ROBOt and sensors integration for Computer Assisted Surgery and Therapy (ICT-2007-215190-ROBOCAST)

Elena De Momi, Pietro Cerveri, Giancarlo Ferrigno

Abstract—**The goal of the ROBOCAST project is to provide a system for the assistance of keyhole neurosurgery. The system envisages a human-computer interface (HCI), with an intelligent context-sensitive communication and a haptic-drive capability, a multiple-robot chain with redundant degrees of freedom and a hierarchical structure, an intelligent autonomous trajectory planner, a high level controller and a set of field sensors. The achievements of the first year are reported. The idea is being developed into a demonstrator for in vitro experimentation in the operating room (OR).**

I. Introduction

Despite being first introduced for neurosurgical intervention guidance, surgical robots have also been used for laparoscopy, prostatectomy, and orthopaedic surgery [1]. Davies [2] was the first to use an active motion robot for soft tissue surgery in early 1991 (the forerunner to the Probot, which is currently used for transurethral resection of the prostate). In 1994, the Automated Endoscopic System for Optimal Positioning (AESOP) (Intuitive Surgical, Inc., Sunnyvale, CA) was developed to hold a laparoscopic camera and was voice activated [3]. The Zeus (Intuitive Surgical, Inc.) [4] and daVinci (Intuitive Surgical, Inc.) [5] robotic systems have successfully been used in cardiac surgery. Shoham et al., [6], [7], presented a new approach to robot-assisted spine and trauma surgery in which a miniature robot was directly mounted on the patient's bony structure near the surgical site. The robot was designed to operate in a semi-active mode to precisely position and orient a drill or a needle in various surgical procedures. The integration of robotic technology into the neurosurgical OR advanced significantly with the adaptation of industrial robots to perform stereotactic tasks. In 1985 Kwoh et al. [8] used a modified Puma 560 industrial robot (Advance Research & Robotics, Oxford, CT) to define the trajectory of a frame-based brain biopsy. When the probe holder reached the target coordinates, the robot was locked in position and the power removed, making it actually a passive system. The surgeon then used the probe as a guide for drilling the bone and biopsy of the lesion. Minerva [9] was designed for stereotactic brain biopsy to meet specifications incorporating safety, geometry, and to perform single dimensional incursions into the brain with the patient placed inside an intra-operative Computed tomography (CT) system that supplied real-time imaging data to the robot. NeuroMate (Integrated Surgical Systems) is the first United States FDA-approved, commercially available, image-guided, robotic-assisted system used for stereotactic procedures in neurosurgery [10]. It has been successfully used in a frameless mode for movement disorder surgery, registration is performed using an ultrasonic system or X-rays. The PathFinder is an image-guided frameless six axis robot that provides a stable, accurate tool position platform for neurosurgery [11]. Fiducial markers are attached to the patient's skin before acquiring the preoperative data. The patient head is held in a Mayfield clamp, to which the robot is also rigidly attached. Since the brain is best visualized with magnetic resonance imaging (MRI), robotic systems compatible to work in this environment have been developed. Masamune et al. [12] designed an MRI-compatible needle insertion manipulator aimed at safety and compactness intended for use in stereotactic neurosurgery. The manipulator frame was manufactured using Positron Emission Tomography (PET) and ultrasonic motors were used for the actuators. The NeuRobot telerobotic micromanipulator has been used successfully to perform an endoscopic third ventriculostomy and dissection of the sylvian fissure in a cadaver specimen [13]. "Evolution 1" (U.R.S. Universal Robot Systems, Shwerin, Germany) is a neurosurgical tool for the steering of instruments within the cranium. Joskowicz et al. [14] recently proposed to mount MARS robot [6] on the head immobilization clamp or directly on the patient's skull via pins in keyhole neurosurgery.

Endoscopes usually used in neurosurgery, particularly ventriculostomy, are rigid and straight [15]. Recently steerable endoscopes have been specially designed and used in laparoscopic procedures [16]. Rigid endoscopes do not allow reaching the targets behind anatomical regions or directing the endoscope towards multiple targets avoiding damaging anatomical brain structures.

The increasing amount of imaging data offers nowadays new possibilities for surgeons within the OR. Preoperative data like CT and MRI allow for detailed anatomical information. Intra-operative imaging like X-ray fluoroscopic C-arms and (regular, endoscopic or intra vascular) ultrasound (US) are increasingly used in the OR for providing real-time anatomical images [17].

