BOrEScOPE – Exoskeleton for Active Surgeon Support during Orthopedic Surgery

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Abstract— **The use of robots in a medical environment is a challenging task not only for system development but also for the actual application in this demanding environment. Robots are used to enhance surgery quality in terms of precision, application of new therapies, or to improve ergonomics - only to name a few reasons. The approach described in this paper is to provide a lightweight exoskeleton worn by the orthopedic surgeon. It is intended to be used during drilling tasks at the spine and to enhance precision as the surgeon is led by optic, acoustic, and haptic perception. The parallel flux of forces and the inherently mobile robot base allow the surgeon to directly maintain responsibility for surgery. Not only the mechanical design of the system but also the control is decomposed into several levels. To do so, a behavior-based approach is used. The system's design criteria are briefly described and first results are presented. The exoskeleton is composed of an anthropomorphic arm actuated by twisted-string actuators. This leads to a lightweight construction. To provide sufficiently fast and precise information about the spatial position and its time derivations, optical and inertial tracking is used. A User Guidance Opto-Acoustic Display is utilized to provide the surgeon with information on position and orientation of the tool in six degrees of freedom with respect to the desired trajectory. First experimental results derived that the intended workspace meets the surgical requirements and the user guidance system enables the surgeon to follow the desired trajectory by intuitive user guidance.**

Keywords- exoskeleton; orthopedic surgery, human-machine interaction; twisted-string actuation; behavior-based system decomposition

I. INTRODUCTION

Medical robotic systems for the use in the operating room (OR) have been under development for more than 20 years. Early systems for neurosurgery [1, 2] and orthopedics [3] proved usefulness and even made it for commercialization. However, their impact was not as high as expected [4]. In the last ten years, many new robotic systems have been developed and even introduced to the market. The most popular is the daVinci Surgical System by Intuitive Surgical, Inc., Sunnyvale, CA, USA. Nevertheless, there are hundreds of different systems and many reviews to learn more about the field of robotics.

Aim of our work is to develop and to design a robotic interaction system for orthopaedic surgery. Here, the surgeon has to fulfil delicate tasks like drilling the spine while maintaining high precision in the sub-millimeter range. Placing a robotic arm next to the OR table [5], the ceiling [6] or even on the patient [7] does not seem to be appropriate. Earlier work of our group showed the high potential of placing the robot in the user's hand [8, 9] to compensate tremor and involuntary movements both from surgeon and patient [10]. This robotic system provides precise movement and ease-of-use. However, its size and weight is not appropriate for longer deployment. Instead of using a passive balancing system we decided to develop a new system worn at the surgeon's arm near to his or her centre of gravity to improve ergonomic handling. In the following sections, we will present and describe the system's concept, basic components, the control strategy, and first results.

II. SYSTEM DESIGN

In this paper, we provide an overview of the BOrEScOPE system. It comprises an external optical high-speed tracking system for six degrees of freedom (DOF) position and orientation measurement fused with data from an inertial measurement unit (IMU), the robotic system including actuation and sensor systems and the mechanical part, the control hard- and software, and finally an opto-acoustic display unit for communication and user guidance. In the following sections, we will address these sub-systems and describe the control strategy.

A. *Robotic System*

The robotic system of the BOrEScOPE basically consists of an exoskeleton for the (right) arm of the surgeon including shoulder and wrist (Figure 1). All together seven degrees of freedom (DOF) are realized to provide good compliance with the human anatomy and the same dexterity. The range of motion of the shoulder (170° abd./add.; 150° flex./ex.; 180° inw./outw. rotation), elbow (100° flex.), and wrist (150° pron./sup.; 20° ulnar flex./ex.; 120° flex./ex.) joints has been derived experimentally. Shoulder elevation is not considered as the abduction angle is reduced to 80°. The arm is attached to a backpack that is carried by shoulder and hip harness.

To achieve a lightweight mechanism, the actuators are placed in the backpack and force is transmitted via Bowden cables. The actuators are based on the twisted string-concept [11], using a bunch of at least two strings that are drilled axially by a DC motor. This causes the string-arrangement to shorten and produces a rather high force. Using a lightweight ∅17 mm DC motor (1741 024 CXR by Faulhaber, Schönaich, Germany) with 8 mNm nominal torque and three strings, a force of 130 N can be produced. Also, no traditional gear reduction is needed leading to very quiet operation. As only pulling forces can be produced, an antagonistic arrangement is used. Sensors are deployed at the string actuator to measure shortening and at the actuated joint to provide precise angle information. Doing so, the elasticity of the Bowden cable is used to derive a series-elastic actuator (SEA) [12]. Prior work of our group showed good results using SEA in human machine interaction [13]. The inherent compliance allows zero-torque control and robust reaction to dynamic external forces. This reduced stiffness “feels better” than a conventional robotic arm.

