODUCTION

Minimally invasive surgery (MIS) differs from open surgery. The surgeon works through small incisions with long slender instruments. Natural hand-eye-coordination is lost due to the entry point that binds two degrees of freedom and requires a reversed motion of the instruments outside the patient. In addition, the haptic perception of tissue interaction is perturbed due to friction at the entry point. These drawbacks of conventional MIS can be reduced by the use of a robotic system which positions surgical instruments equipped with additional degrees of freedom (DoF), and which is teleoperated by the surgeon from an operator console. A prototype system for minimally invasive robotic surgery (MIRS) is MiroSurge from the German Aeropspace Center (DLR) [1]. It offers the surgeon various features, e.g. actuated instruments such that full 6 DoF motions are possible inside the patient. Furthermore, a miniaturised force torque sensor in the instrument tip allows force feedback such that the forces between instrument and tissue are measured and displayed at the operator console. Additionally, the surgeon's motions and the forces that are fed back may be scaled to increase accuracy and sensitivity. Naturally, a dedicated training is reasonable to optimally exploit these features. This paper presents such a skills training platform specifically developed for MiroSurge to train surgeons how the operate the robotic system (see Fig. 1).

Fig. 1. Prototype of the multimodal skills trainer for Minimally Invasive Robotic Surgery

Today various surgical training systems are available for conventional MIS. Surgical simulators for laparoscopy with VR are presented in [2], [3]. The only robotic system for minimally invasive surgery that is commercially available is the da Vinci from Intuitive Surgical Inc. The company offers training in dedicated training centers. The focus is on training the whole surgical team with complete robotic systems containing the console and the manipulator arms. However, training the surgeon's skills in VR is not part of the program. The Robotic Surgery Simulator (RoSS) [4] or the dV Trainer [5] may fill this gap. These systems aim at approximating the touch and feel of the da Vinci system, however the surgeon console is not made up of the same interfaces as the da Vinci system.

The skills trainer presented here offers a training platform for surgeons with an operator console that is identical to the MiroSurge console, while the patient-side part of the system is replaced by a virtual reality simulation (see Fig. 2). The presented work aims to train surgeons the specific skills required to use the complex tool (telerobotic system) rather than to perform surgery in general. Surgeons envisaged are already skilled in either open surgery, conventional MIS or both. The training protocol is closely taking its cue from standard protocols for basic skills training in minimally invasive and laparoscopic surgery. The surgeon can train bimanual manipulation under workspace constraints of the robot and the input devices, and get used to the haptic

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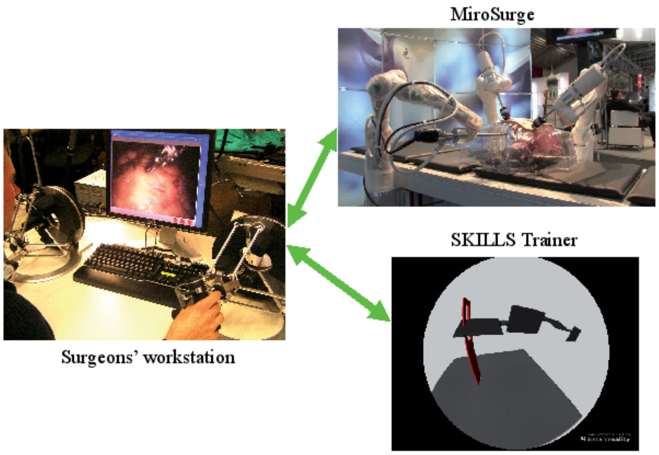


Fig. 2. Concept of the MIRS trainer with the identical HMI as in the real MiroSurge System.

feedback provided by the MiroSurge system. The use of virtual reality to simulate the remote telemanipulator and its environment allows for a reduction of costs since the remote telemanipulator need not be occupied during the training. Furthermore, the various skills to be taught can be introduced step by step, e.g. workspace limits of the real system can be ignored in the first exercises to focus on the use of the operator console.