The ROBOCAST project (FP7 ICT-2007-215190), 2008-2010, focuses on robot assisted keyhole neurosurgery. This term refers to a brain surgery performed through a very small hole in the skull called burr hole. The reduced dimensions are the reason why it is called also "keyhole".

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The ROBOCAST project outcome will be a system for the assistance of the surgeon during keyhole interventions on the brain. It will have a mechatronic part and an intelligence part. The mechatronic device will consist of a robot holding the instruments for the surgeon and inserting them in the brain with a smooth and precise controlled autonomous movement. The trajectory will be defined by the intelligence of the ROBOCAST system and will be approved by the surgeon, which is and remains the responsible of the outcome, before the insertion of the surgical instruments. The project is aimed at introducing robotics and Intelligence Augmentation (IA) in the OR, improving the Human Computer Interface (HCI) with haptic drive and feedback, providing the surgeon with an autonomous planner, increasing robots accuracy and reliability with redundant sensors.

II. The Project Consortium

TABLE I
THE ROBOCAST CONSORTIUM

Partner name	Logo
Bioengineering Department Politecnico di Milano, Italy http://www.biomed.polimi.it/nearlab	
Department of Neurological and Vision Sciences - University of Verona, Italy http://www.dsnv.univr.it/dol/main	
SIRSLab - Robotics and System Lab - University of Siena, Italy http://sirslab.dii.unisi.it/	
Department of Mechanical Engineering and the Institute of Biomedical Engineering, Imperial College, UK http://www3.imperial.ac.uk/mechatronicsinmedicine	
Prosurgics Ltd, High Wycombe, UK http://www.prosurgics.com/	
The Hebrew University of Jerusalem, Israel http://www.cs.huji.ac.il/~caslab/site/	
Faculty of Mechanical Engineering - Technion, Israel Institute of Technology, Israel http://robotics.technion.ac.il/	
Mazor Surgical Technologies Ltd, Cesarea, Israel http://www.mazorst.com/	
Institut für Informatik - Technische Universität München, Germany http://campar.in.tum.de/Chair/ResearchGroupCamp	
Institute for Process Control and Robotics - Universität Karlsruhe (TH) Germany http://wwwipr.ira.uka.de/	
CF Consulting - Finanziamenti Unione Europea S.r.l, Italy http://www.cf-consulting.it/	

III. The Project Objectives

The ROBOCAST objectives are five, and are herewith detailed:

A. Objective 1: Developing intelligence augmentation (IA) techniques and effective human-machine interaction.

Path planning is a key point in surgery as well as in autonomous environment exploration. In the neurosurgical field, intelligent planning collects and manages different sources of information (surgeon experience, sensors data and knowledge database), thus increasing the patient safety and improving the intervention outcomes. Surgical planning is negotiated with the surgeon by context-driven multiple-choice statements. This objective exploits IA techniques both for autonomous task execution and effective human-machine interaction.

B. Objective 2: Providing robots with autonomy (management of failures, negotiation of path execution, optical sensor management).

The system will be able to face unexpected events, as lack of reliability of sensors information and to decide whether to continue working in a safe but limited mode (down-graded mode) or to terminate operations (shut-down), based on the current reliability of position information.

C. Objective 3: Simulating small footprint robots, saving accuracy by feedback control loop and sensor/robot/robot cooperation.

The ROBOCAST system foresees a wide use of redundant sensors both for increasing system reliability and for compensating hardware and software inaccuracies, through a supplementary sensorial feedback. Calibration inaccuracies, typical of small footprint robots with large workspace, will be simulated by superimposing an error matrix (systematic error). Random error matrices will be also added for each of the 6 degrees of freedom.

D. Objective 4: Developing an effective interface between the user and the system and providing a strong integration in the OR.

The fourth objective is aimed at increasing the surgeon acceptance of the robotic system in the OR providing the surgeon with user friendly interaction (input via touch-screen and output via video and acoustic signals) and integrating of the system in existing instrumentation. The graphical interface with a context sensitive information display, predictive behaviour and intelligent augmentation, also improves operative time management.

E. Objective 5: Providing the system with modularity and flexibility characteristics to make it scalable and usable in different applications (surgical and industrial)

Last objective is the modularity, in terms of hardware and software, in order to allow re-using any module of the project into other applications and to facilitate maintenance and repair in the highly demanding surgical application.