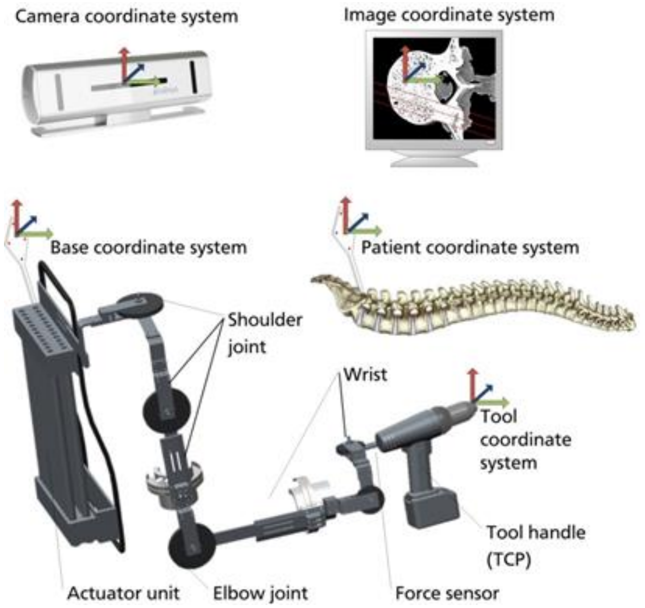

Figure 1 Overview of the robotic subsystem of the BOrEScOPE.

The system is designed to carry a 2.5 kg payload and compensate the gravity force of the human arm up to a body weight of 80 kg. Shoulder and elbow joints can provide speeds up to 6 rad/s. The static force to guide the user can be up to 10 N at the handle.

B. *Opto-Acoustic Display*

One of the challenges in developing a user-friendly Graphical User Interface (GUI) for the Human Machine Interaction (HMI) is to facilitate an intuitive operation and control of the technical system. The basic requirements are to reduce the possible error occurring during user interaction with the machine and to navigate the user. Since the tool position is influenced by the human tremor (frequency range of several Hertz), and since latencies in the feedback-loop must be avoided, a dynamical tool tracking is proposed, consisting of a combination of optical and inertial motion measurements. Based on these data the User Guidance Opto-Acoustic Display (UGOAD) is realized, which navigates the user to the goal pose (position and orientation), displays the processing trajectory, and gives a feedback of pose errors. Display and measurement latency has to be kept low to reduce phase shift in the feedback loop and to provide stable overall system behavior. The goal 6D poses as well as the processing trajectories are provided from planning data, which are defined by the surgeon using 3D patient imaging (CT). According to the requirements, a first UGOAD functional prototype was realized (see Figure 2).

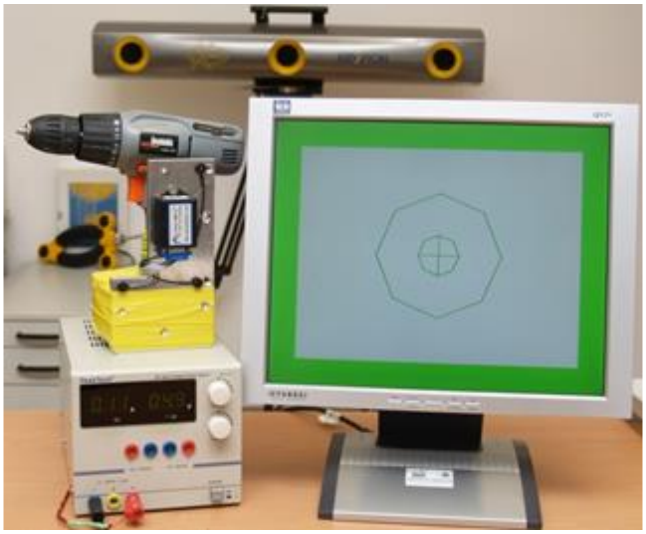

Figure 2 Experimental environment for the first prototype of the opto-acoustic display deployed in the BOrEScOPE system.

