



045201

AccuRobAs

Accurate Robot Assistant

Specific Targeted Research Project (STREP)

Advanced Robotics

Final Activity Report

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

TABLE OF CONTENT

1	EXECUTIVE SUMMARY	3
2	PROJECT EXECUTION	6
2.1	PLANNING	6
	<i>Objectives and research areas</i>	<i>6</i>
	<i>Project results.....</i>	<i>6</i>
2.2	SENSOR SYSTEM.....	8
	<i>Objectives and research areas</i>	<i>8</i>
	<i>Project results.....</i>	<i>8</i>
2.3	MOTION COMPENSATION	9
	<i>Objectives and research areas</i>	<i>9</i>
	<i>Project results.....</i>	<i>10</i>
2.4	SYSTEM INTEGRATION AND DEMONSTRATORS	10
	<i>Objectives</i>	<i>10</i>
	<i>Project results.....</i>	<i>10</i>
	<i>Setup and Evaluation of Laser Osteotomy System.....</i>	<i>10</i>
	<i>Setup and Evaluation of MIRS.....</i>	<i>12</i>
3	PUBLISHABLE RESULTS	13

1 Executive summary

The **ACCURoBAS** project, No. 045201, aimed in developing an innovative and universal robotic assistant system to support a human in dextrous manipulation. Methods to increase accuracy for lightweight compliant robotic systems during surgical procedures supporting different levels of autonomy were focus of the research in **ACCURoBAS**. These levels vary from tele-manipulation to autonomous behaviour. The **ACCURoBAS** approach focuses on adaptive control by exhibiting rich sensory-motor skills and multi-sensor measurement to distinctly increase the system accuracy.

The objectives of **ACCURoBAS** were:

- Increase accuracy of compliant light weight robots through multi-sensory concepts.
- Increase accuracy of robotic procedure planning through adaptive models, soft tissue modelling and online motion prediction.
- Develop new techniques for laser osteotomy to enable contact-free cutting of arbitrary cutting geometries in the human bone with superior accuracy.
- Provide kinaesthetic feedback to robotic systems for palpation in real and simulated environments.

To achieve this goal within the scope of **ACCURoBAS** two demonstrators were developed in order to show the capabilities of the systems:

- Robot assisted bone ablation (autonomous mode)
- Minimally-invasive robotic surgery (tele-manipulated mode)

Minimally-invasive robotic surgery

Conventional minimally invasive surgery (MIS) is performed through small incisions in the patient's skin, preserving healthy tissue. The surgeon works with long slender instruments, and is separated from the operation area. This arrangement challenges the surgeon's skills due to lost hand-eye-coordination and missing direct manual contact to the operation area. Therefore, many sophisticated procedures still cannot be performed minimally invasive. To overcome the drawbacks of conventional MIS, telepresence and telemanipulation techniques play an important role: In case of minimally invasive robotic surgery (MIRS) the instruments are not directly manipulated anymore. Instead, they are held by specialized robot arms and remotely commanded by the surgeon who comfortably sits at an input console. The surgeon virtually regains direct access to the operating field by having 3D endoscopic sight, force feedback, and restored hand-eye-coordination.

The MIRS scenario further developed in the scope of **ACCURoBAS** includes an input (or master) console as well as a teleoperator consisting of 3 surgical robots (MIRO). Usually two MIROs carry surgical instruments equipped with miniaturized force/torque sensors to capture reaction forces with manipulated tissue. One more MIRO can guide a stereo video laparoscope. Both the stereo video stream and the measured forces are displayed to the surgeon at the master console. So users are not limited to see but can also feel what they are doing. An Omega.7 input device is used as force display.

The ultimate ambition of **ACCURoBAS** is robot supported surgery on the beating heart. The application of the heart-lung machine would become obsolete for a whole variety of

