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Medical robotics simulation framework for application-specific optimal kinematics

Abstract: Most kinematic structures in robot architectures for medical tasks are not optimal. Further, the workspace and payloads are often oversized which results in high product prices that are not suitable for a clinical technology transfer. To investigate optimal kinematic structures and configurations, we have developed an adaptive simulation framework with an associated workflow for requirement analyses, modelling and simulation of specific robot kinematics. The framework is used to build simple and cost effective medical robot designs and was evaluated in a tool manipulation task where medical instruments had to be positioned precisely and oriented on the patient's body. The model quality is measured based on the maximum workspace coverage according to a configurable scoring metric. The metric generalizes among different human body shapes that are based on anthropometric data from UMTRI Human Shape. This dexterity measure is used to analyze different kinematic structures in simulations using the open source simulation tool V-REP. Therefor we developed simulation and visualization procedures for medical tasks based on a patchwork of size-variant anatomical target regions that can be configured and selectively activated in a motion planning controller. In our evaluations we compared the dexterity scores of a commercial lightweight robot arm with 7 joints to optimized kinematic structures with 6, 7 and 8 joints. Compared to the commercial hardware, we achieved improvements of 59% when using an optimized 6-dimensional robot arm, 64% with the 7-dimensional arm and 96% with an 8-dimensional robot arm. Our results show that simpler robot designs can outperform the typically used commercial robot arms in medical applications where the maximum workspace coverage is essential. Our framework provides the basis for a fully automatic optimization tool of the robot parameters that can be applied to a large variety of problems.

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1 Introduction

For medical robotic applications, standard industrial robots are often used because of their good commercial availability, product quality, and accuracy, although they do not optimally meet the kinematic requirements for the application. These systems are designed for universal use for a variety of tasks in various industries and are therefore usually oversized in workspace and payload, whilst also being expensive and requiring special security measures.

Some related studies that investigate optimal kinematic structures in medical robotics exist. Yoshikawa [1] discussed the manipulating ability of robotic mechanisms in positioning and orienting end-effectors and proposes a measure of manipulability. Some performance measures were reviewed by Patel [2]. Paden [3] formulated an optimality theorem for six revolute joints kinematics and Nelson [4] proposed a Monte Carlo simulation algorithm for optimizing a redundant serial spherical linkage. Pamanes [5], Zeghloul [6] and Vidaković [7] presented methods to find the optimal placement of robots. Xiang [8] proposes a three-dimensional space path prediction simulation method and a design process method for robotic medical tool-guidance manipulators was proposed by Nouaille [13].

In this work, we perform the analysis of the kinetic requirements, in particular of workspace and dexterity, covering all the above issues. Furthermore, we determine design and a configuration of an optimal robot, especially for applications in the medical field for the manipulation of instruments on the human body, e.g. robot-assisted ultrasound or needle puncture.

2 Methods

To analyse, model and simulate the application-specific optimal robot kinematics we developed and evaluated a workflow and a software framework. The application-specific target workspaces were modelled and compared with the robot workspaces, and the score values were determined according to a dexterity metric, and hence, a manual optimization was carried out.

2.1 Computing targets using anatomical body models

The first section of the workflow was the requirement analysis. We utilized a statistically representative anatomical body model based on anthropometric data containing some variations regarding size and shape to cover the spectrum of human anatomy (section Software and simulation framework). The target areas for the intended medical applications were marked by selecting vertices from the surface of the body model. Likewise, different regions can be combined with each other depending on the application scenario.

In a second workflow step, the models for the target workspace and the robot workspace were modelled in parallel. The target workspace was created by generating multiple body model variations by adjusting the physiognomic parameters for gender, patient size, body mass index, body length, and age to produce a minimal and maximal shell model of the body surface. Based on the DINED Anthropometric Database [1], this range was selected from the 5th percentile (corresponding to the body height of 1.54 m with a body mass index [BMI] of 20) to 95th percentile (1.91 m, BMI = 34) of the anatomical bandwidth (see Fig. 1a).

The generated model data follows an identical general vertex structure, only differing in spatial deformation according to the input parameters. Subsequently, the mapping of the application-specific target areas to the likewise application-specifically dimensioned shell models is performed by assigning the vertex indices. In the following morphing between minimum and maximum shell any number of intermediate shells can be created, controlling the accuracy of the dexterity calculation. The superposition of all vertex points belonging to the target areas from all shells yields the spatial target workspace. Finally, the number of vertex points is reduced to an appropriate ratio (in the present experiment to 1533) in order to reduce the computational demands in the simulation.

