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Hybrid Analysis of a Spherical Mechanism for a Minimally Invasive Surgical (MIS) Robot - Design Concepts for Multiple Optimizations

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Abstract. Several criteria exist for determining the optimal design for a surgical robot. This paper considers kinematic performance metrics, which reward good kinematic performance, and dynamic performance metrics, which penalize poor dynamic performance. Kinematic and dynamic metrics are considered independently, and then combined to produce hybrid metrics. For each metric, the optimal design is the one that maximizes the performance metric over a specific design space. In the case of a 2-DOF spherical mechanism for a surgical robot, the optimal design determined by kinematic metrics is a robot arm with link angles ($\alpha_{12} = 90°$, $\alpha_{23} = 90°$). The large link angles are the most dextrous, but have the greatest risk of robot-robot or robot-patient collisions and require the largest actuators. The link lengths determined by the dynamic metrics are much shorter, which reduces the risk of collisions, but tend to place the robot in singularities much more frequently. When the hybrid metrics are used, and a restriction that the arm must be able to reach a human's entire abdomen, the optimal design is around ($\alpha_{12} = 51°$, $\alpha_{23} = 54°$). The hybrid design provides a compromise between dexterity and compactness.

Keywords. Surgical Robot, Dynamic Optimization, Kinematic Optimization

1. Introduction

Innovations in surgical techniques and equipment allow procedures to beceome more precise, less invasive, and inherently safer. With minimally invasive surgery (MIS), for instance, postoperative hospital stays have been reduced from more than a week (with 'open' surgery) down to just over a day. Integrating robotic systems into the operating

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room will help this trend in healthcare to continue, and has been a research focus for nearly twenty years. In 1995, Taylor [1] designed some of the earliest surgical robots. Shortly thereafter, Madhani [2] developed the Silver and Black Falcons, which were later adapted to become Intuitive Surgical's Da Vinci system. [3], [4],and [5] have also made important contributions with their designs for robotic systems.

The pivot point constraint imposed by the surgical ports in MIS makes a spherical mechanism ideal for a surgical robot. In a previous study [6], we presented the analysis of a spherical mechanism used as a surgical robot for MIS. Using data collected from the Blue Dragon, a device for tracking the position and orientation of MIS tools during in-vivo animal surgeries [7], we defined the dexterous workspace (DWS) as the workspace in which surgeons spend 95% of their time. Another measurement was also taken on a human patient to determine the workspace required to reach the full extent of the human abdomen. In [6], [8] the spherical mechanism was subjected to a kinematic optimization with a link length penalty as a scoring criteria.

For the case of a square matrix, Yoshikawa's dynamic manipulability measure can be calculated by the absolute value of the determinant of the Jacobian matrix divided by the absolute value of the determinant of the inertia matrix [9]. Broken down, this can be viewed as a *hybrid* of the kinematic manipulability measure with the addition of an explicit dynamic penalty on the inertia matrix. In this study, we changed the methodology of [8] and separated criteria into their individual kinematic and dynamic terms. We show how different performance criteria yield different robot designs for the same task-based optimization problem and discuss the advantages and limitations of each of the resultant solutions.

2. Methods

2.1. Performance Criteria

The two kinematic measures used were kinematic isotropy and kinematic manipulability. Kinematic isotropy is typically defined as the condition number of the Jacobian matrix, which is the ratio of the highest singular value to the lowest singular value [10]. The kinematic isotropy is a measure of directional uniformity, which indicates how easily a manipulator can move in any arbitrary direction. As in [6], we wished to express a bounded scoring criterion. We therefore chose to use the ratio of the lowest singular value of the Jacobian matrix to the highest singular value, or the inverse of the isotropy, as our kinematic measure.

The two dynamic measures used were the link length penalty previously used and the absolute value of the determinant of the inertia matrix. Yoshikawa's dynamic manipulability is defined as the kinematic manipulability divided by the determinant of the inertia matrix [9]. We therefore chose to use the inertia matrix determinant as a dynamic element just as we used the Jacobian matrix as a kinematic element. As in [6], we used a link length penalty, the sum of the link angles cubed, because it is proportional to beam stiffness.

Table 1 lists the eight performance criteria. K_1 and K_2 are purely kinematic measures, D_1 and D_2 are purely dynamic measures, and H_1, H_2, H_3 and H_4 are the hybrid combinations of kinematic and dynamic criteria.

