Control and safety architecture for a modular medical robot

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Abstract: In this paper a new approach for a control and safety architecture for a modular task adaptable medical robot is described. The concept has been evaluated with the MINARO robot, which was developed in the OrthoMIT framework for revision total hip replacement (RTHR), being one of several possible applications. By modularizing the system we tried to combine the advantages of medical robots (e.g. higher accuracy, lesser invasiveness) with the advantages of modularisation (increased flexibility, lower costs). Based on the mechanical building blocks and under consideration of the high safety demands in robotic surgery a modular control and safety architecture was developed. Solutions for the automatic identification of the modules and supervision of the system were integrated. Prototypal systems have been used to verify the feasibility of the concept.

1 Introduction

By means of medical robots the work of surgeons can be simplified and the quality of the intervention significantly improved [1]. Individual patient-specific operations can be realized by computer-assisted planning of the surgical procedure (e.g. optimal position of the prostheses [2]). These preplanned interventions can then be conducted very precise and time efficient by the robotic system, while maintaining the ideal processing parameters (e.g. process temperature, forces) [3], [4], [5].

The afore mentioned advantages are a strong indication for the use of robotics in the operating room (OR), but nevertheless there are various risks and limitations. High demands in safety and requirements arising from the direct interaction between robot, patient and surgeon have to be satisfied and pose a challenge for the development of medical robots.

In recent years there have been several approaches to support the surgeon with robotic assisting devices in the OR. Whereas the first systems had disadvantages [6], [3] concerning integration into the clinical workflow, usability, function and costs, robot-assisted surgery was able to show a breakthrough in some areas (e.g. DaVinci). To optimize the integration into the clinical workflow and reduce the invasiveness of the interventions nowadays several systems like MAZOR [7] and Praxiteles [8] have task-adapted kinematics and workspaces, in contrast to the first medical robots (e.g. Robodoc, Caspar) which where based on modified industrial robots,

In order to allow gentle robotic aided therapy and reduce the costs of robotic interventions the advantages of a miniaturized task adapted robot (e.g. better integration into clinical workflow [7]) have to be combined with the advantages of modularization (e.g. cost, development time reduction). This is possible, because several applications in orthopaedic surgery have similar demands in speed, forces and dynamics [9]. Three possible orthopaedic applications are in unicompartmental knee arthoplasty (UKA) in order to generate the joint surfaces for the prostheses, in revision total hip replacement (RTHR) for bone cement removal (Fig. 1.) and in placing of pedicle screws. To reuse expensive parts like the mechatronic units containing motors, encoders and the gearbox in all applications the mechanical structure has to be subdivided into building blocks.

Fig. 1: MINARO minirobot for RHTR mounted on femur

In this paper, a new approach for a modular control and safety system for this kind of modular medical robot is proposed. The modular mechanical design of the medical robot defines the basic requirements for the robot control architecture and is discussed first. Based on this, the architecture of the control and safety system for the robot and new elements necessary for this kind of robot are described. The issue of the high demands in medical safety and the modularization of the corresponding safety and control system are addressed.

2 Modular Robot Control System

To allow an adaption to different applications the mechanical elements have to be modularized. The workspace can then be adjusted by an individual combination of the modules appropriate for the intervention. A combination of actuator modules containing motor and gearbox, kinematic modules, a tool for interaction with the patient and a base plate for mounting the components (Fig. 2) define the workspace and the corresponding application.

Nevertheless, the modularization of the mechanical structure and the requirements arising from the miniaturization have a great impact on the design of the modular robot control system.

Two main parts of the modular robot control system are the real-time system and the modular axis control system, which both include parts of the safety system. The real-time system is responsible for control as well as high-level safety related tasks. It supplies the modular axis control system with set points based on the dataset with e.g. the milling path it received from the planning system and supervises the system with optical tracking and force/torque sensors.

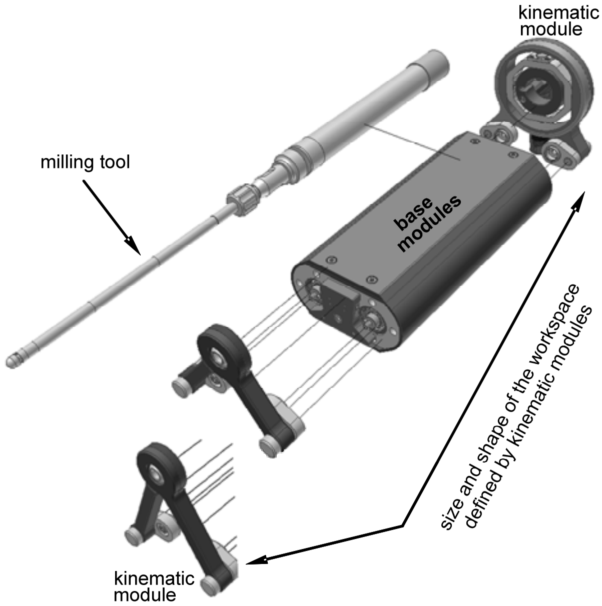

Fig. 2: Modular mechanical structure of RTHR robot

In the following paragraphs the structure of the modular axis control system is described with a focus on the new elements, which had to be adapted or developed (Motion Control System, Module Identification and Safety System) especially for the modular robot.