IV. The Expected Outcome

The expected result is the assessment of the developed prototype (Fig. 1) on the third year of the project with in-vitro tests. The system will fulfil the following outcomes:

A. Exploitation of autonomy of robots and IA techniques for path planning.

The robots must autonomously reason on failure and decide whether to continue operating in down-graded mode or quitting operations in case of sensors accuracy degradation and of unexpected force sensing during the probe advancement in the brain.

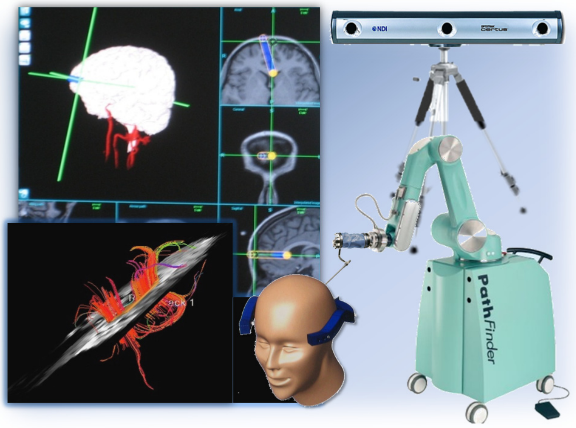

Fig. 1. The ROBOCAST concept: on the left the advanced visualization window, where pre-operative medical images are shown together with other relevant information. On the right, the serial robot (GP) is carrying a parallel miniaturized robot (FP) which is holding the linear or the curvilinear probe [19]. On the top right, the localization system is surveying the whole system, providing a robust feedback control.

Also, the surgical planner must allow the automatic computation of the trajectory of a the surgical probe minimizing the risk for the patient. The plan is based on medical images registered on a labelled anatomical atlas, indicating brain structures and values representative of the risk of damaging particular brain areas or tissues: vascular, fibres, functional areas. Propositions (quasi natural language sentences) are also assigned to homogeneous groups of voxels, thus developing a fuzzy knowledge database derived from the surgeon experience. Such knowledge base is processed by the inference engine that interprets the patient-specific atlas and helps in solving possible conflicts in the optimal trajectory search.

B. Modification of traditional surgical instrumentation to be adapted to robotics.

The flexible probe will carry surgical instruments or optical fibres inside. The biomimetic approach herein proposed uses a probe split into reciprocating parts that actively contribute to the advancement requiring a minimal inward push, so avoiding buckling and therefore tissue damaging. The probe consists of two halves in one shaft, therefore it can act as a needle with two different bevels of the same angle on different sides. A different steering system to trace curved trajectories is obtained. Three reciprocating parts at minimum would be required for a 3D trajectory. In the ROBOCAST project, a 2D demonstrator (i.e. a curved path in a plane) is foreseen [18].

C. Respect of safety demands of the surgical room.

Robots closely interacting with humans and deeply integrated in the surgery space have to be safe and robust to fault tolerance. Therefore the ROBOCAST project is aimed at answering at the dependability technological challenge because of its redundant control scheme. Information coming from sensors allows it to have accurate and robust control: optical and electromagnetic localization devices, which act as visual sensors feedback system, force sensor, which provides the surgeon of the brain resistance sensation, and ultrasound (US) system, which intra-operatively updates the operation plan.

D. Haptic feedback information.

The interface of ROBOCAST is endowed with a haptic device used to convey to the surgeon the resistance of the brain parenchyma to straight probe advancement. Amplification of linear motion and/or force will be provided. The force feedback information comes from the load cell sensing the force experienced by the tip of the probe during the advancement under linear actuator control.

E. Simple and intuitive interface with the surgeon, integrated with advanced virtual and augmented reality techniques.

This task aims at providing the surgeon with the possibility to easy and intuitively plan surgery, interact with the system and to update plans. Man-machine interfaces must allow for efficient and safe user-robot interaction for improving augmented reality immersive environment and surgeons system acceptance..

V. The Achievements So Far

Since the beginning of the project (January the 1st, 2008) the following activities have been carried out toward the accomplishment of the aforementioned objectives:

User requirements were designed in order to define the current status of keyhole neurosurgery workflows, to address the possibilities of using the ROBOCAST surgical robot system, to give an input to the definition of the system specifications and to guarantee the satisfaction of the end users at the end of the project. Three paradigmatic scenarios were chosen for the demonstration of the system. Two of these are nominal (biopsy and multi-target treatment) while the third will be considered in the case of failure of one of the others or resources left (deep brain stimulation-DBS). Questionnaires (qualitative and quantitative) were submitted to relevant users in the neurosurgery field. At the end of the activity, the user requirements list and the ROBOCAST surgical workflow were defined.