Table 1. Performance Metrics

Denom\Num	1	$\|detJ\|$	$\frac{\sigma_{min}}{\sigma_{max}}$
1	n/a	K_1 (Manpulability)	K_2 (Isotropy)
$\|detM\|$	D_1	H_1 (Dyn. Manipulability)	H_2
L^3	D_2	H_3	H_4 (Criteria used in [8])

2.2. *Optimization Method*

Each optimization took into account a performance metric and required workspace. The scoring method uses the average performance of each design over the required workspace as well as the minimum performance within that workspace [11]. Based on previous measurements, we defined the dexterous workspace (DWS) as the workspace in which surgeons spend 95% of their time. The DWS is a conical volume of vertex angle $60°$. We also defined the extended dexterous workspace (EDWS) as the workspace required to reach the full extent of the human abdomen. The EDWS is a conical volume of vertex angle $90°$.

Based on preliminary mechanical design, we add the constraint that the elbow joint can only close to a minimum joint angle of 20° and extend to a maximum joint angle of $180°$. Each design is a pair of link angles, $(\alpha_{12}, \alpha_{23})$, and the design space was the combination of all pairs of link angles, each of which range in 1° increments from 30° to 90°. We sought a design with optimal performance within the workspace that surgeons spend most of their time (the DWS) that could still reach the full extent of the human abdomen (the EDWS). We therefore scored across the entire DWS, and then only considered those designs that contained the EDWS in their workspace.

3. Results

The optimization was performed with respect to each of the eight criteria. When optimized using the DWS as the required workspace for the mechanism, the kinematic measures (K_1,K_2) favored the longest possible links, the dynamic metrics (D_1,D_2)favored shorter links, and the hybrid metrics (H_1-H_4)favored more intermediate results (Table 2).

Table 2. DWS RESULTS Optimal Design of the spherical mechanism with respect to each of the 8 performance metrics. Results for each metric are link angles (α_{12}, α_{23}) in degrees.

Denom\Num	1	$\|detJ\|$	$\frac{\sigma_{min}}{\sigma_{max}}$
1	n/a	K_1:$(90°, 90°)$	K_2:$(90°, 90°)$
$\|detM\|$	D_1:$(33°, 39°)$	H_1:$(34°, 39°)$	H_2:$(40°, 35°)$
L^3	D_2:$(39°, 33°)$	H_3:$(39°, 38°)$	H_4:$(42°, 38°)$

When the above design space results were further subjected to the requirement that the designs needed to contain the EDWS within the reachable workspace, the smallest possible design was found to be larger (Table 3). This result was expected, since the EDWS is a larger workspace. Interestingly, because the optimal designs over the DWS for the dynamic and hybrid metrics were smaller than could reach the EDWS, those designs were filtered out, leaving similar designs with respect to either the dynamic or hybrid criteria.

Table 3. Results of optimization over DWS suject to the requirement that the design contains the EDWS in its workspace.

Denom\Num	1	$\|detJ\|$	$\frac{\sigma_{min}}{\sigma_{max}}$
1	n/a	K_1:$(90^\circ, 90^\circ)$	K_2:$(90^\circ, 90^\circ)$
$\|detM\|$	D_1:$(51^\circ, 54^\circ)$	H_1:$(51^\circ, 54^\circ)$	H_2:$(54^\circ, 51^\circ)$
L^3	D_2:$(53^\circ, 52^\circ)$	H_3:$(53^\circ, 52^\circ)$	H_4:$(58^\circ, 49^\circ)$

4. Discussion

The results have shown eight designs based on different scoring criteria. These scoring criteria take into account well established mechanism analysis methods. However, the optimization does not take into account clinical aspects. Specifically, the mechanism was optimized in isolation of the surgical context. It does not consider multiple manipulators over the patient in the surgical scene. In this section we discuss the advantages and limitations of each of the resultant designs.

When multiple manipulators are placed over the patient in the surgical scene, the manipulators are more likely to suffer from collisions with each other (robot-robot collisions) and with the patient (robot-patient collisions). Damage to the devices could occur from robot-robot collisions, and robot-patient collisions are clearly unacceptable for safety concerns. Robot-patient collisions may be avoided by positioning and orienting the robot so that it is always in an ‘elbow up’ configuration while operating on the patient. In surgical tasks where the tool tips are moved towards each other, such as running the bowel or tying a knot, robot-robot collisions are not always avoidable. This is particularly true for robots with longer links. Figure 1(a) illustrates this problem, showing two surgical manipulators with 90° links that have the tool tips approaching each other inside the patient. Additionally, the longer the link lengths, the more massive the mechanism will be, with greater inertial and gravity loads. This will require larger actuators and higher power consumption.

