CONCEPTS OF HUMAN-ROBOT COOPERATION FOR A NEW MEDICAL ROBOT

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ABSTRACT

In this paper, hands-on concepts for the new medical robot KineMedic are presented and exemplified through a biopsy application. Hands-on provides, by simply touching and moving the robot structure, a highly intuitive user interface for robot positioning. The KineMedic has an anthropomorphic structure with 7 DoF and is fully torque controlled. Due to the kinematic redundancy, the presented hands-on concept is particularly suitable since it allows not only for the TCP positioning but also for the adjustment of the robot pose. Furthermore, split duty is possible through the implemented control structure, i.e. motions commanded by the user through haptic interaction can be mapped into a space of user-controllable motions both in Cartesian and joint space, whereas the remaining motion space is controlled by the robotic system.

1. INTRODUCTION

Currently the interaction of human and robot is in most industrial applications prevented by safety measures. However, potential advantages of close cooperation between human and robotic systems are evident and intensively investigated in research fields such as service robotics or medical robotics. One goal is to combine the strengths of human and robot. Humans are e.g. able to utilise qualitative information and to evaluate unclear information whereas robots provide high accuracy and various control schemes and can apply defined forces.

This work presents a robotic system that assists the surgeon as an *intelligent stand* in tasks such as biopsies and the navigated drilling of pedicle screws [1]. The robot can be repositioned by simply touching and moving the robotic structure (see Fig. 1), and the surgeon is then assisted in guiding the robot to the preoperatively planned position by means of virtual fixtures. Patient safety is increased through virtual safety barriers during robot removal. Experimental results suggest that these hands-on concepts clearly augment the quality of task execution [2].

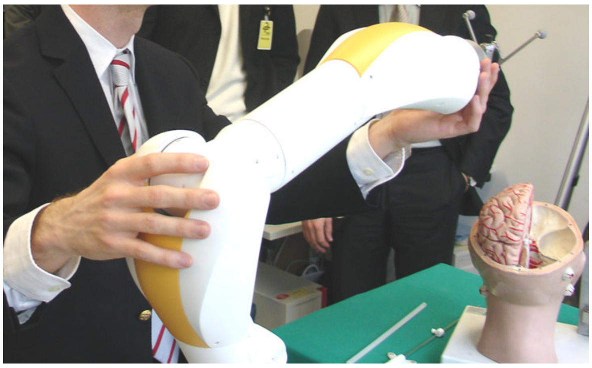

Fig. 1. Hands-on the medical robot KineMedic.

A detailed description of various systems for medical robotics is given in [3]. The systems can be classified according to their degree of autonomy: tele-operated systems [4, 5] are exclusively controlled by the surgeon, and certain autonomy functions such as tremor filtering or motion compensation [6] can possibly be added. Semi-autonomous systems share the task execution between surgeon and robot, see e.g. the independant alignment of the robot-guided instrument with a located tumor [7], the active constraint robot *AcroBot* for knee endoprothetics [8], or the system presented in this paper. Completely autonomous systems, providing e.g. fully automatic endosope guidance via real-time image processing [9], are available as well. However it has been reported that acceptance by surgeons increases if they are closely included into the workflow and especially into the decision making [8]. Additionally to [8], the presented hands-on concept also allows for configuration of the robot pose and needs no additional handle, since the robot structure can be touched wherever it is convenient for the user (see Fig. 1). This is possible through

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the control schemes presented in [10, 11, 12, 13] and summarized in this paper.

Section 2 states the proposed method, implementing torque sensors integrated in the joint units and impedance control. It aimes at combining the strengths of human, robotic system and navigation. Results obtained for the medical procedure biopsy are given in Sect. 3. Section 4 concludes the article with an outlook to future work.

2. PROPOSED METHOD

During a biopsy, tissue specimens are taken from the patient for examination. The tissue is often taken from a lesion when the cause of a disease is uncertain or its extent or exact character is in doubt. Vasculitis, for instance, is usually diagnosed on biopsy. Additionally, pathologic examination of a biopsy can determine whether a lesion is benign or malignant, and can help differentiate between different types of cancer. To locate the target area for the biopsy, either online imaging modalities such as ultrasound or fluoroscopy can be exploited, or a preoperative planning can be carried out, usually based on tomographic data of the patient. In the latter case, after registration the planned positions have to be transferred into the operating room. This can be done e.g. by tracking the (manually held) biopsy needle, leading however to errors due to tremor, fatigue and the required complex multi-axis motion. These errors could be avoided through a combination of robot and navigation system, and robot-assisted therapy may therefore close the gap in the flow of information between therapy planning and therapy execution. The data gained from navigation can be optimally and directly integrated into the therapy with clearly increased accuracy, using concepts as e.g virtual fixtures. Figure 2 shows the experimental set-up with the new medical robot which was built at the DLR. The medical robot is equipped with a guide jacket to align the biopsy needle (see Fig. 3). On the one hand a precise guidance of the needle is guaranteed, on the other hand the surgeon receives a straight haptic feedback of the insertion forces. Furthermore, the responsibility of the intervention is left to the surgeon, the robot acts as an intelligent stand. The robot control is coupled with the navigation system via a TCP/IP connection. The stereo camera of the navigation system tracks both the registered target and the three-marker array attached to the robot tool tip. Based on this information the navigation system calculates the relative pose of the target with respect to the tool tip coordinate frame and sends the data continuously to the robot.