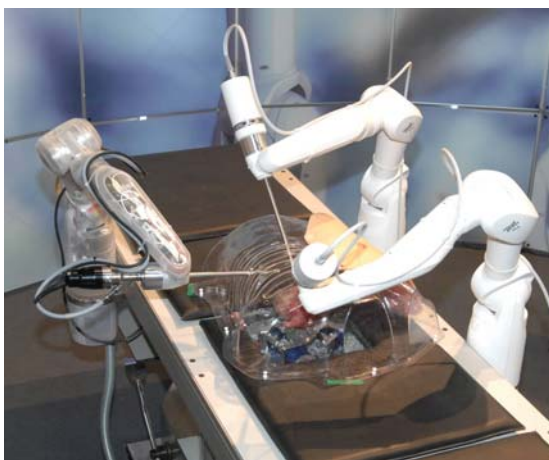
procedures that way. Collaterally, the very traumatizing effects of the heart-lung machine on the patient could be avoided (e.g. blood contact with extrinsic surfaces, inevitable blood clotting attenuation, typical generalized inflammation reaction). Therefore, performance characteristics of the MIROs are designed to follow a stabilized beating heart motion. Additionally, the endoscopic video stream can be stabilized by optical tracking in real time so that a virtually stationary video picture can be consistently presented to the surgeon.

Robot assisted laser bone ablation

In the scope of ACCUROBAS world's first complete setup for robot assisted laser bone ablation was developed. The laser ablation process was modelled discretely and integrated into a Planning and Simulation environment. The surgeon predefines the cutting trajectory on a three-dimensional surface model of the target bone geometrically. Afterwards the geometrical definition is automatically transferred into an ablation pattern. This ablation pattern defines the distribution of single laser pulses in order to achieve the predefined geometry and depth of the cut.

The laser is applied onto the bone by a two-dimensional optical scanning system which is positioned by the robot. For the determined ablation pattern an optimized sequence of scan head locations for the execution is calculated automatically. A Simulator was developed in the scope of ACCUROBAS which allows preoperative simulation of the laser cutting procedure for different robots and optimization of the setup.

The demonstrator shows the current state in technology regarding performance and robustness of a completely tracked system and the cutting performance with a short-pulsed CO₂ laser guided by a robotic system. The correct and working calibration and registration chain is successfully shown with the demonstrator. Furthermore position-based visual servoing methods for compensating breathing motion were integrated and show promising results. The accomplished experimental evaluations revealed the system capabilities and showed feasibility of robot assisted laser ablation. Laser cuts with a cutting width of below 300µm could be performed on ex-vivo animal specimen with an overall accuracy below 0.4mm in a static setup (i.e. fixated specimen).



Setup for minimally-invasive robotic surgery.



Setup for robot-assisted laser bone ablation.

The consortium comprises the following partners:

- **UNIKARL – Institute for Process Control and Robotics (IPR), Universität Karlsruhe (TH):** This institute is part of the computer science faculty and is headed by Prof. Wörn. IPR has its expertise in advanced robotics and automation. Main research topics are industrial and medical robotics. UNIKARL is co-ordinator of the **ACCUROBAS** project.
- **UVR – Laboratory for tele-operation and advanced robotics (ALTAIR) , University of Verona:** This institute has a long history and is a recognized research centre in medical robotics in Italy. Its main focus is on telerobotics control and modeling, with applications to soft objects modeling.
- **DLR – Institute of Robotics and Mechatronics, German Aerospace Center:** DLR, German branch of the Space Agency, serves scientific, economic and social ends. The Institute of Robotics and Mechatronics did Europe's first step into space robotics (ROTEX 1993) and since then developed generations of awarded high end robots such as the DLR lightweight arm and hand.
- **UPMC – Robotics Lab of Paris (LRP), Pierre and Marie Curie University:** This institute groups researchers in the field of Mechanical Engineering, Control Engineering and Computer Science. Their research focuses in design and control of advanced robotic systems handling complex interactions.
- **UMII - Montpellier Laboratory of Computer Science, Robotics, and Microelectronics (LIRMM), University of Montpellier II :** The LIRMM robotics department research activities cover the following areas: Design, modeling, identification, optimization and control of complex robotics systems; Control of networked robots, trajectory and motion planning; Image processing, vision, and 3D modeling; Modeling, control and interfacing the human sensory motor system for the development of palliative solutions for movement deficiencies.
- **BRAINLAB – BrainLAB AG:** BrainLAB is a privately held company specialized in medical technology for radio surgery and radiotherapy, orthopaedics, neurosurgery, and ENT. With about 2170 systems installed in more than 65 countries, BrainLAB is among the market leaders in image-guided medical technology.

2 Project execution

The core objective of ACCUROBAS described above is to develop an innovative and universal robotic assistant system to support a human in dextrous manipulation. In the following the results and achievements in the scope of are ACCUROBAS described.

