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Industrial robots for teleoperated surgery – a systematic review of existing approaches

Abstract: Robotic assistance in surgical interventions has been shown to improve both the surgical outcome and the surgeon's performance. However, cost-efficient implementation of such systems in an operating room workflow is not yet resolved. Most of the current approaches use highly specialized and purpose-built robotic components, resulting in large costs. This paper presents an investigation into the usage of off-the-shelf robots as cost-efficient basis for teleoperated surgery. In addition, the modifications required of the robot and/or operating environment to make it suitable for the medical setting are assessed. The considered systems are found via a literature search and the MERODA-database, specifically focusing on systems designed for teleoperated surgery which use industrial robots. Among the 126 telemanipulated systems found, only 10 use industrial robots for surgical procedures. Overall, due to the better availability, reduced costs, and increased performance, current industrial robots should be further considered for new and versatile low-cost approaches to teleoperated surgery.

Keywords: teleoperated surgery, telemanipulation, medical robotics, robotic surgery, industrial robots

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1 Introduction

Since the 1980s, the use of robotics in the operating room (OR) has been present [1]. Motivated by comparatively good positioning accuracy and repetition, and the increasing availability, numerous robotic systems for various applications have been developed. As the result of common operational scenarios, the majority of present day robotic systems can be categorised into one of four groups. These include: static positioning of instruments/tools, automated movement along

a trajectory according to preoperative planning, remote controlled teleoperation, and the application of forces and movement patterns for rehabilitation purposes.

The first projects in the field of telemanipulation began in the 1990s [2]. These master-slave-systems commonly consisted of a robotic manipulator and an input device from which the robot is remotely controlled. Such teleoperation systems are shown to considerably improve the performance on the surgeon's side by reducing tremor, scaling movements and providing supplementary degrees of freedom (DOF) in the situs [3]. In addition, the ergonomic working posture and the intuitive use of surgical instruments, without fulcrum effects, is shown to benefit the surgeon's work and thus improve surgical outcomes [3].

Conversely, cost-efficient implementation of telemanipulation systems in the OR workflow is not yet resolved [4]. Many current approaches use highly specialized and purpose-built robotic components, resulting in large costs due to the low number of produced units. Aside from the monopolistic Da Vinci System (Intuitive Surgical, Sunnyvale, CA, USA), only a few systems are available for clinical application. However, it is becoming increasingly common that research projects use industrial robots for the setup of telemanipulation systems in the surgical setting [5]. Recent improvements in accuracy, decreases in costs, and high availability makes conventional off-the-shelf robots potentially suitable for medical applications. This could allow for a crucial drop in the costs of relatively complex robotic systems, but also give rise to completely new issues around the modifications that must be done on existing industrial robots.

This paper investigates the use of off-the-shelf robots as a cost-efficient basis for teleoperated surgery (TOS). Industrial robots are assessed in terms of their appropriateness for teleoperation in the OR and which modifications are required of both the robot and/or the operating environment.

2 Material and Methods

Current literature is reviewed in terms of systems that use industrial robots as a basis for their manipulator in the field of TOS. The majority of systems were found using an updated version of the MERODA database [1]. Other publications were found using Google Scholar and PubMed. Search terms

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around the field of robotic surgery, industrial robots, and teleoperation were used. Timeframe of search was between 06 May 2019 and 28 May 2019. Research projects and systems were filtered in the following steps:

1. Systems mainly used in telemanipulation setup
2. Systems based on industrial robots
3. Systems designed for usage in TOS

Setups which were designed for other (sub)disciplines, e.g. teleoperated needle placement, imaging, microscopy or tool guiding were not considered. The found systems were then analysed regarding their underlying robotic manipulator. In addition, the robot kinematics and modifications that were done to both the robot and /or the operating environment were assessed. This review does not claim to be all-encompassing but rather to present a broad overview about industrial robots used for TOS.

3 Results

Overall, 126 medical systems for use in a remote controlled telemanipulation setup were found, of which only 33 systems were based on an industrial robot. Furthermore, only ten of these systems were designed for TOS.