System specification were defined, from the end user requirements. The system architecture was designed (Fig. 2). The result of the activity is the specification document, where a high level definition of the full system is followed by an outline description of each subsystem and then a detailed specification of subsystem components. The robot system is foreseen to be a proof of concept model, designed for evaluation on phantoms and cadavers only. It is not intended to fulfil the CEC Medical Device Directive for clinical use. Risk estimation in requirements meeting was produced, including the evaluation of the impact on system performance and the mitigation actions. Formats for test protocols were designed.

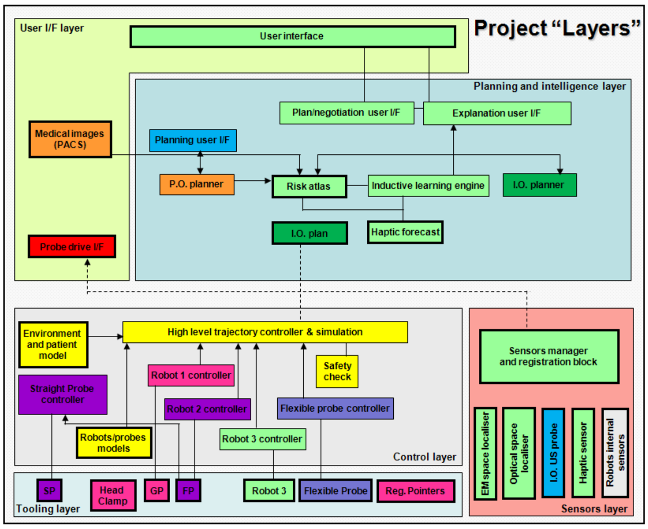

Fig. 2. The ROBOCAST architecture.

An integrated modular robotic system with a hierarchical structure, including two modified commercial robots (PathFinder, by PROSURGICS Ltd. and a parallel micro-robot produced by MAZOR Surgical Technologies Ltd.) and novel end effectors (a linear actuator with haptic feedback and a biologically inspired flexible probe) is being developed. Preliminary designs of linear actuator and of flexible probe were produced and tests on materials and geometries are being carried out. Best design for the haptic feedback controller was explored with a robot-sensor based mock-up. All common hardware and software interfaces will be designed in order to be consistent and robust, which in turn will ensure a streamlined integration process.

Software framework is being designed for preoperative and intraoperative planning. A preliminary workflow was designed including multi-mode medical images processing and surgical planning based on brain atlases. The plan can be intra-operatively adapted based on ultrasound (US) images taken from burr hole and by Doppler modality.

The high level control (HLC) of the robots is dealing with trajectory planning, obstacle avoidance, redundancy management and on the linear path planning inside the brain. The intelligent planner is under development, with two different implementations, it is already able to compute the probe trajectory on the basis of the numerical risk information. Logical constraints and surgeon interface for information upgrading (negotiation and debriefing) are under development.

To facilitate system integration, which will start in October 2009, and assure system modularity, an interface control framework has already started, specifying mechanical and electrical interfaces, as well as software platforms (operating systems, compilers, APIs, CADs, medical images processing software) and communication protocols. In order to cooperate in the software development, a central repository was implemented, allowing partners to use updated software codes.

VI. The Automatic Trajectory Planning

The ROBOCAST system envisages a tool for automatic planning of the best probe path inside the brain, based on the minimization of the patient risk and based on surgeon-dependent rules, stored in a knowledge repository. This approach could as well be used in environment navigation, when risk factors are known and can be incrementally updated. The risk of damaging brain structures comes from crossing important anatomical regions (e.g. the ventricles, the pituitary gland), functional areas highlighted with fMRI analysis (e.g. visual, motor function, Broca's area), blood vessel that become visible through Magnetic Resonance Angiography (MRA), fibre bundles that are tracked on Diffusion Tensor Imaging (DTI) and the target volume (such as the lesion, during biopsies or micro dialysis fluid sampling), which is outlined on T1 MR images. All the aforementioned structures constitute a subject-specific map which has to be considered during planning. The path planning algorithm computes all possible paths from each selected entry points to the selected target inside the patient's brain.