In the following sections the robotic system is introduced, including the chosen kinematic structure, the integrated sensors, and the robot control.

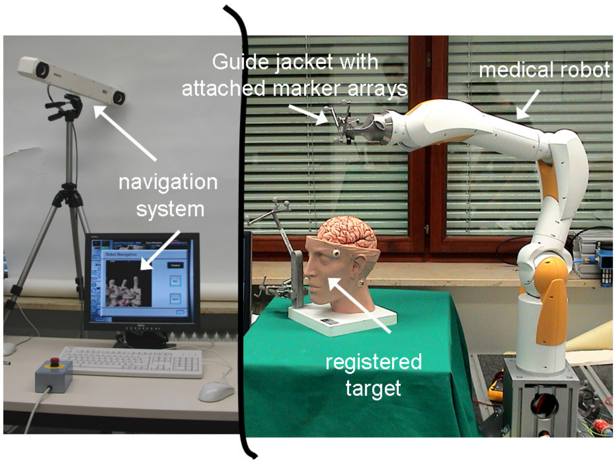

Fig. 2. Experimental set-up for the navigated biopsy with the medical robot KineMedic and the BrainLAB VectorVision navigation system.

Fig. 3. Guide jacket and biopsy needle with attached marker arrays.

2.1. Robotic system

The medical robot has a slender design to comply with the very restricted space in the operating field and the tight interaction of the surgeon with the robot. As the robotic arm represents an additional system near the operating table, the already extremely limited space thus becomes even more restricted. A slender, compact arm reduces the space conflicts (e.g. risk of collision) and thus increases the acceptance of the robot by the surgeon. According to previous experience at the Institute of Robotics and Mechatronics in the field of lightweight robotics (LWR I-III [14]), the medical arm exhibits (a) joint redundancy: a flexible setup in the space-confined operation environment is ensured by 7 joints, (b) torque-controlled joints that enable direct haptic interaction, (c) a robot weight

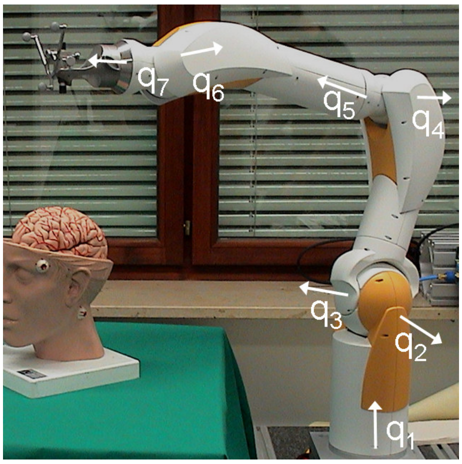

Fig. 4. The kinematic structure of the KineMedic.

of approx. 10 kg that allows a simple handling of the system and reduces the potential risk of injury by collision due to low inertia, and (d) safety of the system by means of sensor redundancy. The joints of the medical robot consist of motors and gears, link side torque and position sensors, as well as motor side position sensors and safety brakes. On the one hand this raises the system safety by the use of redundant sensors, on the other hand the sensor values are needed for the control described in Sect. 2.2. A compact and slender joint grouping was derived: Whilst the lower joint unit has three intersecting axes (roll-pitch-pitch), the other two joint units have two intersecting axes each (pitch-roll), see Fig. 4. The intersecting axes in the joints contribute to a simplified robot control as the inverse kinematics of the robot arm has an analytical solution. In all robot joints a special motor developed by the DLR (DLR-RoboDrive [15]) is used which was optimised for application in robotics with respect to its weight and electrical losses. In contrast to the established industrial robots, the power electronics of the motors are located directly in the robotic arm and not in an external control unit. This brings advantages for the electromagnetic compatibility (EMC): the EMC-problematic cable currents of the motors are generated near the motors and no long transmission cables through the whole robot arm are necessary. The integrated power electronics in combination with the fieldorientated control allow an optimal use of the specialized motors.