3.1 Industrial robots in TOS

All found systems using industrial off-the-shelf robots for TOS and the respective industrial robots are shown in Table 1. It was found that the majority of projects use conventional low payload articulated robotic arms for their setup. Only three of the systems were equipped with seven DOFs, with the remainder of systems having only six DOF. In all the systems considered, only the MIRO commercial robot is specifically designed for medical applications [6].

Table 1: Systems using industrial robots for teleoperated surgery.

Project name	Industrial robot	Type	DOF
A73 [7]	1x Mitsubishi RV-1a (Mitsubishi Electric Corp., Tokyo, Japan)	articulated	6
ACCUROBAS [6]	3x MIRO (DLR, Köln, Germany)	articulated	7
Endo[PA]R [8]	2x KUKA KR 6/2 (KUKA AG, Augsburg, Germany)	articulated	6
	1x PUMA (Unimation Inc.)	articulated	6
ARAMIS [9]	4x Mitsubishi MELFA 6SL	articulated	6

Project name	Industrial robot	Type	DOF
EndoXiroB [10]	1x Mitsubishi PA-10	articulated	7
Song et al. [11]	Mitsubishi MELFA RV-E2	articulated	6
Hoerauf et al. [12]	1x Hexapod Physik Instrumente (Physik Instrumente, GmbH & Co. KG, Karlsruhe, Deutschland)	hexapod	6
MARGE [13]	1x Mitsubishi PA-10	articulated	6
Tholey et al. [14]	1x Mitsubishi PA-10	articulated	7
Kim et al. [15]	2x Rockwell Samsung AS2 (Rockwell Samsung Automation Inc., Korea)	articulated	6

3.2 System Setup and Modifications

Common modifications usually concerned the following subsystems: surgical tool interface at the robotic end effector, force/torque measurement somewhere between tip of the tool and robotic end effector, input device with force feedback, and software-based modifications to reduce control latency and/or restrict kinematic behaviour regarding the invariant fulcrum point around the trocar. In addition, custom-designed surgical instruments, in some cases with additional DOF to gain a certain level of redundancy, were commonly required. Only one of the found systems required considerable modifications to the OR due to its ceiling-mounted approach [9]. Other systems were mainly built up on a movable chassis or do not further specify their implementation due to still being in early development. The setup of the found systems is briefly described below and known modifications are specified.

The A73 system is equipped with surgical instruments suited for tasks in the skull base, such as drilling and flushing [7]. Inputs for telemanipulation mode are generated using a SpaceBall joystick control (3Dconnexion Inc., Germany) [16]. The robot itself is modified by adding additional brakes to all axes for enhanced safety and stiffness in case the motor power is cut-off. Furthermore, an additional force-torque sensor is added to limit the applied forces and provide the robot with a certain sensitivity. Mounted on a movable platform and with the possibility to adjust the height, the robot is designed to be fixed to the operating table.

Within the ACCUROBAS system the MIRO robots are equipped with endoscopes as well as surgical instruments with force sensing for MIS [6].

The two manipulating robotic arms of the Endo[PA]R system are equipped with surgical tools from Intuitive Surgical (Intuitive Surgical Inc., Sunnyvale, CA, USA) [8, 17]. The third arm is carrying a stereo camera system. The instruments themselves already offer three DOF. As there is one

equivalent axis between the robot and instrument, one whole arm of the system forms a manipulator with eight DOF [8]. User input is performed via two Phantom devices (SensAble Technologies, Inc. now known as 3D Systems, Inc., Rock Hill, SC, USA) which also offer force feedback. As a result, strain gauge sensors are attached to the Intuitive Surgical instruments. Additionally, collision detection between tools and partial autonomic tasks like knot-tying were implemented [8].

In the ARAMIS system, the four robotic arms are mounted upside down on a gantry, therefore allowing easy access to the workspace [9]. The system, with its attached force-feedback instruments and endoscopic stereo camera, is remote-controlled by two Phantom devices. Together with the instruments, each arm of the system has overall eight DOF. The inverse kinematics calculation considers the fixed fulcrum point as the only rotational point for the instruments. Thus avoiding excessive bruising of the tissue around the incision point. In addition, automated tying of knots has been successfully implemented [9].