2.1 Planning

This workpackage addresses the issues of pre-operative modeling and planning of surgical procedures. Its objective is to develop methods and algorithms for a surgical robot that could improve procedure's accuracy and reduce risks for the patient.

Objectives and research areas

A surgical procedure is generally composed of a number of sequential and/or parallel, elementary tasks combined into fixed recipes described into surgical manuals. During the execution of the procedure, it is up to the surgeon's ability and experience to adapt each step to the specific anatomy and pathology of the patient. Surgery is often prepared by studying the patient's CT scans, whose 2D representation is not immediately amenable to interpretation and use. Thus, the need of better visualization and planning tools in support of pre-operative analysis is evident.

AccuRobAs improves preoperative planning, by pursuing the following objectives:

1. development of semi-automatic segmentation procedures of CT scans,
2. development of patient-specific models of the surgical area (virtual abdomen),
3. development of procedures to touch the model by using haptic devices,
4. development of simulations of the interaction among organs and surgical tools,
5. development of automatic planning aids to generate a nominal surgical sequence.

When reached, these objectives will allow the visual and haptic (by touching) rendering of the surgical area, the computation of organ displacements when the patient moves, and the simulation of the surgical procedure. The surgeon will then be able to try out the procedure with the haptic interface, or to examine the steps suggested by the planner. In the following section, the results achieved towards these objectives during the reporting period are summarized.

The research work is divided into three complementary elements, the first involving modelling, the second planning, and the third the execution of a plan on a specific set-up, organized in the following tasks:

- Identification of uncertainties
- Formal description of uncertainties
- Preoperative offline planning
- Estimation of the failure impact
- Intraoperative online planning
- Documentation in database
- Performance analysis and verification

Project results

Inaccuracies and uncertainties are **predictable and unpredictable differences between a representation of the world and the real one**. Inaccuracies are referred to error source that

is possible to measure (position error) and uncertainty are related to indirect aspect non directly measurable (process variable error). Uncertainty is inserted in the task description referred to each action, and for the overall task the sum of action uncertainty is computed. We went through the MIRS and LASER scenario and we identified and classified online and offline inaccuracies; the offline inaccuracies are inserted into the task plan and the online inaccuracies are accounted and compensated for during the execution.

For the LASER scenario, the robot is used as a positioning device and therefore needs to have high positioning accuracy, implying also high precision. This way, achievement of high positioning accuracy is a main design goal in both scenarios. The means to achieve this accuracy are however different, since the used sensors are fitted to the applications.

In the MIRS scenario, additionally *transparency* is crucial for high *haptic accuracy*. In the scope of this project, measures are used to evaluate and maximize the quality of the haptic feedback. In terms of force based motion compensation, the accuracy of the used force sensor is of high importance. The choice of an adequate calibration procedure for the highly miniaturized force/torque sensor at the tip of the actuated instrument is ongoing research work.

The purpose of the AccuRobAs framework is being able to plan and execute different medical interventions in the category of laser ablation and laparoscopy. Therefore the workflow language should be as expressive as possible, must support capabilities like analysis, simulation and model checking, ambiguous semantics or unclear definitions must be avoided. Because different scenarios and operations must be supported, different planning modules will plan parts of the complete interventions. For example an intervention on the head may be executed automatically and require well-planned steps while an intervention in the abdomen we may compute possible paths and optimal setup, entry points and collision free workspaces. The Task Planner produces an intervention plan suited for a specific patient given its medical records and a general description of the intervention.

The planning phase is composed of the distinct components: plan formalization, plan initialization, and plan specialization. The first is the act of writing the description of the surgical intervention. The second is the act of choosing the information needed to perform the intervention on a given patient while the third is the act of generating the actual plan from the given data.

We propose a replicable experimental setup in which we benchmark a palpation task. In general, palpation is used as part of a physical examination in which an object is inspected to determine its size, stiffness, and location. We account for different target conditions. In our analysis we tested the perceptual capabilities in stiffness discrimination, the capabilities in size discrimination and in locating stiffer inclusions. Each task can be evaluated according to different experimental conditions: by involving a teleoperation setup, a virtual environment or a direct hand-object manipulation. A total of 10 participants have been examined (age range from 23 to 36) in all the experimental conditions. The first 9 participants have been recruited by word of mouth within the staff of the ALTAIR laboratory of the University of Verona (Italy); the latter one was a specialty surgeon, with more than 5-years daily experience in laparoscopic surgery, working in a private clinic near Verona (Italy). They were not informed of the experimental goals and were simply instructed to carry out the task. All the participants have a normal sense of touch and have used their dominant hand to perform the task.