The target point is manually chosen as 3D point in the T1 MR space. The allowed entering regions on the skull are manually selected by the surgeon on the patient specific head surface (outlined on the T1 MR images). This represent an heuristic input allowing to reduce the searching space and spare computation time. The voxels of these regions represent hard constraints for the automatic trajectory computation.

The cost function (CF) to be minimized depends on the risk factors both linearly and non linearly (through a threshold value):

$$\begin{aligned} CF(N, x_e, y_e, z_e, x_t, y_t, z_t) &= \lambda_1 \sum_{i=1}^{N} R_1(i) + \\ &+ \lambda_2 \sum_{i=1}^{N} R_2(i) + +\lambda_3 \sum_{i=1}^{N} R_3(i) + \lambda_4 \sum_{i=1}^{N} R_4(i) + \lambda_5 \sum_{i=1}^{N} R_5(i) + \\ &+ \lambda_6 \sum_{i=1}^{N} (R_1(i) > th_1) + \lambda_7 \sum_{i=1}^{N} (R_2(i) > th_2) + \lambda_8 \sum_{i=1}^{N} (R_3(i) > th_3) + \\ &+ \lambda_9 \sum_{i=1}^{N} (R_4(i) > th_4) + \lambda_{10} \sum_{i=1}^{N} (R_5(i) > th_5) \end{aligned} \quad \textbf{(1)}$$

R_j indicates the *j-th* risk (1: vascular, 2: fiber, 3: anatomical, 4: functional, 5: target area value of the voxel *i* (x, y, z) crossed by the planned trajectory. λ values are representative of the importance of the represented structure:

hitting a vessel is more critical than crossing a fiber bundle. Those values are given by a priori initial guess agreed with surgeons and by an heuristic tuning based on test examples taken by images of surgeries already planned and executed, since no analytical way exists to determine those parameters. Each time the risk associated to a voxel on the path overcomes the threshold th_j, λ_j is added to the summation. These threshold accounts for very critical areas not to be crossed for long paths. N is the number of voxels belonging to the trajectory starting from the entry point (x_e, y_e, z_e) and ending to the target point (x_t, y_t, z_t), thus a minimum length criterion is implicit. The presence of many local minima does not allow using to use a gradient or simplex based algorithm. The first approach that was followed was an exhaustive search bounded by heuristic input. On the basis of first field tests a branch and bound approach on the solution tree will be added if the informed search will show to be more economical than the exhaustive, i.e. the time wasted for the tests along the branches and the added memory usage will lead to a significant reduction in the overall search time.

Starting from all the possible entry points on the head surface, the algorithm computes all the possible trajectories toward the selected target point, using a 3D extension of the Bresenham line algorithm, for each crossed voxel [19], which gives a discrete contiguous integer set of points for a given line.

The risk value is computed (using the cost function (1)). For each crossed voxels two checks are performed: whether it had been labelled as a NO GO region or if there are one or more propositions associated.

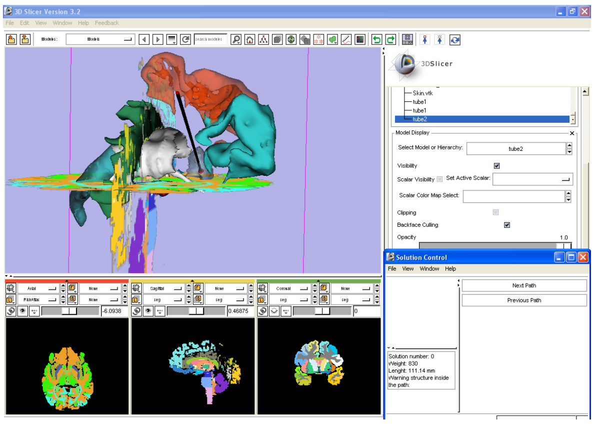

Fig. 3. The automatically computed trajectory .

In order to code surgeon knowledge and previous experience, a propositional atlas was developed. It allows the user to add propositions to all the labelled area (anatomical and target area). Fuzzy risk is coded as pseudo-natural language sentences easily understandable by the surgeon that can be created thanks to an intuitive interface. This interface includes pre-conditions, conditions, attributes and actions. Currently only one action: <avoid to cross> is defined and the attributes are only allowed to be <never> or <as long as possible>. This choice guarantees that no conflicts can exist, only redundancy can derive. In fact a rule containing <avoid to cross always> will dominate any other <avoid to cross as long as possible>. The latter, if referring to the same voxel, will be just redundant, but will not conflict. So a conflict arbitration is not necessary and at the moment a redundancy pruning has not yet been implemented. The atlas is mapped on the patient space together with the anatomical atlas. The rules are in fact associated to labelled voxels.

