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Cooperative robotic system to support surgical interventions

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1. Introduction

Currently computer assisted surgery is dominated by use of navigation systems. These systems track the position of surgical instruments by the use of a 3D digitizing system and insert a corresponding symbol in the pre-operative image on the computer screen. First originating from applications in neurosurgery, Ear-Nose-Throat (ENT) and spinal surgery, such systems have found wide acceptance in most bone-related surgical interventions. However, surgical instruments are still guided manually. Unintentional deviations caused, for example, by hand tremor, slipping or inhomogeneous bone structure can occur.

Robotic systems for computer assisted surgery have gained a lot of interest and are investigated by several research groups, but they are rarely found in clinical practice. The concept of commercial systems like Robodoc (Kazanzides, 1999) and CASPAR (Grueneis, 1999), which have been introduced for milling the stem cavity in total hip replacement surgery, has turned out to be not convincing. Many of those have been removed from the OR. There are other robotic solutions for surgery, including tele-manipulator systems like the daVinci system from Intuitive Surgical Inc., and robots for endoscope guidance in abdominal surgery, like the AESOP system (developed by Computer Motion, Inc.) or the EndoAssist from Armstrong Healthcare (Davies, 2000). However, the operational mode of these systems is not based on computer assisted pre-operative planning and intra-operative registration, and they will not be discussed in this paper.

The interaction between surgeon and robotic system is a very important issue when thinking about its introduction within surgical interventions. Autonomous systems have lost acceptance in the surgical community because the surgeon wants to be in charge of the operation instead of acting only as an observer. In such scenario, the human experience, intuition, capability of react in front of unexpected situations is lost. An alternative solution is to provide a cooperative system where benefits of both can be derived. Some work has been done in relation to haptic interface for direct cooperation between surgeon and robot. Robotic systems like the JHU Steady Hand Robot from the Johns Hopkins University (Bettini, 2004) and the Hands-On Robot, also known as Acrobot (Davies, 2004), use active constraints to limit the motion of the robot within predefined regions.

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This paper discusses the concept of a cooperative robotic system to support medical interventions in several surgical disciplines. A modular structure facilitates the adaptation of a common basic hardware platform to specific applications by adding associated software modules as well as appropriate robot mounted surgical tools. Our approach represents a versatile surgical assistance system which is based on the combination of an optical navigation system, a robotic arm, and a haptic interface based on a force-torque-sensor mounted at the robot's wrist. Compared to manual instrument guidance in pure navigation, the integrated system offers significant additional advantages by guaranteeing precise positioning and guidance of surgical instruments according to pre-operative planning. Moreover, the system offers an intuitive interaction between surgeon and robot; where the surgeon has complete control over the operation by grabbing the tool mounted on the robot's wrist and moving it with his own hands. The issue of mishandling is avoided with the introduction of virtual constraints based on the pre-operative planning. In this way, regions outside the operating zone can be avoided or the surgeon can virtually guide the tool along a certain path. Any intent to move the robot along a forbidden direction will be rejected. The virtual constraints are defined in relation to the patient thanks to the information provided by the 3D digitizing system.

2. Concept of a navigated robotic system for universal surgical application

2.1 Combination of Navigation and Robotics

Although navigation solves the basic problem of providing the surgeon with information for the exact localization of his instrument in the anatomic structure of the patient, there are two important issues which can be significantly improved by adding a robotic component to the navigation system. First, mechatronic supported instrument guidance eliminates the need for the surgeon to constantly move his attention from the operating area to the computer screen where he has to monitor the instrument position. This means he can concentrate fully on the operating area. Second, no unintentional deviations caused, for example, by hand tremor or slipping can occur.

Our patented approach, using robotic systems in surgery, is based on the integration of a navigation system and robotic arm into one system that appears as a single unit, combining the specific advantages of each of the two components. Patient registration is performed by using only the navigation system, while the robotic arm positions and guides the surgical instruments during the intervention.

Instead of designing specific robotic systems which are exclusively tailored to certain applications, our approach adapts the design philosophy of existing commercial navigation systems. A common hardware platform is used for all applications, i.e. a robotic system which fulfils basic requirements, such as easy setup, sufficiently large working space, high safety standards, etc. Adaptation to various surgical procedures is carried out by adding procedure specific software modules and specific tool systems to be mounted at the wrist of the robotic arm. Fig. 1 shows the different components of the navigated robotic system.