The experimental handheld drilling tool (Figure 2, on the left) was equipped with three active optical LED markers and an IMU device (Crista IMU, Cloud Cap Technology, Inc.). The monitor (Figure 2, on the right) can provide both optical and acoustic information. In the final implementation, a miniaturized screen will be attached directly to the tool. The optical tracking system (Krypton K600, Nikon Metrology, Inc.) (Figure 2, in the background) is used in addition to the Crista IMU to collect the motion data of the handheld device. Data fusion is accomplished using Kalman-filter based methods [14]. The resulting filtered variables for position, orientation, velocities, angular rates, and linear acceleration are utilized for navigation purposes and provided to the lower levels. In later development stages the complete handheld device can be mounted and aligned to the exoskeleton. The 6 DOF user navigation is realized by 2D representations of the tool pose on the UGOAD which is described below in detail.

C. *Control Structure*

The control system is developed according to Nested Recursive Behavior-based Control (RNBC) structure [15]. Accordingly, the hardware is realized as a number of components (Figure 3) interacting on diverse behavioral levels. In contrast to a one-to-one mapping of the behavior levels, one single behavior level can be distributed on multiple hardware components. Several behavior levels may be aggregated in one single hardware device. In the latter case, behaviors are realized as software processes. For the BOrEScOPE realization, the upper levels, i.e., *mission*, *navigation* and *trajectory control*, are realized as software processes integrated into a QNX-based (QNX Software Systems Ltd.) real-time PC. The behavior levels for *position control*, *collision avoidance*, *velocity control* and *force control* are realized using an embedded PC based on xPC Target™ (The Mathworks, Inc.). The xPC^{TM} Target PC is interconnected with the QNX PC via a serial link and to the motor controllers (type EL7342 by Beckhoff Automation, Verl, Germany) via EtherCAT. The motor controllers directly control the currents of the actuators. Position constraints for link actuation are calculated using the robot kinematics in order to avoid internal collisions. Additionally, external ultrasonic (US) sensors can help to avoid collisions of the robot with its environment. A milling tool can be aligned with the patient coordinate frame and a target bone can be processed with the preplanned trajectory.

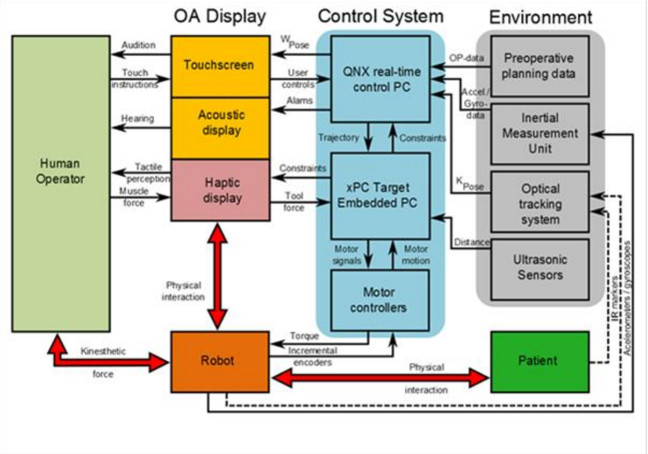

Figure 3 System architecture of the BOrEScOPE system

To achieve compliance with the behavior of the operator, three interaction modalities are realized: The opto-acoustic display provides optical (1) and acoustical output (2) while the robot provides haptic feedback (3). The control algorithm's input is a virtual static force field generated around the main axis of the bore and depending on the actual distance, speed and direction of movement of the BOrEScOPE's end effector [16, 17]. When the patient is moving, this force field also moves in space. To achieve smooth and comfortable movement, the real force acting between BOrEScOPE and the wrist are measured. The user tries to minimize the forces following the BOrEScOPE system.

Using this algorithm, the 7 DOF redundant robotic system can be controlled easily and intuitively while maintaining the human's dexterity. As both, the linear displacement at the actuators and the angular displacement in the actual joints are measured and controlled, serial-elastic actuation is achieved.

III. RESULTS

The BOrEScOPE system is still under development. The two main subsystems *opto-acoustic display* and *robotic system* show first and promising results that are described in the following.

The measured peak response time of hand movement as a result of optical stimuli amounts to around 250 ms. The requirement of visually provided information should be adapted on this process time. The reaction time of the UGOAD as well as the robot must be kept within a limit of 10-20 ms (10-20-fold faster). Thus, the calculation of graphical contents and of the control algorithm should terminate within this time. Based on this knowledge the sensor data acquisition, the global-control loop, and UGOAD were implemented as real-time processes in the QNX Neutrino operating system.