The following section gives an introduction to the MiroSurge system. Then, the components of the training platform are described, and the implemented training scenarios are presented. The paper concludes with an outlook on future work.

II. THE MIROSURGE SYSTEM

The basic component of MiroSurge is the versatile light weight robot MIRO, designed for various medical applications in open and minimally invasive surgery [6], [7]. It is kinematically redundant and fully torque controlled. To operate through a small entry point in MIRS, the MICA instrument was developed. In combination with the MIRO, the MICA offers full 6 DoF intra-corporal manipulability with force/torque measurement in all DoF [8], see Figure 4. The instrument has a universal joint with a force/torque sensor mounted at the distal end. The workspace of the universal joint is limited to 45 degrees in all directions. An actuated and sensed gripper is attached for manipulation of tissue.

The surgeon can comfortably operate the telerobotic system from an operator console. Two interaction modalities are available: Haptic interfaces using the haptic hand controllers Omega.7 devices from Force Dimension (Fig. 5), and tracked pincers with visual overlay of the forces (Fig. 6).

There are currently two technologies for stereo display in use: Displays with polarized light that force the user to wear glasses (Fig. 5), and auto-stereoscopic displays that do not require to wear glasses (Fig. 6). The two interaction modalities and the displays can be arbitrarily combined [1].

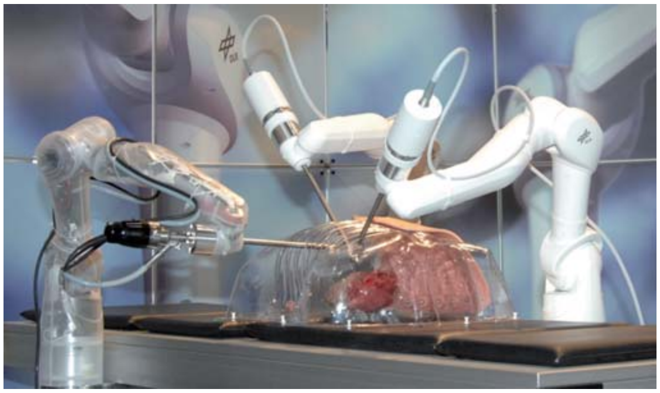


Fig. 4. The remote telemanipulator of the DLR system for minimal invasive robotic surgery. Three versatile light-weight robots MIRO with 7 DoF and torque control, carrying two surgical instruments with force-torque sensing (attached to the white robots), and a stereo endoscope (carried by the transparent robot).

Fig. 5. Surgeon's workstation with two haptic devices and a stereo display with polarized light

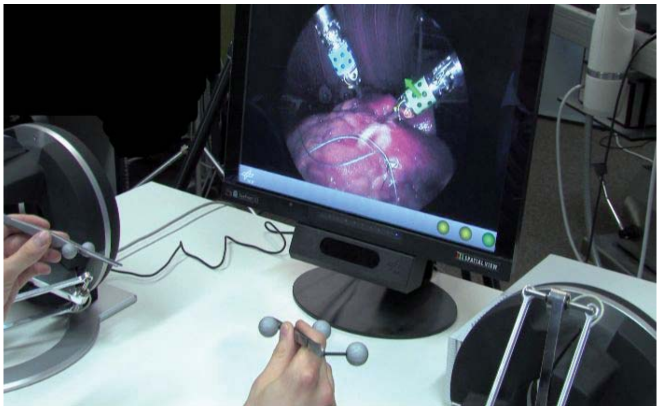


Fig. 6. Surgeon's workstation with tracked pincers as input devices and an autostereoscopic display; Forces are augmented into the 3D-scene (green arrow).