At the other end of the spectrum, optimization based purely on dynamic criteria yielded designs with very short links. The more compact a device, the less likely is to suffer robot-robot and robot-patient collision problems; however, as the tools reach the edge of the workspace, the manipulator’s kinematic performance would suffer from a kinematic singularity at the workspace boundary. A singularity within the surgical workspace would be completely unacceptable. As the link lengths become shorter, the mechanism’s mass and inertia decrease, resulting in better dynamic performance and requiring smaller actuators and lower power consumption.

Some of the hybrid cases provide a reasonable compromise between the desire for a compact and lightweight mechanism and good performance throughout the surgical workspace. Optimization over just the DWS leads to link angles ranging from 34° to 42°. When only the designs that contain the EDWS in the workspace are considered,

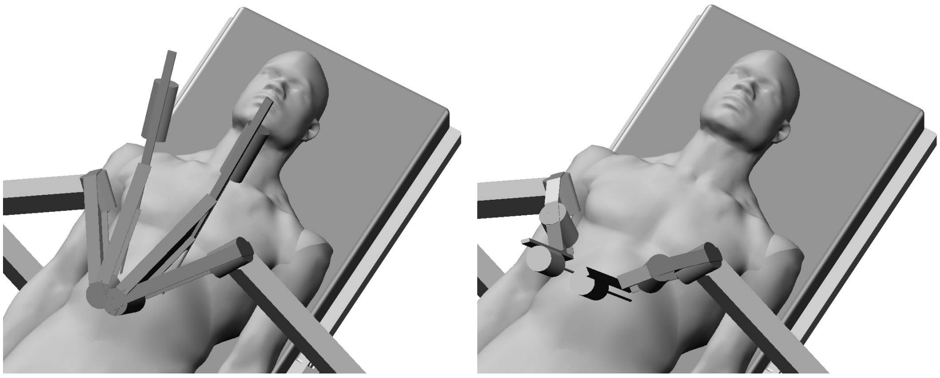
(a) (b)

Figure 1. (a) Robot arms with long $(90^\circ, 90^\circ)$ links suffer from elbow collisions when performing tasks such as running the bowel. (b) Robot arms with short $(39^\circ, 33^\circ)$ links suffer from kinematic singularities at the workspace boundary.

the link angles range from 49° to 58°. The requirement to reach the EDWS causes a considerable increase in the overall size of the surgical links, but adds the benefit of increased dexterity.

5. Conclusions

Before this study with multiple performance metrics was conducted, we performed a preliminary optimization of the spherical mechanism for MIS applications using the H_4 metric, kinematic isotropy with a link length penalty [8]. Due to differences in the optimization methodology, the previous optimization yielded different results. At that time we determined the optimal link angles to be $(\alpha_{12} = 75^\circ, \alpha_{23} = 60^\circ)$. A cable-actuated surgical manipulator based on this result has been designed and fabricated. The surgical manipulator features six degrees of freedom for tool orientation, tool insertion, roll, wrist, and grasp and supports the additon of a second wrist axis. The tool tips are Computer Motion MicroAssist 5 mm tools modified with a quick release system that we developed for interchanging tools with the ability to use a robotic tool changer.

5.1. Future Work

This study has presented the optimization of a spherical mechanism for robotic MIS applications. We have presented eight performance criteria from which designs were generated and discussed the advantages and disadvantages of each. We now understand that the results from our previous study may be overly conservative with respect to the desire for a large reachable workspace. Future development of our MIS robot system may include designing and fabricating new link pieces based on the results of this study. While more compact links will reduce the reachable workspace, it will allow for lower gravity torques on the joints and overall better dynamic performance. Future work will also include clinical trials with surgeons operating on porcine models, in both local and remote teleoperation environments.

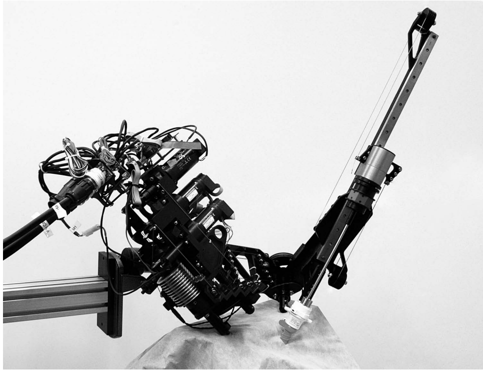

Figure 2. The University of Washington, BioRobotics Lab, 6-DOF Surgical Manipulator

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