DLR MiroSurge – towards versatility in surgical robotics

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Abstract:

Surgery is a rapidly evolving field of applications for robotic systems. Different surgical applications, techniques and workflows as well as varying operating room setups and control methods can be realised by separate specialised robotic systems. In contrast, the DLR MiroSurge robotic system focuses on the aspects of versatility and modularity for a broad range of surgical applications. It combines three DLR MIRO robot arms with specialised endoscopic instruments, endoscopic stereo vision and a bi-manual control interface with force feedback for the surgeon. The integration into different operating room setups is simplified and the safety of the system is enhanced by its lightweight and compact design. Additionally, pre-operative planning software supports optimised setup of the robotic system in the operating room regarding singularity avoidance, maximum workspace and best dexterity.

key words: telerobotics, versatility, force feedback, 3D vision, lightweight

1 Problem

Surgical robotic systems can be divided into two major groups: specialised and versatile systems. Specialised systems focus either on a dedicated surgical technique, like endoscopic surgery [1], or on the treatment of a specific medical disease (e.g. cancer [2]). These systems fulfil the dedicated task very well. However, their amortisation and achieved benefits are linked to single medical procedures. On the other hand, today's versatile systems often base on the adaptation of industrial robots [3]. The standard manipulator design of industrial robots is targeted on high absolute accuracy which is achieved by stiff structures and thus relatively high mass. Safety and adequacy in the crowded and difficult to predict environment of an operating room combined with close human robot interaction are questionable.
In contrast, the research on surgical robotics at the DLR Institute of Robotics and Mechatronics focuses on versatility and lightweight aspects of robotic components to grant adaptability for a broad range of surgical applications and simplified integration into the operating room. One configuration of these components is the DLR MiroSurge telerobotic system targeted for applications in endoscopic surgery (Fig.1).

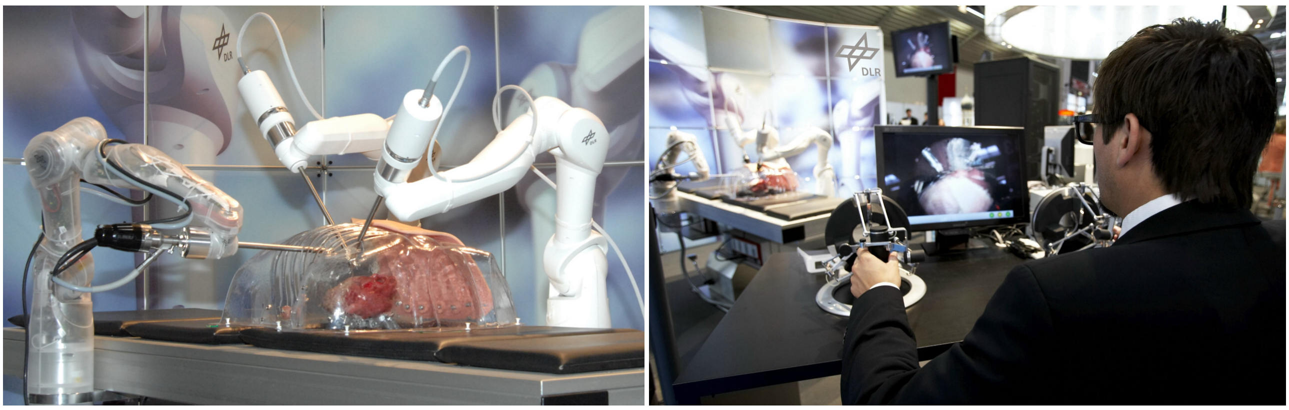

Fig. 1: The DLR MiroSurge telerobotic system for endoscopic surgery

2 Methods

The core component of the DLR surgical robotics research is the DLR MIRO robot [4], the second generation of DLR robot arms for medical applications. It has been designed to achieve the requirements of a broad range of surgical applications. By adding specialised instruments the MIRO robot can be adapted to specific applications in endoscopic and open surgery. Moreover, integrated multi-modal sensors and different control modes allow system configurations for telepresence as well as for autonomous (e.g. navigated laser osteotomy) and soft robotics [5] applications. To simplify the integration of the robotic system into the operating room, the design of the components aims at compact dimensions and low weight.