Motion-Control System
All three applications can be considered as medical CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) and need to be able position the tool tip of an interlinked kinematic with six degrees of freedom. This can be realized based on the basis of commercially available motion controllers. To comply with the requirements from the mechanical structure it has to be possible to change the amount and type of the motion controllers. A possible solution for this is the CAN-bus (Controller Area Network) and the CANopen protocol which is widely used in the industry as well as in medical devices as a reliable medium for real time data exchange [10], [11]. The CAN data bus allows the flexible interconnection of motion controllers and thus a variable axis count which is primary limited by the maximal data rate of the bus and the necessary control frequency.

Safety System
Due to the limited and task-adapted workspace of the modular robots, the potential risk and hazards for the OR personal is very low. Nevertheless, a false positioning of the tool tip is potentially dangerous and may lead to excessive forces applied to the patient. Due to the direct interaction between robot and patient during the surgical intervention, measures have to be taken to assure the patients safety.

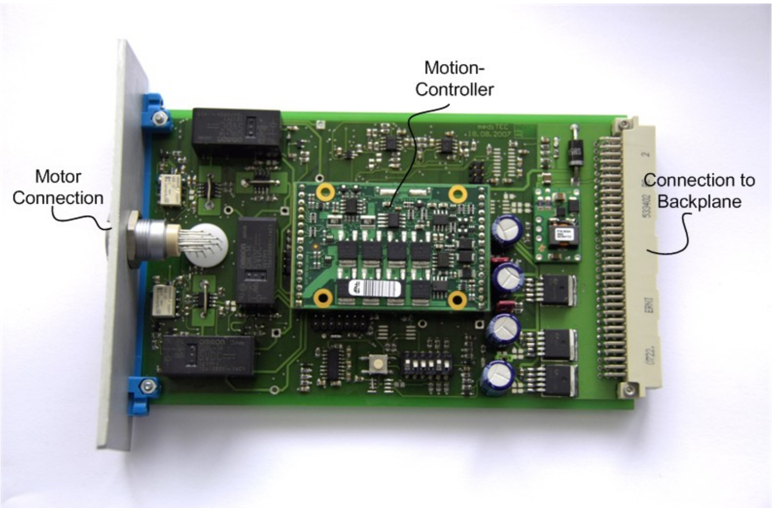

Fig. 3: Safety System PCB

Redundancy is not necessary because, dismounting of the robot from the patient can be done quickly in both applications, due to its miniaturized mechanical structure. The operation may be then continued with the standard method or a spare robot.
This concludes that the safety system has to be able to detect all critical faults and to bring the robot into the safe-state, without harming the patient. The possibility to safely stop the procedure at any given time represents the safe state.

However, the safety systems which are described by [12], [13] and [14] cannot be used without modifications for a modular robot. But the fundamental ideas behind these designs provide a valuable contribution to the basic features of the modular safety system. Some of the elements can be directly transferred to the new modular design. These common elements are, the dead man switch (DMS), the emergency switch(es) and the watchdog.

Beyond these common elements the safety systems architecture has to be designed based on the risk analysis of both applications. A variation of the kinematic modules induces different applications specific risks and requires the monitoring of a different set of parameters. Actually, the safety system is a piece of hardware, which cannot be changed and thus needs to be as generic and configurable as possible.

Monitoring of all local axis-specific values, including the phase currents, position sensors, supply voltage, set-points is integrated into one printed circuit board (PCB) which also carries the motion controller (Fig. 3). The position of the motion controller on the safety system PCB allows a direct acquisition of all input and output signals as well as the messages sent between motion controller and main control system. The data processing is realized with a DSP (TMS320F2809, Texas Instruments) which is intended to be used for motion control applications. Thus, most of the necessary interfaces for supervision are integrated. In order to have a maximum bandwidth available for the motion control data, the communication of the safety system with the master controller is done on a second channel (Fig. 4).