The EndoXiroB system initially used off-the-shelf industrial robotic arms but then later introduced a prototype with a parallelogram structure [1, 10]. Using their specially developed surgical instruments it was able to provide three DOF around an invariant trocar point [1].

The teleoperation approach of Song et al. offers haptic force feedback in three axes [11]. As a result, the robotic arm is equipped with a three-DOF force sensor. Additionally, a CCD camera is attached to the robotic hand to also provide visual feedback of the surgical site.

Within the MARGE project, a purpose-designed instrument is attached to the robot's end effector [13]. To align this instrument with the main axis of the trocar while controlling its penetration depth, a minimum of six DOF are necessary. On the robot itself, substantial modifications implementing a force-position control with a zero-force constraint on the invariant trocar point were performed. Furthermore, an active trocar was designed, aiming for high quality force feedback by reducing friction forces.

Also aiming for high quality haptic feedback, Tholey et al. attached a custom-designed laparoscopic grasper to the robot's end effector, with the capability of force measurement in three axes [5, 14].

Kim et al. mounted specially designed instruments, a cutter and a grasper, on the robotic end effectors [15]. By adding strain gauge sensors on both instruments, interaction forces in three axes could be haptically displayed on the input console with an update rate of 30 kHz. For improved accuracy when operating on small structure the position-control allows for the scaling of movements.

4 Discussion

More than 100 medical systems for a remote controlled telemanipulation setup were examined. Out of these, only ten systems are based on off-the-shelf robots and designed for TOS. The found systems based on industrial robots are seen to be among the very early approaches in this field, with the most recent publication being over ten years old. As a result, most of the projects have not been continued. This was likely motivated by the lack of safety features for collaborative use of industrial robots at that time, as shown by the additional sensors, brakes and control algorithms implemented to try and make it suitable for the OR environment (Section 3.2). However, previously these robots were designed for industrial application within a safety-fence, and several recent advancements made them more suitable for the OR setting.

In modern day industrial robots, seven DOF are becoming commonplace. The six DOF seen within the majority of previous approaches resulted in limited dexterity in the OR environment. Moreover, the redundancy of a seven-DOF robot allows the same end effector position with several joint configurations, making it better suited for collaborative use in the limited space around the situs. This is for example necessary for movements of the instrument along the main axis of the trocar [13]. Furthermore, in the case of MIS, this allows more movement possibilities inside the body in regard to trocar kinematics around the invariant fulcrum point. However, a similarity between all the considered projects was the complexity of the inverse kinematic calculations. Specifically, the challenge of restricting the forces in the trocar.

Additionally, integrated torque/force sensors within robotic joints are also becoming standard. However, the reviewed papers showed that it was commonplace to add additional sensors to the instruments and/or manipulator arms, as the existing/or non-existing sensors were not sufficient.

In all of the reviewed projects, a specialized manipulator was created for the desired application, with only one project using an existing surgical instrument (Endo[PA]R system [8, 17]). This is likely due to the lack of commercialized robotic instruments, highly specialized tasks requiring more custom-designed manipulators, and the significant restrictions of using manually operated surgical instruments. Therefore, more research into versatile design of robotic instruments is required.

Almost no statements could be found regarding cost or resource efficiency. Neither in terms of development or investment costs nor concerning the implementation of the system into an existing OR workflow. This could be caused by potential agreements with manufacturers or it could lead to the

assumption that the considered projects are mainly focused on functionality and performance due to their early phase of research not considering costs or other resources.

Building up on an existing off-the-shelf robot has several advantages, including relatively low costs, high reliability and of course fast availability which benefits rapid prototyping in research [18]. In addition, industrial robots have been shown to be suitable for various tasks in the field of TOS. Thus, modern day industrial robots prove to be able to provide a potentially significant reduction in cost of TOS.

In conclusion industrial robots have been previously successfully used in the field of TOS research. In contrast to most of the previously used industrial robots, current off-the-shelf robots are often available with integrated torque-sensing and seven DOF, which enables the easier implementation of various safety features required for collaborative use. Additionally, due to better availability, reduced costs, and increased performance modern day industrial robots should again be considered for new and versatile low-cost approaches to TOS in contrast to the existing specialized and expensive systems.

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