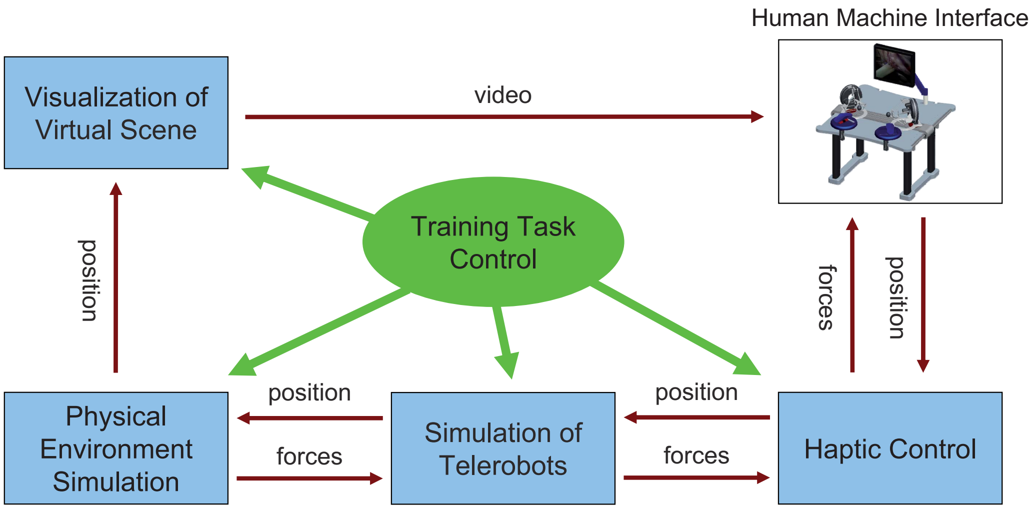


Fig. 3. Overview of components of the multimodal skills trainer for MITS

Both interfaces map the motion between the surgeon's fingers onto a virtual point between the branches of the MICA instrument inside the patient's body. The surgeon controls the tip of the instruments in a manner similar to the way of controlling one's hands. Motions can be scaled and the surgeon has a foot pedal to couple and decouple the input console and the remote instruments at any point in space [9]. This way the surgeon can take advantage of the full workspace of the telerobotic arm independently from the input device's workspace. It is even possible to disconnect the haptic interface and to continue with the tracked pincers and vice versa.

III. DESIGN OF THE MUTLIMODAL SKILLS TRAINING SYSTEM

The prototype of the multimodal skills trainer for MIRS is focused on the specific features and training needs for the newly developed minimally invasive robotic surgery system MiroSurge by DLR. Namely, the following training skills were identified:

1) Use of the foot pedals: Two foot pedals are used, the first connects the operator to the telemanipulator when pressed, while the second switches between teleoperation of the instruments and teleoperation of the endoscope.
2) Workspace constraints of the operating console: The workspace of the input devices is limited. Once the limits are reached in a desired direction, the surgeon has to disconnect the teleoperator from the operator console using a foot pedal, move the input device back to the center of its workspace and reconnect in order to further move the teleoperator in a certain direction (indexing). During a delicate task such as suturing, indexing should be avoided to achieve a fluent motion. This requires the surgeon to anticipate the motions to be performed and to position the input device optimally before connecting to the teleoperator.
3) Workspace constraints of the telemanipulator: These constraints reduce the workspace and the manipulability of the instruments, a situation a surgeon should be trained to deal with.
4) Stereo visualisation of the scene: Learn to estimate distances and relative poses in the displayed stereo scene in presence of e.g. lense distortions.
5) Use of force feedback: To benefit from the available force feedback, the surgeon needs to learn what sensations can be expected from the system during interaction (e.g. learn to substitute the sense of touch by the displayed resultant interaction forces).
6) Motion and force scaling: Motions commanded to the teleoperator and forces measured at the instrument tips and displayed at the haptic master consoles can be scaled (in the limits of stability of the control loop). According to the stage in task execution, the appropriate values for the scaling have to be chosen.

The human machine interface for the training platform is identical with the surgeon's workstation to control the robotic arms of MiroSurge. The surgeon perceives 3D visual and haptic feedback either from real robotic interaction or from the simulation. The implementation of haptic interaction is technically more demanding than reaction free optical tracking of pincers. Therefore, an implementation with the haptic interfaces of MiroSurge is chosen for the first prototype of the trainer and referred to in the following.