A control computer system is used to synchronize the operation of the robotic arm and the optical 3D digitizing system. An important integration aspect is the alignment of the various coordinate frames that are assigned to all relevant system parts and structures, including the base frame of the digitizing system and the base frame of the robotic arm, the surgical instruments and the patient structure to be operated on. The actual position and orientation of the frames can be measured by fixing small rigid bodies (DRB = dynamic reference base elements) to them which can be localized by the stationary cameras of the 3D digitizing system. Part of our research is dedicated to determining homogeneous transformation matrices which establish mathematical relations between the various frames.

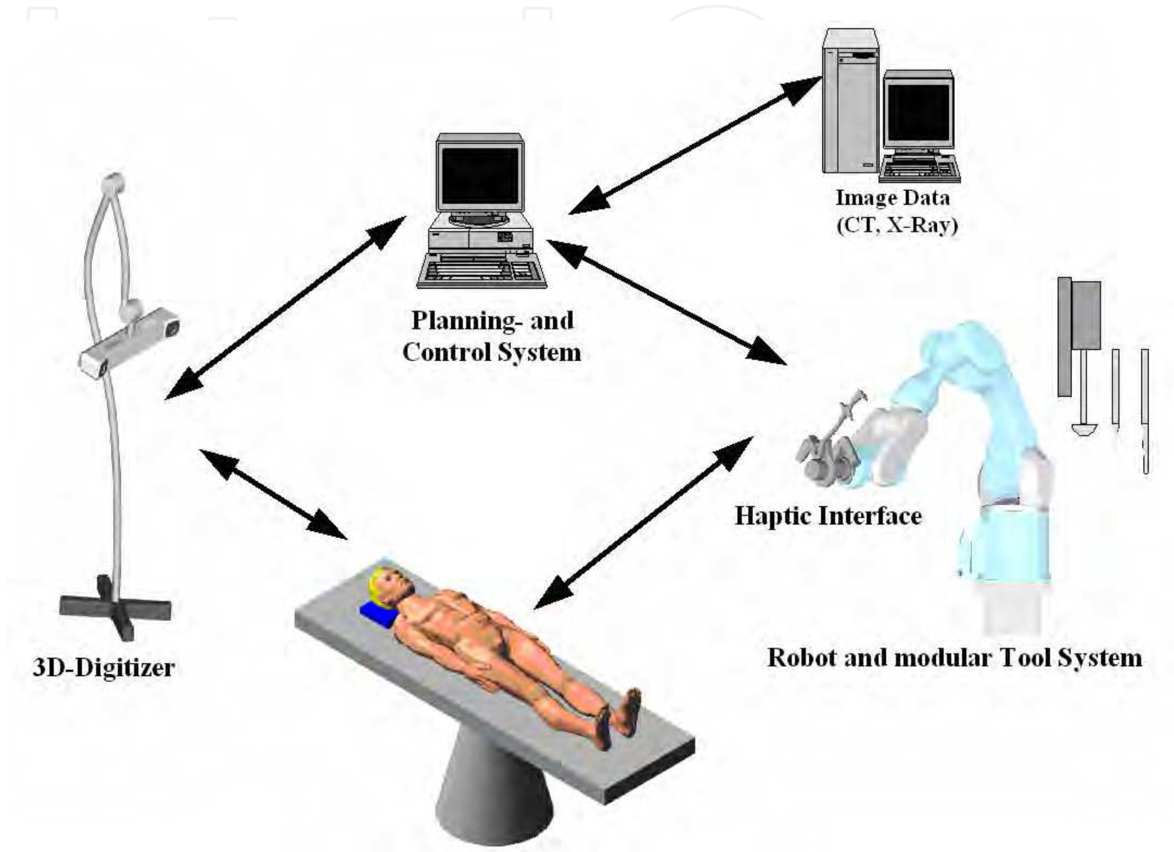

Figure 1. Components of the navigated robotic system for surgical assistance

For example, a setup procedure is carried out during system initialization to align the coordinate systems of the robotic arm and the digitizing system. Once the corresponding transformation matrix, transforming the position of the arm into the coordinates of the navigation system, has been determined, all arm movements can also be specified with reference to the coordinate system of the digitizing system. The robotic arm may then be regarded as a mechatronic unit of the navigation system for automatic positioning and guiding of surgical instruments. Furthermore, the DRB element mounted at the wrist of the arm also provides redundant measurement of the surgical tool position by two completely independent systems: a) the digitizing system detecting the DRB element, and b) the in-built encoders of the arm joints. This is an important feature to meet the high safety requirements applicable to surgical robotics.
A special feature of the robotic arm is its ability to automatically track potential movements of the patient in real time, eliminating the need for rigid fixation of the anatomic structure that is to be operated upon. In the first step, a DRB element of the navigation system is