These results are highly comparable to the ones collected in the full teleoperation scenario, letting us to conclude that the involved teleoperation setup let the user to transparently feel the perceptual experience.

2.2 Sensor System

Objectives and research areas

In state of the art applications, robot movements require a static world model. In surgery such models are not feasible since patient movements and handling of soft tissue change the world continuously. Therefore robotic surgery needs adaptive models that are continuously updated with the help of redundant and complementary sensors. The goal of this work package was to combine different sensors into an accurate and fault tolerant system and to develop methods for calibration. With this knowledge a precise and robust intraoperative registration and navigation is possible. Following tasks have to be accomplished to establish the sensor system:

- Sensor Architecture
- End effector measurement sensors
- Data fusion algorithm
- Automatic solution for sensors self calibration and localisation
- Development of an automatic robust registration algorithm
- Optimization of the registration algorithm
- Set up and evaluation of an experimental sensor system

Project results

The software architecture uses realtime CORBA for the communication between all components. For the implementation TAO is used. TAO generates C++ class files from the IDL specifications for the interfaces. The system was tested with the Open CORBA Benchmarking suite. The test revealed with standard hardware a ping time of lower than 0.5 ms achieved on Gigabit Ethernet. The robot has an update cycle of 12 ms and the tracking system delivers the data with 16 ms. The communication delay compared to standard socket IPC is approximately 10% higher with TAO and is not resulting in any advantages in this scenario. The demonstrator and the performance analysis show the feasibility of the architecture. It is possible to control the hardware with a 12 ms update rate. It is even possible to read the data from the laser distance sensor with 1 ms update rate. To lighten the implementation interfaces for Matlab/Simulink have been developed.

For the laser system an end-effector was designed. A body consisting of marker spheres is attached to the end-effector of the robot to measure the actual position with the optical tracking system. The end-effector consists of a colour camera, a scanhead, a flange for the laser mirror arm, a laser distance sensor and the already mentioned body.

One approach in the AccuRobAs project was to combine a standard vision camera at the front of the end-effector with the optical tracking system. Different trials have been performed but until know the accuracy is not sufficient for laser ablation. The appendage will be continued in the FP7 project Safros.

While a standard point to point transformation for the transformation between optical tracking system and robot is inadequate, a special registration algorithm was developed and therefore is used. This allows an automatic registration by moving the robot to different positions and store the position of a body attached to the robot TCP. The scan head is registered to the optical tracking or to the robot using a camera that tracks the prototype laser. Only the patient must be registered manually. With the known registration between robot and tracking system the robot can also be controlled via visual servoing.

The marker based standard registration method is used for the registration. Marker spheres are attached to the skull to track it. Additional titanium screws are drilled into the skull and a CT scan is performed. The titanium screws can be identified inside the segmented CT data. On

the real bone a standard pointer device is used that is tracked by the same tracking system. To acquire the position of the marker the points acquired by the tracking system have to be fitted to a sphere. The following method describes the estimation of the points via using a tracked pointing device. The tip pointer device is put to the screw and moved. The tracked position of this pointer is fitted to sphere and the middle point of this sphere is the position of the screw. The Gauss–Newton algorithm is a standard method to solve such. Each titanium screw is pivotized using the pointer and the resulting point cloud is then registered to the point cloud from the CT data set to acquire the transformation between the two coordinate systems. The method used for the registration between the two point clouds, one from the CT Data and one from the tracking system, is the method from Horn et al.

For the optimization of the registration two different approaches have been tested. The first calibration method uses the FARO measurement arm, this method was developed for the static case. In the second case a tracked pointer device is used for the dynamic case. The accuracy for the dynamic case is 0.5 mm that is outperformed by the registration for the static case, because the FARO measurement arm has a better accuracy. The drawback is that this method can not be used for the dynamic case.

2.3 Motion Compensation

An important research topic in the ACCUROBAS project was the introduction of motion compensation. Its objective was to develop new control algorithms for physiological motions compensation. Two main applications have been taken into account in this workpackage: laser osteotomy and minimally invasive surgery.