One important factor beside the functionality of a surgical robotic system is the aspect of safety, especially during close interaction with patient and user. The reduction of accelerated masses (robot and instrument) through lightweight design and the application of enhanced control methods reduce significantly the severity of collisions between man and machine [6]. Application specific software is used to adapt the robots to different surgical interventions. Rapid prototyping enables quick implementation of software prototypes for control. Established software components are embedded in this rapid prototyping process. Therefore new medical applications can be developed in reasonable time.

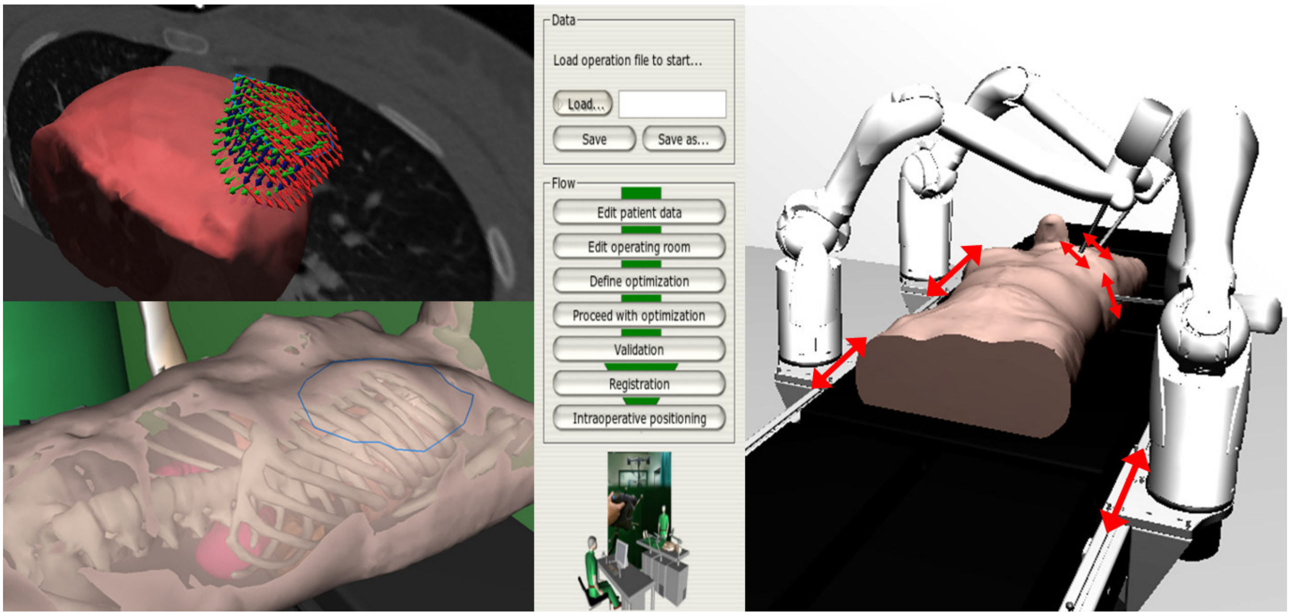

Fig. 2: Preoperative planning environment

Planning Software as shown in Fig. 2 calculates optimized setups in the operation room and leads through the setup procedure: The surgeon coarsely provides areas for entry points and operating field (left), and an optimization algorithm determines according optimal positions for the robot bases and entry points into the patient (right). Markerless surface based registration and a new localization method [7] then allow the user to establish the optimized setup in the operating room.

3 Results

With the first prototype of the DLR medical robot KineMedic, successful experiments were carried out for tasks such as navigated pedicle screw placement [8] and biopsies [9]. The versatility of the components can be further shown by the DLR MiroSurge setup described in the following and summarised in table 1. DLR MiroSurge (Fig. 1) is a configuration with three MIRO robots for telerobotic endoscopic surgery providing bi-manual 6 DoF (degrees of freedom) manipulation of the surgical grippers inside the patient's body, force feedback, and stereo vision. The DLR MIRO robot arm integrates 7 joints with dedicated torque sensors. With its space saving design (kinematic arm length 760mm; shoulder joint to flange) and its low weight of below 10kg the setup of three or more arms at the operation table is simplified. In the setup shown in Fig. 1 (left), one MIRO robot is equipped with a stereo endoscope, while the two other arms guide the DLR-MIS-instruments (Minimally Invasive Surgery instruments) [10]. These specialised endoscopic tools cover two main tasks: full dexterity inside the patient's body and sensing manipulation forces/torques. To achieve full dexterity inside the patient's body despite the limitations through the trocar point, the instruments can be angled distally in two DoF.