attached to the bony structure by a suitable fixation mechanism and the patient anatomy is registered using common procedures of the navigation system. If any patient movements are detected during the surgical intervention, a control computer generates corresponding motion commands which move the mechatronic arm to follow the patient, thus keeping the surgical instrument always in the pre-planned position and orientation related to the patient anatomy.

2.2 Cooperative interaction

The robotic arm is equipped with a haptic interface based on a force-torque-sensor mounted at its wrist. This feature facilitates manual-driven motion of the arm, back and forth on the working area. The surgeon easily guides the arm by grabbing a handle, and by pulling it in the desired position. This means the arm is seamlessly integrated into the operating procedure because there is no need to use any input-device like a mouse, a touch screen or a keyboard. The real-time patient-tracking mode of the arm can only be activated when the surgical tool has reached a predefined small working space around the operating area. During the intervention the surgeon can stop the tracking mode at any time to manually move the arm back and then pull it to the operating area again. It will automatically resume tracking exactly at the position before the interruption occurred.

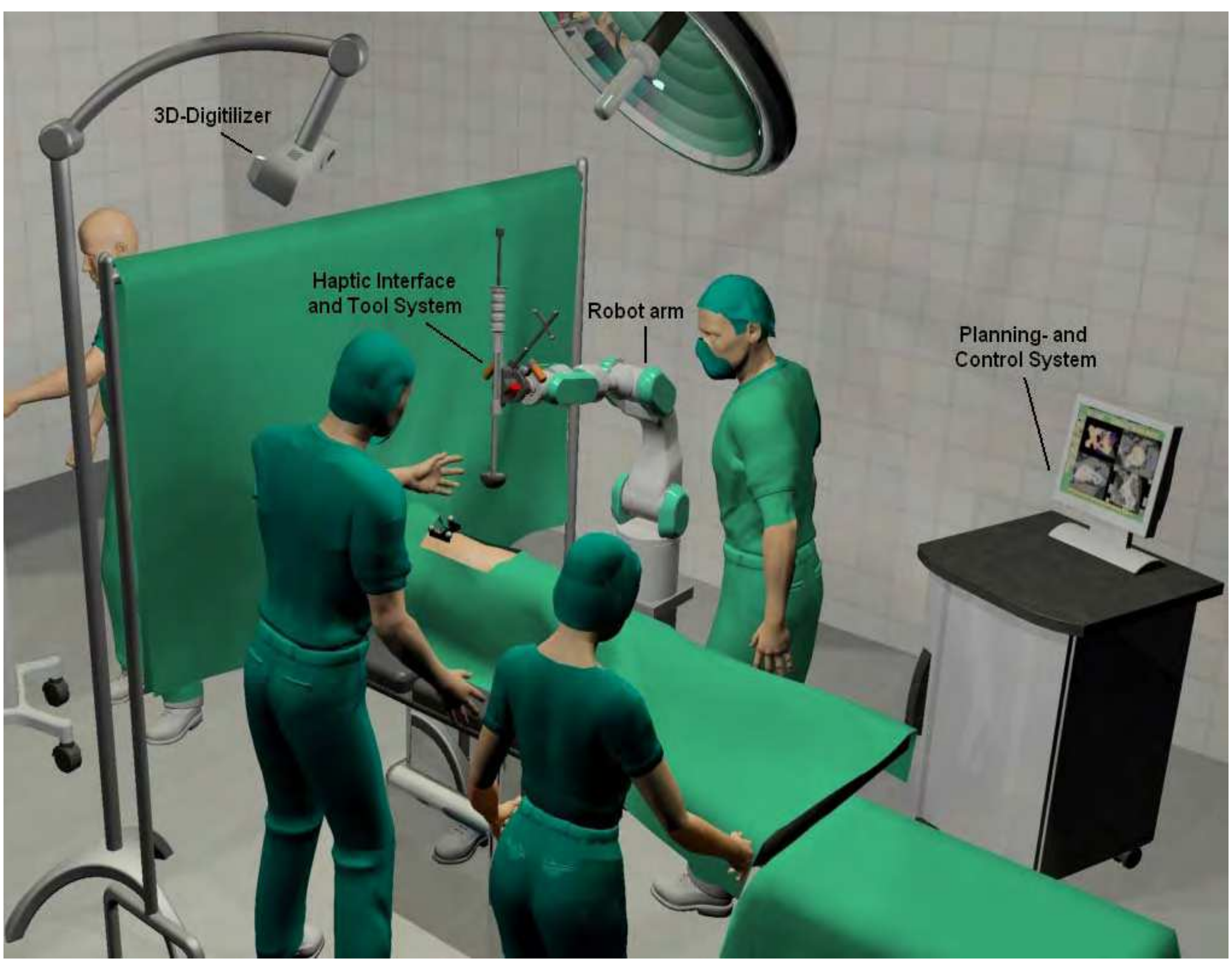

Figure 2. Example of surgical intervention scenario

Figure 2 illustrates the setup of the system for a surgical intervention in the OR. Notice that the surgeon has freedom to move the robot at any time; however, safety measurements are applied in order to avoid any danger to non-specified regions. Therefore, any movement commanded by the surgeon is virtually constrained, which means the system can only move along allowed directions defined in relation to the patient. The constraints can vary depending of the proximity to the patient, where the stiffness and allowed degrees of freedom are switched to achieve different effects. For instance, at first a simple linear movement on the operating normal direction with high stiffness is applied in order to get out of the critical area nearby the patient in a safety way. After a certain distance, the virtual constraint is shifted to an inverted conic form giving the possibility to locate the robot out of the way not to obstruct any other activity of the surgeon. On the same way, once the robot is pulled back to the working area, the virtual constraints procure that the final operating position and orientation are achieved (Marayong et al., 2003).