2.2. Control scheme

In the following the impedance control scheme for the medical robot is outlined shortly. For this in particular the joint flexibility due to the *Harmonic Drive* gears of the n joints is relevant. Accordingly, the reduced flexible joint robot model from [16] is considered. Since the medical robot is equipped with sensors for the joint torque $\tau \in \mathbb{R}^n$ in addition to the common motor position sensors this allows to measure[1] the complete state of the robot. The link side position $q \in \mathbb{R}^n$ and the motor position $\theta \in \mathbb{R}^n$ are related to the joint torque via the diagonal joint stiffness matrix $K \in \mathbb{R}^{n\times n}$ by $\tau = K(\theta - q)$.

The controller design for the medical robot is based on the concepts developed for the DLR lightweight arms [12, 13, 17]. Therein a passivity based approach was followed which endows the controller with advantageous robustness properties. The controller basically consists of two cascaded loops (see Fig. 5). In an inner loop a torque feedback controller of the form

$$\tau_m = \tau_d - K_\tau(\tau - \tau_d) - K_s\dot{\tau} \qquad (1)$$

with positive definite gain matrices $K_\tau \in \mathbb{R}^{n\times n}$ and $K_s \in \mathbb{R}^{n\times n}$ is used for computing the commanded motor torque τ_m. The vector $\tau_d \in \mathbb{R}^n$ is an intermediate control input corresponding to the desired torque from an outer loop impedance control law. In [12, 13] a detailed analysis[2] of this type of impedance controllers is given.

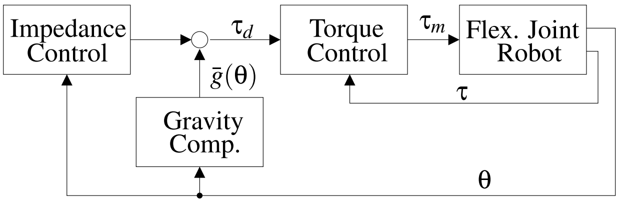

Fig. 5. Impedance controller structure for the medical robot.

The purpose of the inner torque feedback loop is twofold. On the one hand, the torque feedback causes a decrease of the effective motor inertia for forces acting on the link side [12]. Thereby it enhances the vibration damping effects of an additional outer control loop. On the other hand it also diminishes the effects of motor side friction since the joint torque sensors are placed on the link side. Consequently, the torque controlled robot becomes very sensitive with respect to forces applied by the user at any point on the robot structure.

In addition to the inner torque controller an outer loop compliance behavior for the link side positions q can be designed as follows. It is assumed that the desired compliance can be described by a suitable potential function $V(q)$ together with an appropriate positive definite damping matrix $D(q)$. In the following it is shown how this link side compliance can be combined with the underlying torque controller under consideration of the joint flexibility. Therefore, a *quasi-static* approximation $\bar{q}(\theta)$ of q is computed which is a function of the

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[1] Let us assume that the first time derivatives of the motor and link side positions can be determined by appropriate filters.

[2] Therein a physical interpretation of the inner torque feedback loop was given in the sense that it scales the effective motor inertia from B to $(I + K_\tau)^{-1}B$. This physical interpretation of torque feedback can be seized for the stability analysis.

motor side position only. According to [17] this function $\bar{q}(\theta)$ can be chosen as the solution of

$$\tau = K(\theta - q) = g(q) - \frac{\partial V(q)}{\partial q} \qquad (2)$$

for q, where $g(q)$ are the gravity torques acting on the link side. This equation ensures that statically the gravity compensation as well as the desired compliance relationship is fulfilled. Based on $\bar{q}(\theta)$ the input τ_d for the underlying torque controller is given by

$$\tau_d = g(\bar{q}(\theta)) - D(\bar{q}(\theta))\dot{\theta} - \left(\frac{\partial V(q)}{\partial q}\right)_{q=\bar{q}(\theta)} . \qquad (3)$$

More details on how to solve (2) and the stability and passivity properties of this controller design can be found in [17].

3. EXPERIMENTAL RESULTS AND DISCUSSION

In order to ensure a safe medical application, a workflow (i.e. a sequence of modes) was developed which is described in detail in the following. Before starting with the intervention, the biopsy is planned based on patient specific tomografic data, i.e. the target location as well as the access are defined. The patient is then registered with respect to the attached tracking markers by means of a surface based method: surface points on the head are collected with a tracked pointer and then matched to the CT data. Registration of the guide jacket is not necessary since the attached markers have a known relative pose to the robot tool tip.

The robot control is in different impedance-controlled states according to the mode commanded by the graphic user interface. The robot does not actively carry out any movements (with the exception of mode 4) but is guided manually by the user. Depending on the mode, only certain directions of movement along given trajectories are allowed.

Mode 1 (pre-positioning): From its starting position, the robot arm is freely manoeuvrable in all directions of the Cartesian space. In the presented application, the kinematics of the medical arm are not included in the preoperative planning. To guarantee that the operation is feasible, the surgeon can check if the surgical site is accessible in the current setup by simply moving the robot around. Alternatively, the optimal base position could be determined through the preoperative planning (see e.g. [18, 19]). This requires additional steps such as the localization of the optimal robot base position (e.g. through navigation) and the accordant positioning of the robot. Since however the considered setup is rather simple compared to e.g. multi-robot configurations in minimally invasive robotic surgery, the former approach is chosen. The user switches to mode 2 if the arm is pre-positioned.