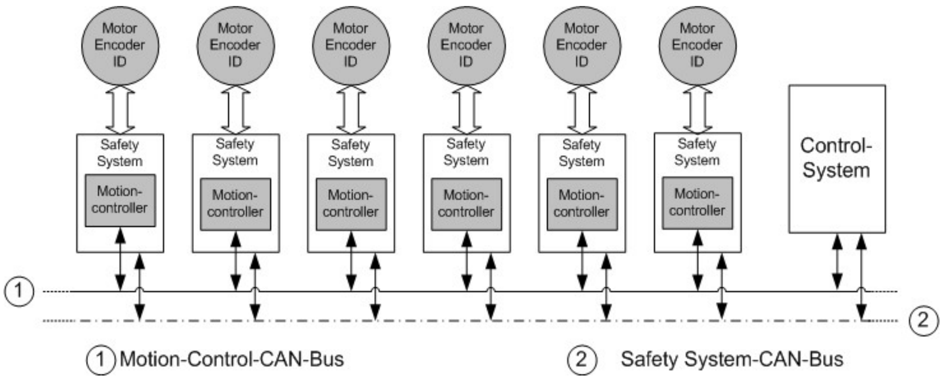

Fig. 4: Modular safety and motion control system architecture

The information gathered by all axis safety systems allows to make an assumption only of the tool tips position, based on a mathematic model of the kinematic structure (e.g. broken bar may not be detected). To detect these failures, measures described in [12], [15] and [13] (e.g. optical tracking, force/torque sensor) can be used.

Finally, a fault may be detected by three sources. Any of the axis bound safety systems, the overall supervision instance which also controls the additional sensors (e.g. optical navigation, force torque sensors) and the surgeon are able to do this.

In any of these cases the system has to switch off all motors as fast as possible and thus change from any possible state, into the safe-state. While the motion controller is able to stop a motor very fast autonomously, an additional method is implemented which allows an emergency stop in case of a damaged motion controller or a loss of power. This is solved with three relays which are integrated on the safety system to disconnect the motor from the motion controller and to shorten the phases to allow a fast stop and hold the current position.

Due to its importance for the systems safety concept, the emergency brake procedure has been tested (Fig. 5) with different motor speeds, to verify that the motors are switched off fast enough. After around 10ms the relay has switched and after around 80ms the motor has stopped. In the RTHR application the switch off may be faster due to the resistance and brake effect of the bony structures.
All systems (emergency switch, dead man switch, axis safety system, overall safety system) are able to trigger an emergency off. Hardwired logic then switches the relays off. This also permits that the relays may be switched off by the local DSP.

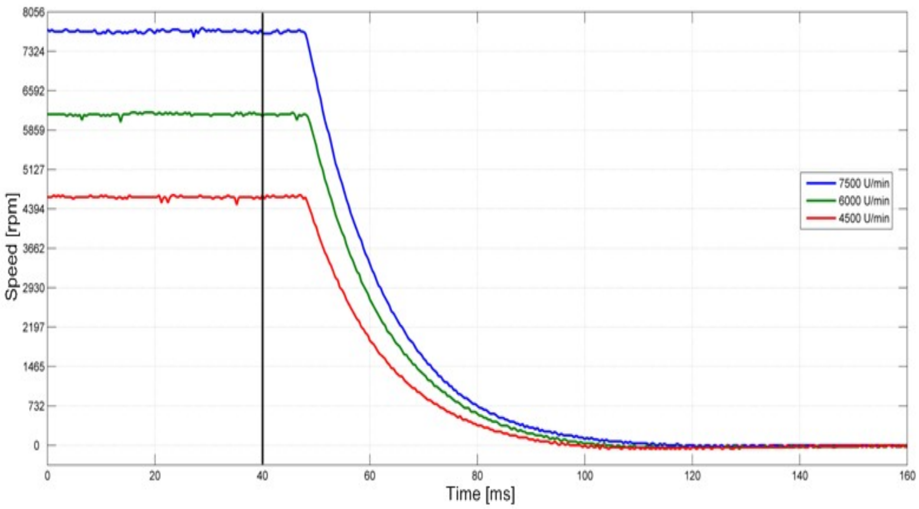

Fig. 5: Test of emergency brake procedure

Module Identification
To reduce the amount of different building blocks for the modular motion control system, the mechanical connectors of all axes are of the same type as well as the interconnection cables which allow the linking between each individual axis of the motion controller and the robot.
To determine the configuration of the axis to motion controller interconnection a fast and fail-safe method is to automate the procedure with an intelligent module identification system, which is mounted on every motor module. The detection of each module and a configuration independent of the global motor and axis interconnection is then possible.
A microcontroller (MC9S08QG8, Freescale) is responsible for the communication, handling of the ID and parameters for the associated module. To keep the architecture simple and safe a serial point to point interconnection based on the RS-232 standard is chosen for communication.

3 Discussion and Conclusion

This paper describes the architecture of a control and safety system for a modular medical robot structure. We were able to show that it is possible to develop a modular control and safety structure for a medical robot. The modular safety system is supported by the module identification system which allows a safe detection of the robots actual structure. Their basic function was verified and it was shown that the modular approach can be transferred from the mechanical domain into the control domain for a medical application with its high demands in safety.

An important advantage of the modular control and safety system is that besides the necessity to monitor the parameters on a flexible axis base, the processing power needed for data acquisition, preconditioning and verification is scaled automatically with the axis count. This permits deterministic execution of algorithms on each safety system regardless of the axis count.

In future work several issues have to be assessed in more detail including the test of all functions in one of the applications.

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