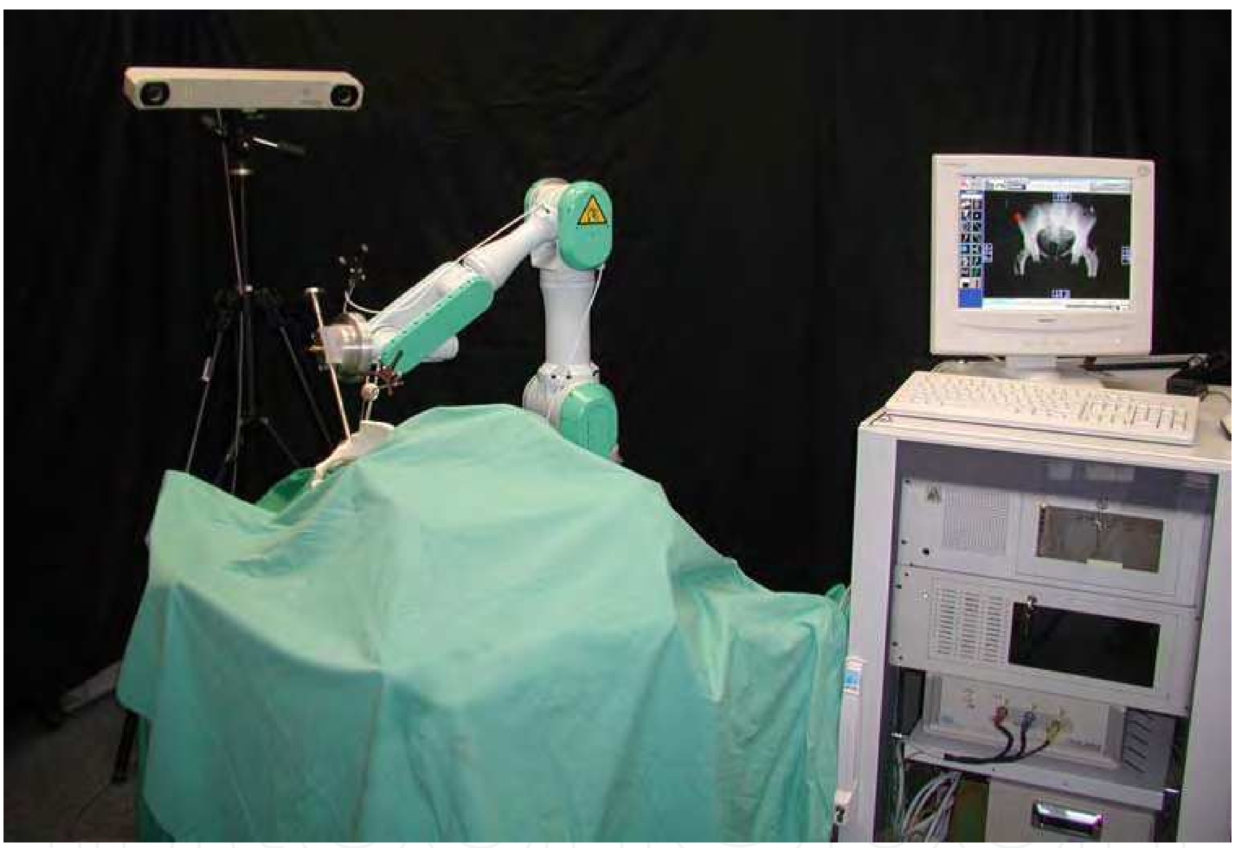

Figure 3. Prototype of the navigated robotic system

3. Setup of a prototype system

3.1 System components

A prototype of the navigated surgical assistance system has been set up in our laboratory. It consists of an optical 3D “Polaris” localizer from NDI Inc., a light weight (35 kg) robotic arm from Mitsubishi Heavy Industries, Ltd. and a mini45 force-torque-senor from ATI Industrial Automations. Fig. 3 shows a photo of the whole system. This hardware is embedded into the development of our “modiCAS” system (modular interactive Computer Assisted Surgery), which comprises hard- and software-modules to facilitate the use of CAS techniques at different levels, starting form pure pre-operative planning, intra-operative registration, up to mechatronic-supported interventions. It is possible to upgrade the system to a higher level by adding further modules, while maintaining a common user interface and retaining the experience already gained. A modular surgical tool system can be mounted to the wrist of the arm. In combination with appropriate software modules, it tailors the systems to various surgical applications.

3.2 Software architecture

The modiCAS framework is developed to maintain modularity as the backbone of its software architecture, making distinctions between fundamental functionalities of the system and application-oriented tasks. The latter makes use of the former to satisfy its specific requirements. Such distribution allows the flexibility to adapt the system to fulfil the demands of different surgical procedures.

On the one hand, the fundamental functionalities are implemented in an embedded target computer that runs a real-time operating system. This guarantees deterministic behaviour of the time critical tasks. On the other hand, a second computer (the Host) runs Microsoft Windows to implement the graphical user interface (GUI) as well as the application-oriented tasks. Both computers are connected by a fast Ethernet link.

The Host computer communicates with the Target using a Command-Based architecture, which provides access in the form of commands, to all functionalities available at the Target. Fig. 4 illustrates the organization of this architecture. The command interface looks like a simple library of functions that can be called on by the Host. Plausibility is checked by the Target each time a command is requested before it can be executed.