Mode 2 (towards biopsy axis): The user-accessible subspace contains only translations along trajectory 1 (see Fig. 6) and rotations towards the target orientation of the needle axis according to the pre-planned biopsy axis (along trajectory 2) so that both axes coincide at interception point P. This is carried out by Cartesian impedance control, whereby the direction along trajectory 1 and towards orientation according to trajectory 2 shows zero stiffness and all other directions possess a high stiffness (see Sect. 2.2). On reaching the biopsy axis it is automatically switched to mode 3.

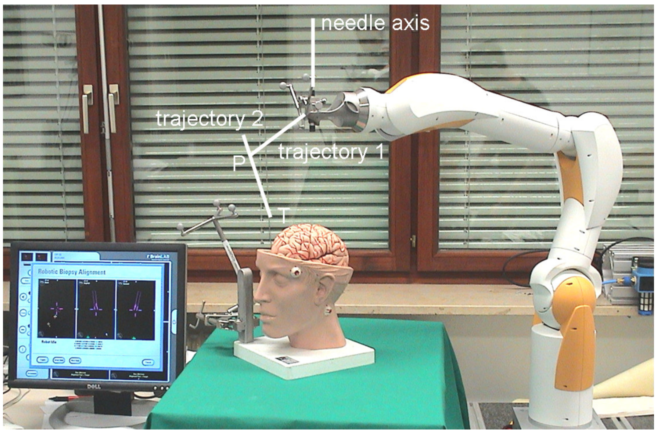

Fig. 6. Implemented workflow: The impedance controlled robot is manually guided by the operator to the target point T along automatically generated trajectories.

Mode 3 (along biopsy axis): After the needle axis is lying on the biopsy axis it is guided by the user along trajectory 2 to the target point T. The control is analogue to mode 2. Shortly before reaching the target point it is automatically switched to mode 4.

Mode 4 (fine tuning): The user now releases the robot arm. The robot can thus align the pose of the needle axis autonomously, without external disturbances and with highest possible accuracy, based on the current pose measured by the navigation system and the planning data. Since the biopsy needle is not yet inserted into the guide jacket, there is no contact between robot and patient. As the robot carries out movements independently and actively in this mode, speed and motion limits are very strict. The flow control allows switching to mode 5 only if the pose error lies within certain tolerances.

Mode 5 (biopsy): The impedance-controlled robot runs with maximum stiffness (this basically corresponds to a position control). The user now manually inserts the biopsy needle with the help of the instrument guidance. Since he directly operates on the biopsy needle, he receives straight feedback of occuring forces. The insertion depth is measured by the navigation system on the basis of the relative pose of the three-marker array with respect to the two-marker array (see Fig. 3) and displayed graphically to the operator. After the biopsy has been taken the needle is removed. The user then switches to mode 6.

Mode 6 (safe removal): The robot arm only allows movements along the biopsy axis - for safety reasons only away from the patient. As from 100 mm above the target point it is automatically switched to mode 7.

Mode 7 (free motion): The robot arm is now freely manoeuvrable again (as in mode 1). The vertical position, however, is restricted to 100 mm above the target point, whereby it is made sure that the robot tool tip can not come into contact with the patient.

4. CONCLUSIONS AND FUTURE WORK

This paper presents the hands-on concept of the new medical robot KineMedic. Direct haptic interaction between the operator and the kinematically redundant robot is possible through the torque sensors integrated into the joints, allowing not only for moving the tool tip, but also for configuring the robot pose inside the nullspace by simply touching the robot structure. By means of impedance control the operator is assisted in guiding the robot along automatically generated trajectories to the preoperatively planned target axis for the biopsy. Possible pose errors are captured by the intra-operative navigation system and corrected by the robot. Consequently, a precise intra-operative transfer of the operation planning into the operating theatre is possible - even by a less experienced surgeon. The insertion of the biopsy needle itself is carried out manually by the surgeon whilst the robot controls the correct pose of the biopsy axis. In this way the surgeon has full control over the workflow and can flexibly react in the case of unexpected events.

The medical robot KineMedic can serve as an *intelligent stand* in tasks such as biopsies and the navigated drilling of pedicle screws [1]. However, the robot is optimized to assist also in other medical applications such as e.g. minimally invasive surgeries [20], with at least two robotic arms holding instruments and one robot holding a stereo endoscope. The use of force-torque sensors near the instrument tips [21] will allow for measuring and eventually feeding back the manipulation forces, providing a better perception compared to manual minimally invasive surgery.

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