The training system consists of the components shown in Fig. 3: The *HMI* integrates two haptic interfaces dedicated for left and right handed use. It is connected to the *Haptic Control* that implements e.g. the scaling of forces and motions. The *Haptic Control* is connected with the *Simulation of Telerobots* which includes e.g. the kinematics, hand-eye alignement and kinematic constraints. The transformed positions are forwarded to the *Physical Environment Simulation* that computes the physics engine for haptic rendering and provides the object poses to the *Visualization of Virtual*

Scene. The environment forces and pictures are sent back to the surgeon's operating station. Different training conditions can be controlled by the *Training Task Control*.

In the following the different software and hardware components of the multimodal training platform are presented.

A. Human Machine Interface

The physical human machine interface is identical to the one used in the MiroSurge system and described above (see Sec. II).

B. Haptic Control

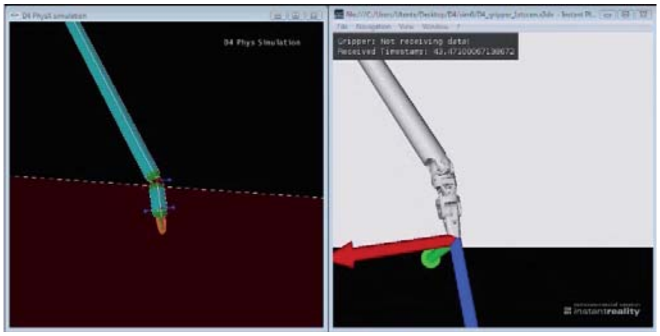
The Software component *Haptic Control* contains sophisticated controllers for a realistic force feedback control of the haptic handcontrollers, which care for the stability of interaction [10] thus guaranteeing a maximum of transparency [11]. In particular the *Time Domain Passivity Control* approach is used and adopted for the specific interface and application [12], [13]. Similar controllers are used for the control, when the surgeons workstation is coupled with the MiroSurge System, which guarantees an almost identical behavior of the training platform compared to the real operation to ease the skill transfer to the real world. In addition this block contains haptic guidance functionalities, in particular *virtual walls, time-dependent attractors* and *haptic paths* can be rendered upon the simulated force feedback from the task environment.

C. Simulation of Telerobots

In this software component the telerobotic system is simulated taking into account the kinematic structure and the dynamics of the robot and the instrument. External constraints like the trocar point, i.e., the entry point of the minimally invasive instrument into the body, joint angle limits and the dynamic behavior of the robots are simulated with variable reality levels. Joint angle limits as well as the trocar point constraint can be switched off, if desired for training purposes. The bilateral control structure of MiroSurge is based on a position-force architecture using fast position controllers for the MIRO robots and the MICA instruments. In the simulation the closed loop position controllers of the MIRO and the MICA's cardanic joint were approximated with first or second order phase lags. There is no local compliance on the telerobot and stability of the haptic loop is guaranteed as described above. However, this approach leads to stability problems for the gripping DoF, when grasping non-deformable rigid objects. Therefore, the mechanical gripper of the instrument was modeled as a one DoF admittance with an impedance controller. The compliant spring-damper behaviour of the gripper results in a stable interaction with the environment simulation.

D. Physical Environment Simulation

The physics simulation for the training system for MITS has the objective of providing a realistic environment for the execution of the exercises. The focus of this simulation is not on realism in terms of a surgical procedure but on maintaining the skill fidelity of interaction. The simulation is characterized by a training environment composed by the following objects: the robotic instruments, the objects to be manipulated, and the static environment.



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Gripper: Not receiving data!
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Fig. 7. Comparison of Physics model and Graphic model of the robotic arm

All the interactive objects are rigid and implemented as composition of convex elements. The convex decomposition of the objects, in particular for the ring, allows to maintain a high rate in the collision detection implementation.

The robotic instruments are modeled as a complex structure of rigid bodies, expressed as simplified primitives generated from the available CAD models. See Figure 7 for a comparison between the two representations. The dynamics of the robotic arms and the interaction of their individual parts is computed by the component for simulation of the telerobots, therefore they are classified as independent kinematic objects in the physics simulation.