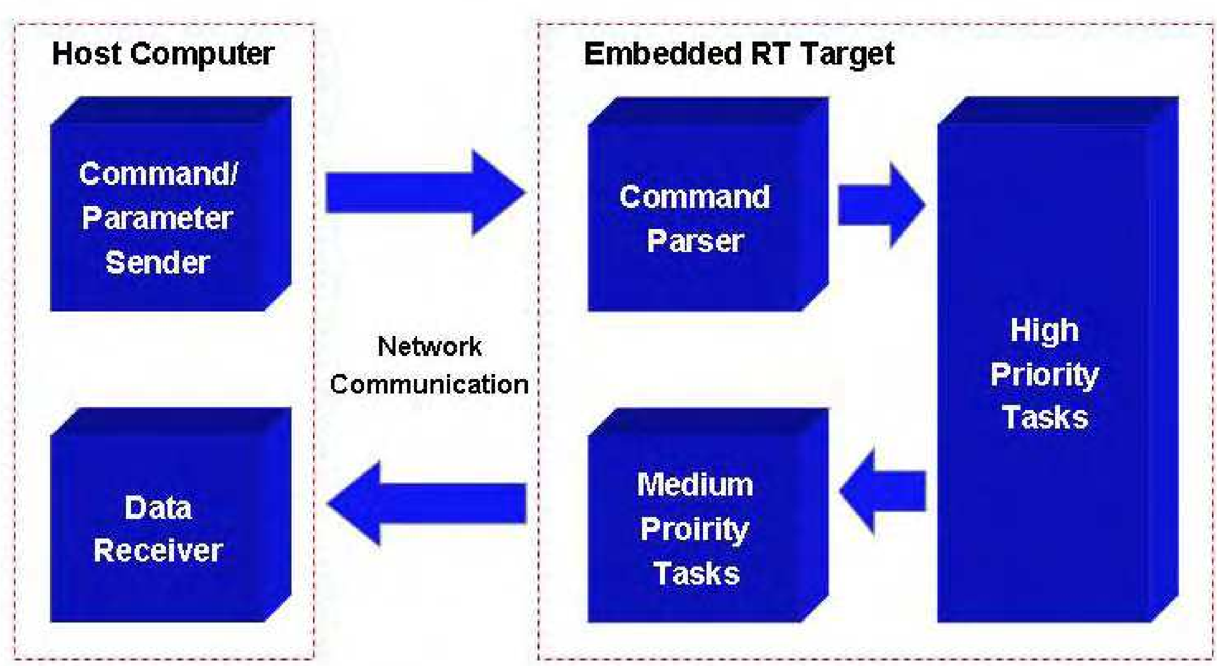

Figure 4. Command-based architecture

4. Application in various surgical procedures

In comparison to conventional navigation systems which are still based on pure manual instrument handling, precise instrument guidance by navigated mechatronic assistance systems offers significant additional advantages. Those include:
the use of novel minimal invasive operating techniques

- application of new surgical instruments (such as medical laser systems or micro tools which cannot be used in manual surgery)
- high certainty in the execution of pre-operative plan even under difficult circumstances (minimizing the risk of cost intensive post-operative treatment)
- the possibility to reduce the assistant staff numbers in the operating theatre

This will lead to patient benefits, better support of the surgeon and improved cost/benefit ratios.