An additional functional DoF allows tissue manipulation within the working space in any arbitrary pose. To measure reliable manipulation forces/torques a miniaturised 6 DoF force/torque sensor is integrated in the distal end of the instruments. Gripping forces are additionally measured distally, largely independent of manipulation forces/torques. Two common tasks were considered to determine the required resolution and measurement range for the force/torque sensor. A force of up to 0.2 N along the needle tip was required to insert a commonly used suture needle (Ethicon Prolene 6-0 "C-1", 3/8th circle, 5.5 mm radius, round body) into muscle tissue. This manipulation force has to be displayed with sufficient resolution to convey the surface penetration and needle insertion to the user. As upper bound the tying of sutures and holding of needles were considered for manipulation and gripping forces respectively. Optimal suture tying forces can reach up to 4 N [11] and grasping forces for securely holding a needle can exceed 10 N. Therefore, the force/torque sensor is currently designed for a usable measurement range of ± 10 N and a resolution of approximately 0.02 N.
The surgeon tele-operates the system by a remote workstation equipped with haptic hand controllers and stereo vision. With the haptic interfaces the surgeon guides the instrument tips in 6 DoF and with accurate hand-eye coordination. An additional DoF actuated by one finger is used to control the functional degree of the surgical instruments. The manipulation forces/torques measured at the tip of the instrument are returned to the surgeon as force feedback by the hand controllers.
Since direct access to the operation site is lost for minimally invasive surgery, visual feedback to the surgeon has to be provided by an endoscopic camera system. To achieve 3D vision as in open surgery, a stereo endoscope is used. The stereo image stream is captured by a video server. The resulting stereo image stream can be distributed via Ethernet to a flexible number of clients. This client-server approach enables the easy integration of various 3D output devices, e.g. standard 3D displays with special glasses, ocular systems or autostereoscopic displays. The autostereoscopic display integrated in MiroSurge provides 3D vision without the need of special glasses and enables free movement of the viewer by tracking the position of the eyes of the viewer in realtime. Moreover, the stereoscopic image stream can also be used to implement vision-based control applications, e.g. instrument tracking for automated camera guidance [12] or tracking of organ movements for motion compensation [13]. In the application scenario of automated camera guidance the task of the assistant surgeon directing the endoscope to the field of surgery is transferred to the robot. This can be achieved by automatically detecting the instrument position from the camera images and adjusting the robot arm holding the endoscope such that the instrument remains in a central image position. Compensation of organ motion can help to facilitate surgical procedures or to enable the performance of complicated tasks using minimally invasive surgical techniques. To achieve the goal of motion compensation, motion is detected from endoscopic images, which can then be used as a feedback to the robot system to compensate for this motion.

	Component	Parameters (per single component)
Telemanipulators	Three DLR MIROs	7 Degrees of Freedom
		Weight < 10kg
		Payload 30N
		Kinematic length 760mm (shoulder joint to flange)
		position, torque and impedance control modes
Instruments	Two DLR-MIS-instruments	2 Articulated wrist joints
		1 Articulated functional degree of freedom
		6 DoF force-torque sensor in the instrument's tip
	WOLF Stereo Endoscope	endoscopic stereo camera pair
Control interface	Two Force Dimension OMEGA.7	6+1 DoF (3+1 DoF with force feedback)
Display	SeeFront 3D	Autostereoscopic 3D Display

Table 1: Components of the DLR MiroSurge telerobotic system for endoscopic surgery

4 Discussion

The DLR MiroSurge system supports the key aspects of modularity and flexibility both in hardware and software design. Partitioning the robotic component of the system in versatile robot arms and specialised instruments simplifies the development of new setups, e.g. systems with more than three arms. The technologies developed in MiroSurge such as 6-DoF manipulation, force/torque measurement at the tip of the instruments, force feedback, versatile control modes and safety strategies can thereby benefit various surgical procedures.
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