The Physics simulation interfaces with the Graphic part of the multimodal simulation to communicate the position and orientation of every rigid body object in addition to contact information that can be used for providing relevant visual feedback. The interface towards the Telerobotic part receives the poses of the robotic instrument parts and provides the feedback forces computed from the interaction with the objects. Finally the Physics simulation is interfaced with the training manager to receive parameters of the simulation and its configuration, in addition to sending information about the simulation for the real-time assessment of the exercise execution. All communication is implemented with a structured protocol over UDP.

The implementation of the physics simulation is performed by means of the commercially available PhysX engine by NVidia that is one of the most used engines in games and in simulations. The quality and speed have favored the selection of this engine, although other Open Source alternatives are possible [14].

E. Visualization of Virtual Scene

Visual rendering in the multimodal skills trainer is based on the InstantReality framework [15] from Fraunhofer IGD, which builds on top of the X3D standard. This framework is a high-performance Mixed-Reality (MR) system, which combines various components to provide a single and consistent

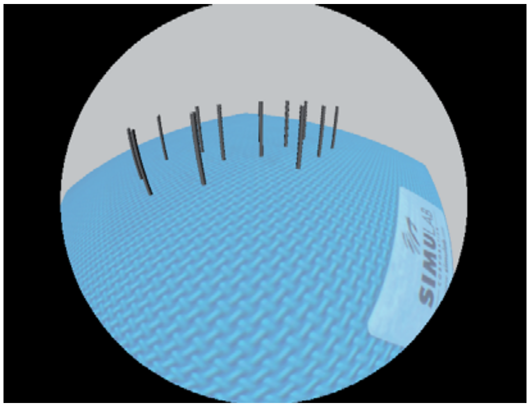

Fig. 8. Simulated distortion of a fish-eye camera under use of dynamic cube mapping.

X3D based interface for AR/VR developers and includes recent research results in the fields of high-realistic rendering, 3D user interaction and total-immersive display technology. Furthermore, the system utilizes the latest GPU hardware features to perform advanced real-time shading techniques including real-time shadows. The middleware components of the framework provide system-specific synchronic and asynchronic high performance network-interfaces to incorporate application data at runtime, e.g. from simulator packages. A data-stream based IO-declaration pyramid provides various levels of abstraction to control all device and data-IO aspects of the application.

In addition to the visualization of the training task environment, a simulation of the laparoscopic lenses is implemented, which uses specialized shaders and multipass rendering technologies. It takes into consideration the distortion of the lenses and the circular section, which is visible to the surgeon. The simulation of the laparoscopic lenses uses real calibration data from the used camera system. The implementation of the lens simulation is based on *dynamic cube mapping* [16]. *Cube mapping* is a special type of texture mapping. A 3D direction vector is used for indexing into a texture that is arranged in 6 quadratic 2D textures, which cover a 360 degree view of the environment. Cube mapping is a standard texture mapping approach that is frequently used. Since we must consider a changing environment, dynamic cube mapping must be used instead of a static one. In this approach the cube map texture is regenerated every frame. The texture is applied to a window sized view aligned quad. This quad also makes use of a shader (a piece of program code running on the GPU that replaces the standard rendering pipeline). The shader evaluates the polynomial, which is determined during the calibration of the laparoscopic lenses.

Thus, an appropriate vector for indexing into the texture lookup is calculated. To simulate the circular view of the lens, every pixel outside the calibrated radius of the real lens is determined to be black. In Figure 8 an extreme view of fish-eye lenses is presented to show the effects of the lens simulation.

F. Training Task Control

The training task control element communicates to all blocks to handle the exercise variables. It parameterizes each of the previously presented elements regarding the current training task and difficulty level. This presents the interface for the human trainer to control and moderate the training process.