Objectives and research areas

Physiological motions are motions of the patient's organs or bones induced by breathing or by heartbeat. These motions decrease the accuracy of the surgical task. Thus, the objective of this workpackage is to develop new control algorithms for physiological motions compensation.

The work is subdivided into four main tasks, namely:

- Modelling and identification of physiological motion
- Visual servoing for approximate motion compensation
- Force feedback control for fine motion compensation
- 3D reconstruction and hybrid vision/force control

During a laser osteotomy operation the end-effector of the robot which is holding the laser has to be positioned accurately with respect to the bone to be cut. Some bones, for instance the bones of the thorax, undergo periodic motions due to breathing and these motions can affect seriously the accuracy of the task. Thus, the robot has to perform movements synchronized with the bone in order to compensate the breathing motions. However, due to the limited bandwidth of surgical robots, classical high gain controllers are not able to achieve such a compensation. Therefore, new control algorithms have to be developed. Thus, the objectives of this workpackage as far as laser osteotomy is concerned are:

1. Development of a visual servoing control algorithm in order to accurately send the robot's end-effector in a desired pose (position and orientation) with respect to the bone.
2. Enhancement of this control scheme with a learning algorithm in order to synchronize the motions of the robot with the motions of the bone. This learning algorithm has to exploit the repetitive properties of breathing motions in order to predict and anticipate them.

When reached, these objectives will allow an accurate positioning of the robot's end-effector with respect to the bone even when the bone is affected by breathing motions. This will increase the accuracy of the laser osteotomy operation.

In surgical operations As far as minimally invasive surgery is concerned, physiological motions are very disturbing for the surgeon especially in beating heart surgery. Moreover the accuracy of the surgical gesture is closely related to the surgeon's ability of compensating of these disturbing motions. Since the physiological motions and especially beating heart motions are doted with high accelerations, then it will be a very difficult and even a challenge for the surgeon to compensate them manually.

Nowadays, the existing solution consists in using mechanical stabilizers. But the use of such a method has diverse drawbacks as damaging the heart surface and tissues, and causing irreversible local damage by traumatizing the underlying microcirculation. The best way, to overcome this problem, is to compensate these disturbances by a robotic assistant, where the manipulator arm is controlled to compensate accurately the physiological motions while enabling the surgeon to add his gesture. The objectives of this workpackage go in this direction that is:

- 1) Control the robot in order to perform tool movements synchronized with those of the beating heart.
- 2) Use haptic interfaces in order to provide the surgeon with force feedback. This may enable him to feel the interaction forces between the tool and the organ.
- 3) Use of (high speed) cameras and force sensors as feedback for the compensating algorithm.

Project results

The main achievements on motion compensation in the project include:

- The development of modeling and identification methods for physiological motions.
- The proposition of visual servoing algorithms and of force control algorithms for motions compensation and their evaluation thanks to simulations.
- The improvement of these algorithms and their experimental evaluation.
- The development of 3D reconstruction methods and of hybrid vision/force control algorithms.

2.4 System Integration and demonstrators

Objectives

According to the specifications the goal of this work is to integrate the above described modules into experimental setups which are then used for benchmarking. Key questions are therefore the optimisation of a modular concept able to integrate the work of the partners into experimental setups such as a minimally invasive robotically assisted surgery setup and a setup for laser osteotomy.

Project results

Setup and Evaluation of Laser Osteotomy System

During the third year the demonstrator for CO₂ laser cutting including the lightweight robot and the tracking system was established. The demonstrator shows the current state in technology regarding performance and robustness of a completely tracked system and the cutting performance with a CO₂ laser guided by a robotic system. The correct and working calibration and registration chain is successfully shown with the demonstrator. The motion

compensation algorithms of UPMC have been integrated to the system. This shows also the benefit of the underlying system architecture that allows a modular system and a fast integration of algorithms. The current motion compensation algorithms allow accuracy up to 0.5 mm that is still improvable and reflects the possibility with algorithms and used technology.