2.2 Optimizing kinematic structures

We varied all the relevant kinematic parameters that form the workspace of an articulated robot arm (namely number, types, range and axial offset of the joints and the arm link lengths) and the design of the tool geometry of the application-specific instrument given by the tool-tip coordinates. The general functional requirements for the kinematic design were evaluated using the design process by Siciliano [9]. The design goal is a simple, lightweight, dynamically stable and cost-effective robotic arm. The structure with as few joints as possible represents the most important optimization criterion that meets all goal criteria.

2.3 Dexterity simulation

In the simulation, as the third workflow section, the two model components were integrated into a common simulation environment and virtually interconnected, whereby the kinetic performance was determined. A test algorithm has been implemented to approximate the functional requirements of the intended medical application and tests the kinematics using a dexterity metric defined as follows: It tests whether the instrument could be virtually positioned at all target positions and oriented in some different rotations (next section) in parameterized Tait–Bryan (roll-pitch-yaw) angles. Target positions for testing are all selected vertex points contained in all layers of the target workspace model. Those were assigned with direction vectors normal to the model surface. The base of the robot model was positioned relative to the target model in the simulation space, whereby the position has significant impact on the result and is also subject to optimization. The dexterity estimation was implemented using an algorithm for inverse kinematics calculation and path planning (section Software and simulation framework), which attempts to find all target configurations on collision-free paths from the starting position to the target position. Self-collisions and (layer-selective) collisions with the phantom must be avoided.

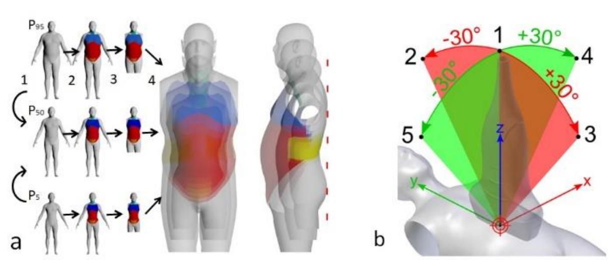

Figure 1: (a) Anthropometric shell model generation of 5th and 95th percentile of the population and an intermediate shell by morphing operations (1), marking of grouped colored target areas (2), cropping (3) and superposition in supine (4, frontal and lateral view) yields the 3D target workspace embracing solely the colored vertices. (b) Discretization scheme of 5 orientations of the medical instrument for dexterity test to apply on every vertex position in target space relative to their direction.

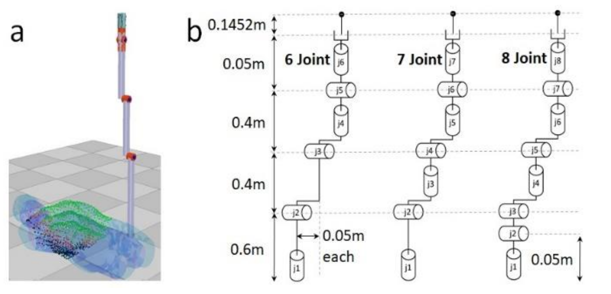

Figure 2: (a) Virtual simulation scene including target workspace phantom and 6-Joint kinematic. (b) Design and dimensions of the self-designed kinematic structures..

For planning of the collision-free paths to the target configurations, a sample based tree planner search algorithm (section Software and simulation framework) operating in joint parameter space is used. It selects always the shortest path out of the generated plans.

2.4 Dexterity metric

To evaluate the positioning and orientation capability of the tool tip at all given target points, we defined a scoring metric. The orientation around the spatial axes is not continuously analysed but tested in discrete steps [10], [1]. In these steps, the angle of attack of the instrument is varied with respect to the phantom surface. Not all axes need to be varied if the instrument is inherently rotatable.

Fig. 1b shows a five-stage discretization scheme in which at first the virtual tool is set to the same orientation as the target point vertex and is subsequently varied by +30° and -30° for the pitch and roll axis of the instrument. The score is increased by one for each collision-free position reached. The maximum achievable score value per single target point in this scheme is therefore 5. In our results, we used this scoring range in Fig. 3.

2.4.1 Software and simulation framework

The three-dimensional body models are created using the UMTRI Human Shape online platform (University of Michigan, USA), which is mainly used for ergonomics studies in product design. This tool contains a statistical anthropometric data model prepared from whole-body laser scans of humans. After selection of physiognomic parameters, a series of two or more differently dimensioned polygonal models of the body surface can be exported by this tool into structured text files.

These polygon models are modified by custom scripts using 3D Blender Suite (Blender Foudation, Amsterdam, The Netherlands), highlighting the vertex groups belonging to the target areas within the polygon models and reducing the total number of vertices. Subsequently, the polygon models within the series are interpolated by morphing and spatial alignment from which the target workspace volume is generated. The alignment can be application specific, e.g., for horizontal or vertical patient positions. Alternatively, in the target workspace model, irrelevant body regions can be removed, e.g., the extremities.