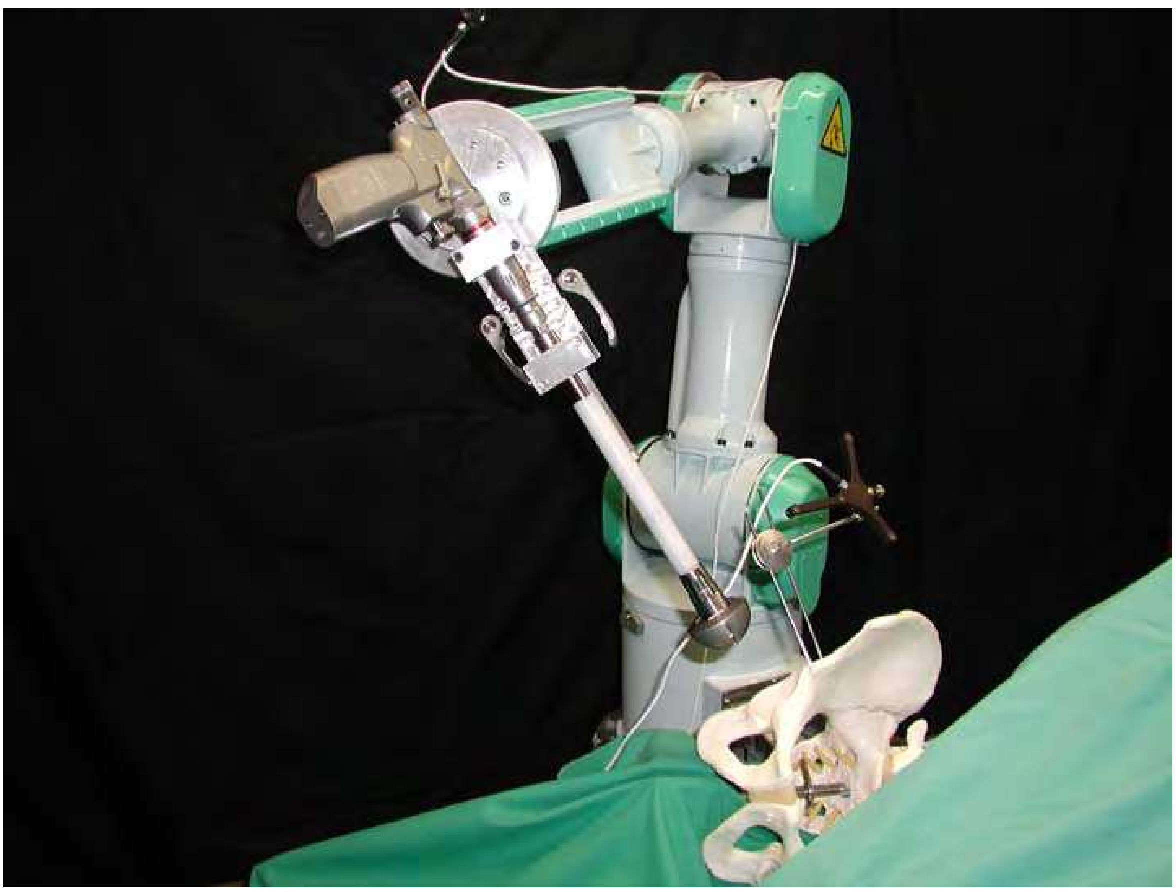

Figure 5. Preparation for the cup implant in total hip replacement surgery

1. Orthopaedic surgery: The first clinical application of the robotic assistance system has been carried out in total hip replacement surgery. It has been world's first robotic system to support the implantation of the acetabular cup, which has been facilitated by using its unique patient tracking capability (Kerschbaumer et al, 2003). A specific tool system for mechatronic-based preparation of the bony bed and mechatronic-supported placement of the cup implant has been developed. It is based on the design of conventional components (reamers, surgical drives, etc), see Fig. 5. The tools are fixed

on a one-degree-of-freedom linear slider mounted at the wrist of the robot. The operation of the surgical tool itself is still manually controlled by the surgeon. In this way he keeps control over the operation, while he can be certain that the tool maintains its correct orientation and that there are no unintentional deviations caused by inhomogeneous bone structure. Furthermore the system prevents the surgeon from reaming too deep into the acetabulum.

2. ENT surgery: The application under investigation is Functional Endoscopic Sinus Surgery, a standard minimal invasive procedure in ENT. In conventional operating technique the surgeon requires one hand to guide the endoscope and can use only one instrument with the other hand. Single-handed operating can become extremely frustrating during delicate manoeuvres. It is therefore a significant improvement if the robotic assistance system can be configured to partly guide the endoscope but fully controlled by the surgeon. It therefore facilitates safer and more comfortable two-handed operating. In haptic mode, the wrist of the arm can be manually positioned close to the desired operating zone above the patient’s head. Then either cooperative or teleoperative moves the endoscope to the pre-operatively planned intranasal location, taking the meatus nasi externus as a relative pivot point and respecting pre-operatively defined safety regions. The virtual constraints assure that the correct direction is maintained and prevent the endoscope from reaching dangerous internal regions in the patient.