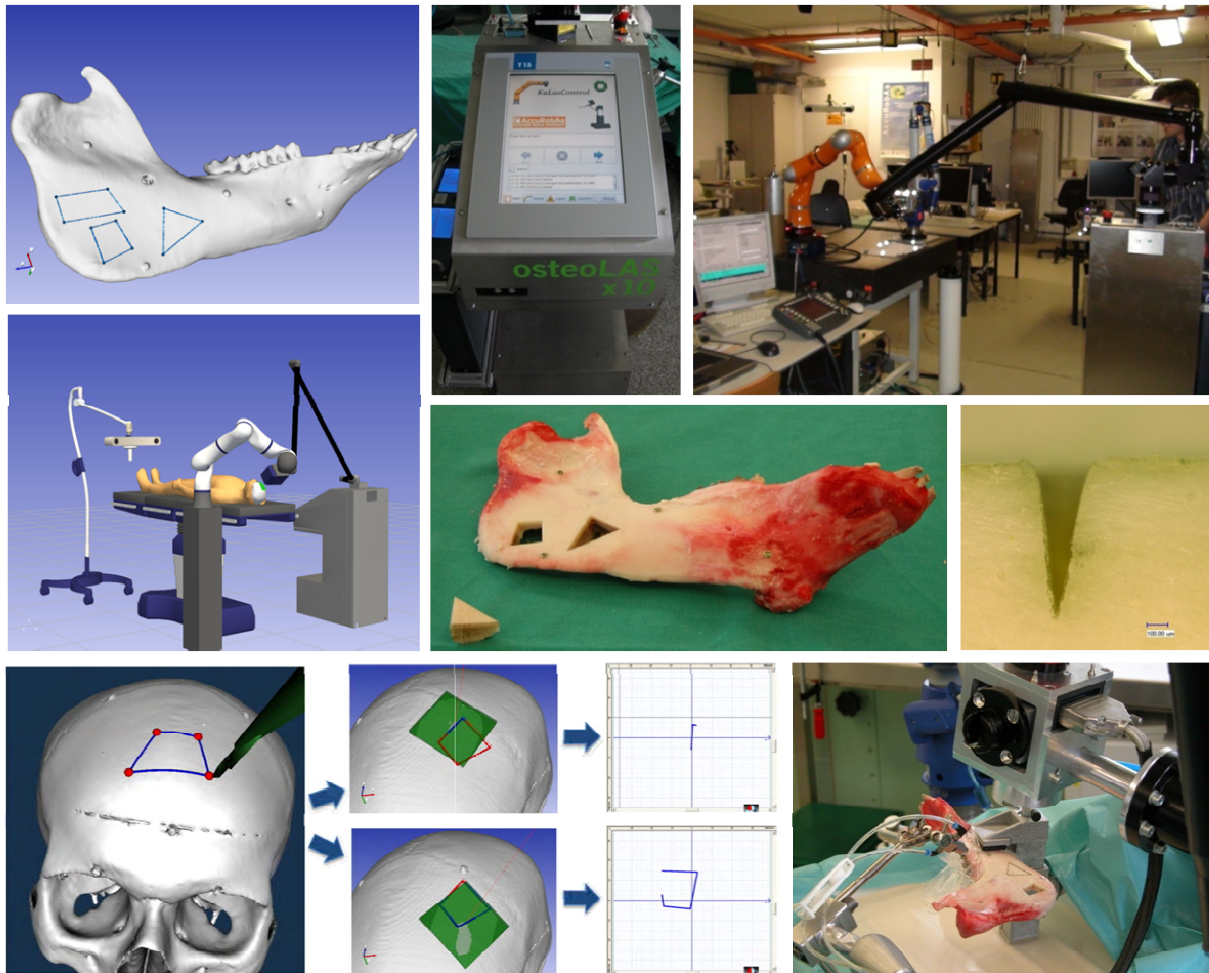


Figure 1: Robotic guided laser system including planning and experimental results

During the project the necessity of a process model required analysis and evaluation of parameters which influence the ablation of bony tissue in order to facilitate preoperative planning of laser cutting. In the scope of the project a conventional short-pulsed CO₂ slab laser was utilized. With a wavelength of 10.6 μ m the laser shows optimal absorption characteristics in the main bony tissue components. The bone removal in laser cutting is realized by applying consecutive single laser pulses according to a predefined cutting trajectory. Each single laser pulse removes a tiny piece of bone and the concatenation of pulses results in increasing cutting depth. In the scope of AccuRobAs the laser ablation process was modelled discretely and integrated into a Planning and Simulation environment. The surgeon predefines the cutting trajectory on a three-dimensional surface model of the target bone geometrically. Afterwards the geometrical definition is automatically transferred into an ablation pattern. This ablation pattern defines the distribution of single laser pulses in order to achieve the predefined geometry and depth of the cut. The laser is applied onto the bone by an two-dimensional optical scanning system which is positioned by the robot. This scan head has a limited working volume and the utilized flat-field lens results in different