All the paths not discarder are ordered with increasing risk values and, for equal risk values, with increasing length. All the possible path are presented in the 3D and in the 2D visualization environments to the surgeon, together with information regarding the path risk, length, and possible warning messages (derived from the stored explanations of the propositions). The user could add new propositions to the knowledge database.

VII. The Impact of the Project

All the activities proposed in this project specifically address the issues of effective medical diagnostics and therapeutics, which will enable the development of effective diagnosis and preoperative planning for neurosurgery, the purpose of which is to make treatment quicker, less invasive, and more effective. In particular, the development of a biomimetic steerable miniature probe will enable a range of new surgical tasks (e.g. curved trajectories between an entry point and target lesion) which are currently impossible with today's technologies (Fig. 4). At the same time, the system will extend and refine the use of conventional instrumentation in the operating theatre through better

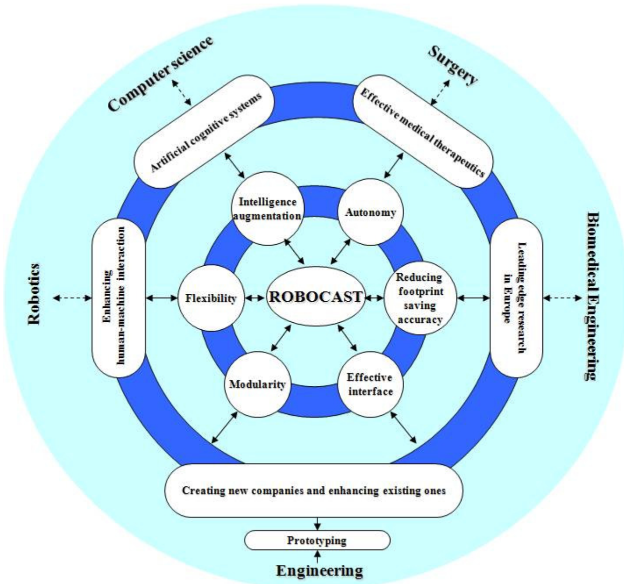

Fig. 4. The ROBOCAST impact.

targeting and enhanced haptic perception.

The integrated approach to planning, intervention, and assessment put forward in the study will also ensure products that provide a rapid training process for medical practitioners, which will deliver consistent high quality surgery from relatively inexperienced surgeons. This approach will also play a key role in the training of future medical staff by providing a systematised and structured workflow in addition to enhanced precision of interventions.

The ROBOCAST project is expected to widen and accelerate the safe use of medical robotics, while the methods to be developed will be applicable to other non-medical domains. The advanced safety protocols and strategies will be particularly of benefit in those non-medical applications where robots are used in close proximity to humans e.g. military and defence, search and rescue, and robotic systems for the home.

Differently from past experience with surgical robots used in neurosurgery, the ROBOCAST project aims at realizing a durable alliance between existing companies (PROSURGICS and MAZOR) in order to start and then strengthen a new market totally devoted to surgical robotics. Currently, the two involved SMEs are watching developments with interest, and may be able to incorporate some of the technology into their product ranges: P5-PROSURGICS is interested in developing its product range through diversification to new areas of therapy and through upgrading the technology of existing applications and it is possible that some of the concepts under development in ROBOCAST may be licensable for direct incorporation into the next generation of surgical robots. PROSURGICS expects to engage in active discussions with the partners involved to explore ways in which these advances in technology demonstrated in ROBOCAST can be implemented into a new generation of image guided surgery robotics. MAZOR products (SpineAssist and C-Insight) can benefit from the technology developed in ROBOCAST since they are overlapping in many respects. Also the flexible probe developed within the consortium is possible add-on to MAZOR 's robot for neurosurgical applications. In a long scale prevision, we foresee other companies and industries in Europe could import the ROBOCAST mutually agreed public interface (e.g. motion, monitoring commands, constraints specification) for interaction among the different components of the integrated system. Taking advantage of public modules of our prototypal system, it could be easily estimate that robotics market will receive a deep push towards the competitiveness increase auspicated in EUROP platform .

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