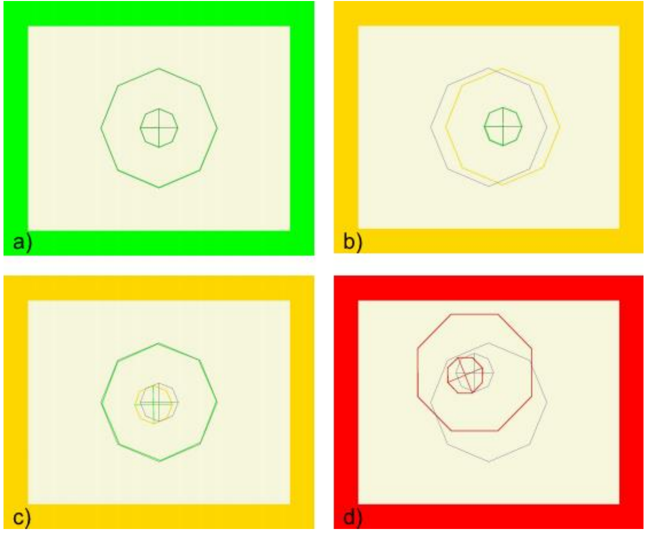

Figure 4 Three operate zones of the UGOAD: a) No displacement, b) Translational displacement in x-axis, c) Rotational displacement around x- and y-axis, d) Displacement in view axes

The first display prototype was realized by a 2D representation of the 6 DOF pose data. Accordingly, the actual and the reference pose of the tool are shown in the x-y-plane of the display. The z-axis is perpendicular to the display plane. In order to intuitively capture the 6 DOF contents in the 2D image a two body projection metaphor is realized. In this imagination one small colored octagon is mounted virtually at the tool tip and one large colored octagon at the rear of the tooling machine. Looking from above in direction of the drilling tool (z-axis) corresponds to looking through the large octagon and through the small octagon on the tool tip, which is in the center of both. The small black octagon with crosshairs and large black octagon are virtually mounted at the target (reference) pose. If the tool is aligned (Figure 4a), the small octagons are aligned and the large colored octagon has its original size in the central position. If the tool is misaligned in the x-axis (Figure 4b) the large colored octagon is shifted correspondingly in the x-direction. The same holds for the y-axis. A misalignment in the z-axis is represented by the size of the large colored octagon. A deviation in the positive z-direction means that the tool is too far away from the user, which is shown by the reduced size relatively to the large black octagon. Negative deviation means, that the tool is too narrow, displayed as increased size. A deviation in the orientation is displayed as shift of the small colored octagon.

For example, if the tool is turned around the y-axis (Figure 4c), the tool tip is moved in x-direction, displayed as x-axis-shift of the small colored octagon. The corresponding principle holds for the orientation error around the x-axis. Here, a y-shift of the small octagon can be observed. The orientation error around the z-axis is directly displayed as a rotation of the colored octagons around their centers.

As additional element, a rectangular border is shown in green color, which indicates that the pose is in the desired workspace. If the tool approximates the limit positions for at least one axis, the color changes firstly from green to orange, showing that a user intervention is required. In critical vicinity to the constraints the color changes to red (Figure 4d) asking for urgent motion actions. The color change is supported by changing the waveform of the acoustic channel.

IV. DISCUSSION AND CONCLUSION

To set up a robotic system with close human-machine interaction in a medical environment is a delicate task. However, the project is still in progress and work starting from the presented concept to the final realization is still ongoing. We managed to define interfaces between the robotic system and the human operator not only mechanically but also visually and using the audio channel. Smooth and comfortable working with the system is strongly dependent on low latency, high update rates, and actually predictable behavior. Here, our system will have to deal with some drawbacks as the force field generation is depending on data quality of the optical tracking system which tends to jitter and noisy signals. This will be addressed in future by using redundant LED markers and by combining data of an inertial tacking system. Furthermore, the quality of real-time data transfer will be improved.

First tests with users demonstrate that the 6 DOF can be captured by the majority of subjects without further explanation. Thus, the usage of the UGOAD as a feedback in the human interaction with the machine implicates a massive improvement of human performance to achieve the common tasks and there is every indication that the developed UGOAD insure an intuitive operation and an intuitive control.

Mechanically, the robot will have to cope with force-depended friction in the Bowden cables. This issue will be addressed by a model-based controller with individual parameters for each axis.

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