inclination angles of the laser beam in the scan plane. For the determined ablation pattern an optimized sequence of scan head locations for the execution is calculated automatically. A Simulator was developed in the scope of ACCUROBAS which allows preoperative simulation of the laser cutting procedure for different robots and optimization of the setup. The accomplished experimental evaluations revealed the system capabilities and showed feasibility of robot assisted laser ablation. Laser cuts with a cutting width of below 300 μ m could be performed on ex-vivo animal specimen with an overall accuracy below 0.4mm in a static setup (i.e. fixated specimen).

Setup and Evaluation of MIRS

The MIRS setup is an integrated telepresence system for robotic endoscopic surgery. Three MIRO robot arms are combined with MICA instruments and an endoscopic camera (see Fig. 2).

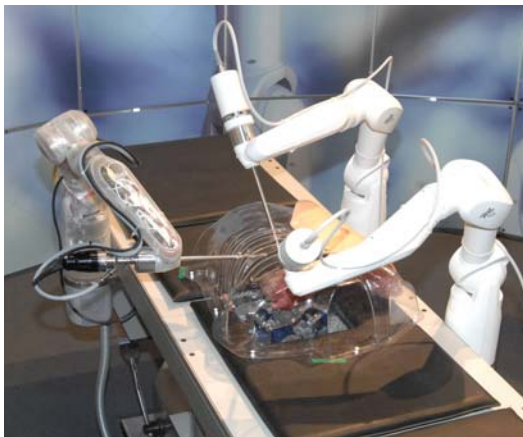


Fig. 2 The MIRS robotic setup integrating three MIRO robots, two MICA instruments, an endoscopic stereo camera and the heart simulator



Fig. 3 The MIRS remote master station with two haptic devices and a user testing the force feedback with a beating heart

The surgeon controls the motion of the instruments and robots by a remote master station with haptic handcontrollers and a 3-D display (Fig. 3). In addition, the manipulating forces exerted are rendered as so called force-feedback. The haptic interface is realised as shown in Fig. by the integration of two “omega.7” devices (Force Dimension, Switzerland). The whole setup with three MIRO, two MICA, and two haptic devices has 41 DoF.

3 Publishable results

Dissemination activities of the results of the ACCUROBAS project are organized into three main areas: education, academic, and industrial. Educational dissemination refers to the development of schools on robotic surgery and the development of appropriate courses and/or curricula addressing the needs of this subject. Academic dissemination is done by publishing the project results to scientific journal and by participating to conferences and special sessions in the field. Finally, industrial dissemination will address the needs and interests of the two communities of potential users and developers of the project results.

To reach these goals, a plan of dissemination has been drafted and carried out by each partner. This plan includes participation to conferences and interaction with medical advisors as the first group of potential users. Also, contacts have been established with potential industrial stakeholders, who have shown significant interest in the potential capabilities of the system. In the following, the main dissemination activities of each partner are briefly summarized.

Knowledge dissemination and management

Three instruments are used to provide the public with the developed knowledge of the project: continuously updated project web site, yearly revised project brochure and project posters for conferences and workshops. For internal usage of the partners a project repository was established for the distribution of software, publications, presentations and multi-media.

Academic dissemination

For academic dissemination the project results have been published at scientific meetings (51 contributions) and in journals (7 papers) and books, starting with series of survey articles. The consortium also organized various special sessions and workshops in association with international conferences in the field of robotics, and computer assisted surgery.

Industrial dissemination

The consortium was active to get in contact with medical technology companies. An Industrial forum was organized in the form of a workshop with enterprises, which are active in advanced surgical equipment and robotics. For companies which are interested in developing add-ons and extensions a developer group was organized. To interact with the user community a user group was established.

Educational dissemination

Curricula were developed to include some of the concepts compiled in the project. The project partners also contributed extensions to the curricula of other European high education institutions. The project concepts and results were presented during two summer schools in Montpellier, 2007 and 2009.

Project sustainability

Based in the excellent results and the cooperation in the project a new FP7 EU project called SAFROS (Safety in Robotic Surgery) was proposed and approved and will start in January 2010. A spin-off company for modelling, simulation and training in computer aided surgery called AltairMed was founded by University of Verona.