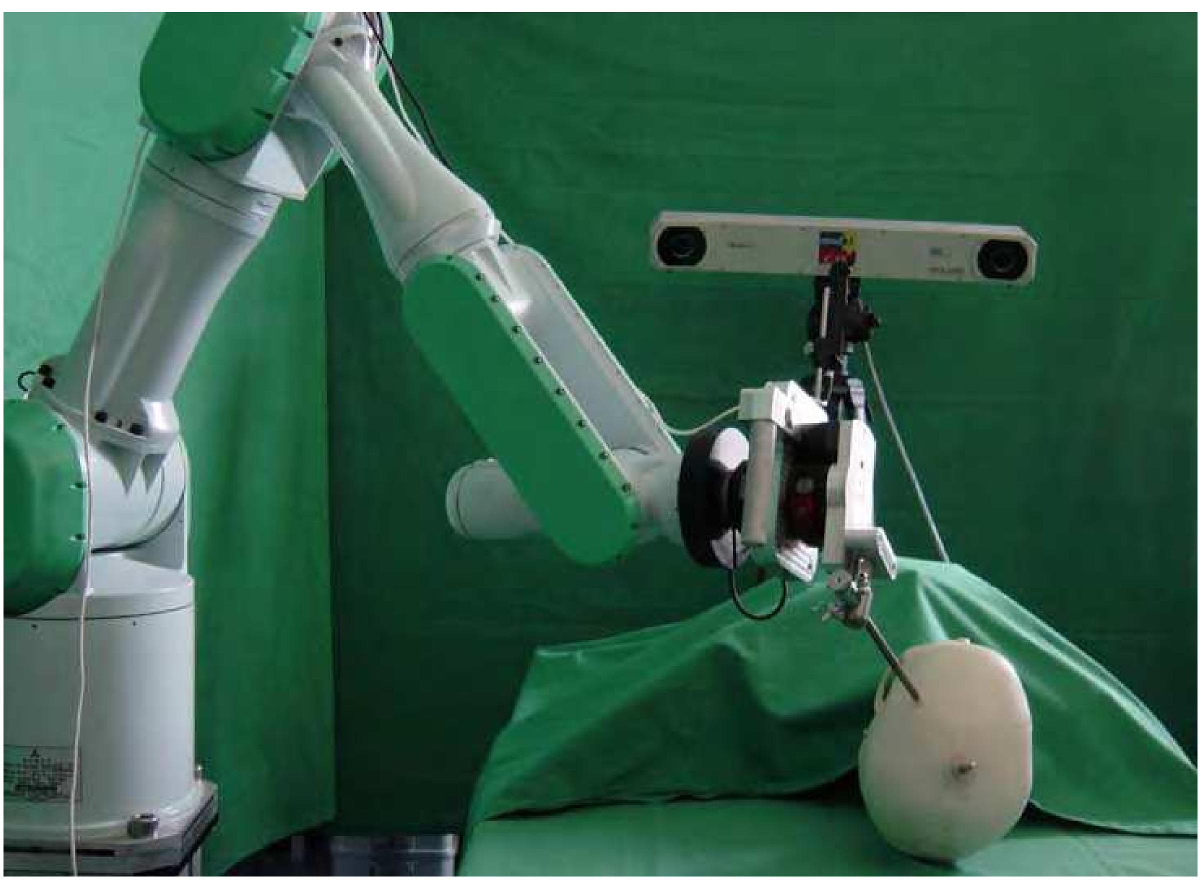

Figure 6. Endoscope guidance for neurosurgical applications

3. Neurosurgery: Intracranial endoscopic approaches require high accuracy to reach the target point. The free-hand approach, combined with neuronavigation, is usually used for a precise access to small ventricles or cysts. To improve the accuracy and to provide a stable holding system, the navigated robotic system will be used for guiding the endoscope. Once the burr hole has been made and the dura has been incised, the endoscope is inserted by the robotic arm along the planned trajectory to the target point. It can be moved by the arm under teleoperative control while the surgeon is looking at the monitor screen or directly, in a cooperative fashion, using the haptic interface. At the end of the intervention, the endoscope is retrieved manually exactly along the trajectory as it has been inserted. Fig. 6 illustrates the laboratory setup.

5. Conclusion

The interactive robotic assistance system can be considered as an intelligent instrument that supports surgeons to achieve more precise and reproducible surgery. It combines the advantages of navigation and mechatronics by using the navigation system for registration and position measurement, and the robotic arm for precise positioning and guidance of the surgical instruments. The integrated haptic interface offers a seamless incorporation of the robotic system in surgical intervention. The surgeon maintains full control over the operation procedure. Moreover, safety measurements are introduced, using the concept of virtual constraints, in order to avoid any mishandling due to excessive manipulability freedom. For instance, by defining forbidden regions that the robot is not allowed to enter, or guiding the tool along a desired direction through direct cooperation between surgeon and robot.

A command-based architecture is used for the software development to provide a solid foundation for a flexible and scalable framework. This is divided by hardware in two main parts: The embedded target with a pool of modules for the different functionalities, and the Host, which use these modules together with the GUI to build the different applications. The modular system design facilitates its adaptability to a variety of surgical applications. In particular, in cooperation with clinical and scientific partners, we will further investigate the robotic-guided application of new surgical instruments (e.g. laser systems, micro tools, radiation devices) which cannot be used in manual surgery, in order to demonstrate their benefits in surgical treatment.

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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