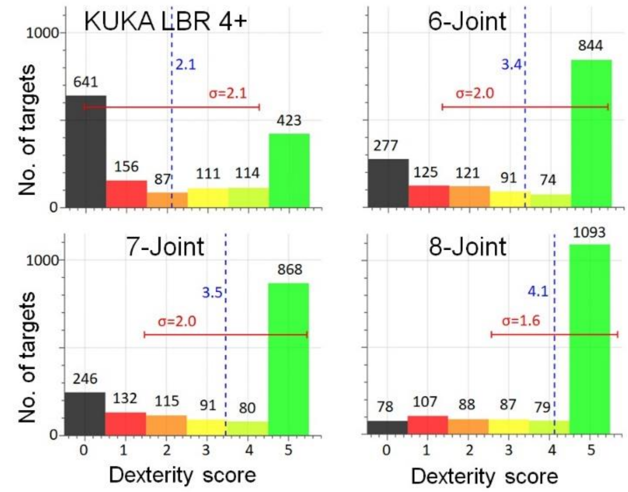

Figure 3: Numerical dexterity distribution of the four examined robot kinematics including mean dexterity score and standard deviation. In each experiment 1533 targets had to be reached.

Kinematic simulation scripts were developed using the Virtual Robot Experimentation Platform V-REP (Coppelia Robotics GmbH, Zurich Switzerland). Its integrated inverse kinematics IK Calculation Module was used. The open motion planning library plug-in [12] was used to generate collision-free paths.

3 Results

We simulated a series with a target workspace phantom using the aforementioned properties for the simulation of the ultrasound imaging task with a lying patient phantom and four different kinematics (Fig. 2a). The first kinematics (virtual model of a 7-joint robot KUKA LBR4 +) served as a reference and was replaced by three optimized kinematics (the 6-, 7- and 8-joint kinematics). The spatial arrangement of the robot base with respect to the patient model was placed at a distance of 50 cm from the centre of the torso at the height level of the lying surface. The design of the three self-made kinematics with associated parameters is shown in Fig. 2b. In the design of the kinematic basic structure, only rotational joints with

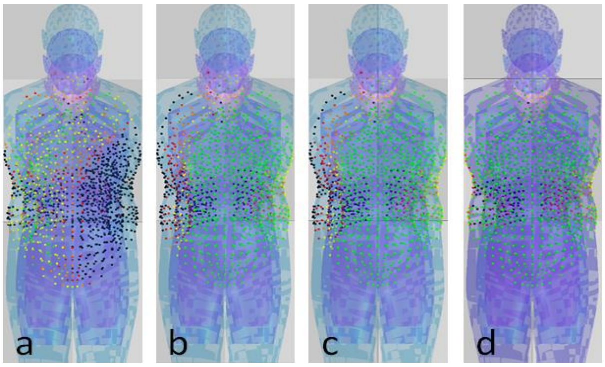

Figure 4: (a) Graphical visualization of the spatial dexterity distribution for the reference kinematics (a) and the self-designed 6-, 7- and 8-joint kinematics (b, c, d) in the target space. The same colors as in Fig. 3 were used to indicate the dexterity score value on target points.

axial offset as well as from distal to proximal increasing link lengths were selected.

We compared the mean score value of all end effector positions of our baseline, the KUKA LBR4+, 2.1 ± 2.1 (mean ± standard deviation), with optimized structures of a 6-joint arm 3.4 ± 2.0, a 7-joint arm 3.5 ± 2.0 and an 8-joint arm 4.1 ± 1.6. Fig. 3 shows the numerical simulation results for the four examined kinematics.

The spatial dexterity distribution of the non-optimized kinematics focuses more on a lateral region in target space while it spreads more evenly with optimized kinematics and an increasing number of joints as shown in Fig. 4.

4 Conclusion

A simulation framework was developed to investigate an objective assessment of kinematics for their usability in medical robotic applications. Due to the complex relationship between kinematic design and resulting dexterity, such examinations cannot be intuitively tested, but require systematic evaluation. In the experiment, a commercial high dexterity robot was used as a reference. We compared a 6-joint kinematics to redundant designs and we found that redundancy does not necessarily lead to a high dexterity, and can be compensated or outperformed by structural optimization. This includes a larger arm length and joint displacement enabling over-rotation of the joints. The implementation of structural improvements is more cost effective in real hardware than appending additional joints.

Ultimately, by using lightweight and simple medical robots with a correspondingly low energy balance and a specific design that satisfy the requirements, the injury risk can potentially be decreased to an acceptable level. In this study we investigated the benefit of optimized kinematic structures in medical applications. This is the first step towards a fully automated framework that optimizes the robot placement and the tool geometry in addition to kinematic structures. In future work we will use such a system also for other applications beyond medical robotics.

Author Statement

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