The external parameters to control the simulation regarding the training variables or difficulty levels of manipulation are the following switches:

- Joint limits (on/off)
- Simplified kinematics - no trocar (on/off)
- Dynamic behavior (on/off)

Using these switches the surgeon can be focused on the various training skills described above. In addition, the level of difficulty of the training task can be adjusted.

IV. TRAINING TASKS

The implemented training scenarios are used to develop standard training protocols for the training of tasks in minimally invasive telerobotic surgery. In particular the *Pegboard* is used for simple and intermediate skills training for depth perception and bimanual dexterity. In this section the implemented training environments and the assessment scheme used for the MIRS training within the multimodal skills trainer are presented. The training scenarios originate from standard laparoscopic training boxes, which are used for surgical training in state-of-the-art training programs, see [17], [18]. Note that in these training programs, the basic skills are taught in an environment not similar to the surgical operating theatre. This is in line with the intentions of the training platform presented in this paper.

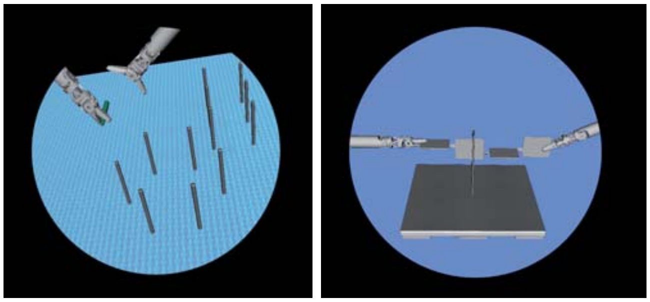

Fig. 9. Training Task Environments, Pegboard (left), Keyhole (right)

Currently two different training scenarios (environments), adopted from the Laptrainer by Simulab Corporation [19], have been implemented, in which specific training tasks can be performed:

- Pegboard Tasks (Fig. 9, left)
- Keyhole Task (Fig. 9, right)

The difficulty of the tasks is manipulated by increasingly restricting the accessible workspace towards a realistic condition with an operational space constrained by the intracorporal situation (organs) and the joint limitations of the surgical robot/tool.

Fig. 10. Training a pegboard with haptic feedback and stereo imaging with polarized light.

V. CONCLUSIONS

This paper presents the technical components of a multimodal training platform for minimally invasive robotic surgery. The training platform is based on DLR MiroSurge and shares the same operator console. The presented training platform allows for a basic training on the MiroSurge console without using the robotic arms with instruments. The virtual environment training thus helps to reduce costs for introducing MiroSurge to surgeons. The selected training tasks are similar to state-of-the-art surgical training for laparoscopic surgery that most surgeons are familiar to, such that they can focus on the robotic system. They can train bi-manual coordination and get easily used to features such as indexing, motion scaling and haptic feedback. First tests with various users showed that a significant portion of the learning procedure can be implemented using the shown training platform. This way, the surgeon is already familiar with the system features and limitations when switching from the training platform to the real robotic system. In the future, the training platform will be enhanced with features such as virtual attractors or a score rating to accelerate the skills learning curve. Additionally, since the current environment simulation only includes stiff contacts, a more enhanced simulation allowing for soft tissue deformations will help the surgeon to gain a deeper understanding of the potential of force feedback, e.g. when doing palpations. The training platform can also be used to compare the different interaction modalities of MiroSurge, i.e. to compare the haptic interface with the tracked input devices and visual force augmentation. With more accurate modeling of the robotic system and its environment, the simulation may also be used for monitoring during the real intervention, thus e.g. indicating potential technical problems or discrepancies between the intervention plan and the actual realisation.

VI. ACKNOWLEDGMENTS

We acknowledge support for this work from the European Commission for funding of the project IP-SKILLS-35005.

cooperation of the people that have been involved in integrating the hard- and software for this prototype: Paolo Tripicchio, Yvonne Jung, Timm Drevensek, Arturo Guzmán Carballido, Philipp Kremer, Jordi Artigas, Thomas Hulin, Daniel Gopher, Sile O'Modhrain, Grigori Evreinov, and many more.

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