Spherical wrist dimensional synthesis adapted for tool-guidance medical robots

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Abstract:

The objective of this paper is to present the dimensional synthesis of serial and parallel spherical wrists, an important step in the design process of medical robots. This step is carried out to obtain optimal dimensions of tool-guidance medical robots. In this goal, we have first studied the specifications of two robots with different medical applications: one for minimally invasive surgery and one for tele-echography examination. Then, we have established that the medical needs expressed by the expert were very different but the specifications in robotic terms have a lot of common points (kinematics, workspace, bulkiness). Both types of robots need a mobility of three rotations around a fixed point (trocar incision or probe contact point on the patient's skin). So a spherical wrist structure is adapted to their needs. An important constraint related to medical applications is that the robot must be compact in order to not obstruct or collide with its environment (medical personnel or patient). We perform dimensional synthesis allowing determination of mechanism dimensions for a spherical wrist, serial and parallel for a tele-echography robot, and serial for the minimally invasive surgery robot. We use multi-criteria optimization methods minimizing a cost function to obtain both good kinematic performance and compactness for the structure. The differences between the presented studies are in the choice of design criteria describing the performance and the constraints of the robot. These parameters must faithfully represent the specifications of the robot so that its performance can respond to the medical requirements. We show, here, the different methods used for optimizing the chosen kinematic structure for the particular medical application. These studies lead to prototypes which are validated by medical experiments. This process of dimensional synthesis will be used to other medical applications with different sets of specified constraints.

Keywords: Tool-Guidance Medical Robot, Dimensional Synthesis, Spherical Parallel Manipulator, Spherical Serial Robot, Optimization

1 Introduction

In the last decades, a number of medical robot prototypes have been created but they are designed to respond to precise tasks in various medical applications. Their kinematic structures have evolved and their capabilities have improved. The problem is that the medical robots often remain as prototypes, while few robots are used in real medical applications. The most successfully commercialised example is the Da Vinci robot used in minimally invasive surgery. This observation leads us to be interested in studying the dimensional synthesis step for medical robots used in different medical applications. First, we detail the medical applications studied - tele-echography and minimally-invasive surgery - and present the specifications of the two medical robots. We point out the common specifications and the different points between the two medical applications. Then, we present the methods used for the dimensional synthesis. Finally, we compare the different approaches to develop solutions to carry out dimensional synthesis for other medical robots.

Several studies on optimizations of spherical mechanisms have already been carried out. A serial spherical wrist mechanism, used for minimally invasive surgery, was optimized by Lum using a cost function depending on the mechanism isotropy and stiffness [1], [2]. Gosselin optimized a 3 DoF spherical parallel manipulator to obtain an isotropic robot [3]. Others authors sought optimum design of parallel spherical manipulators considering only dexterity [4], [5]. Chaker et al. investigated a design and analysis of a spherical parallel mechanism (SPM) to be used as a haptic device for a medical application. An optimization procedure was carried out to find the optimal spherical manipulator with the closest workspace to the desired one [6], [7].

The particularity of our process of optimization is taking into account opposite criteria (kinematic performance, size) to make a design compromise to obtain a compact, lightweight robot, having good path following used in medical robotics.

2 Medical robot specifications

The medical needs of tele-echography robots and minimally-invasive robots are detailed. Then, the specifications of the two medicals robots are described.

2.1 Echography robot

Echography is an imaging technique widely used for all kinds of examinations (abdominal, fœtal, emergency diagnostic). This technique has the advantages of being rapidly implemented and inexpensive. The result of the diagnostic can be given immediately to the patient. Otherwise, this technique is expert dependent and there is a lack of experts in regional hospitals or in isolated sites. A tele-echography robot allows a medical expert to perform this clinical act on a patient at a distance. The doctor operates a fictive probe in the "expert premises," as shown in Figure 1. The probe movements are sent to a slave robot situated at the "patient premises" by satellite or terrestrial links. The robot is designed to hold the real ultrasound probe on the patient's body and reproduced the fictive probe movement. Ultrasound images are sent back from the patient site to the medical expert who can perform his diagnosis in real time like he would perform a real echography examination.

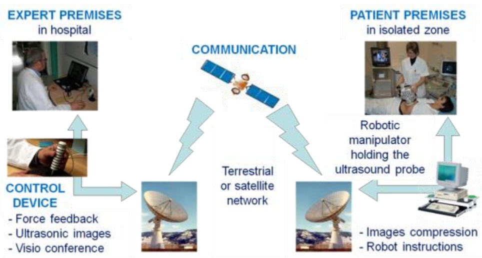


Figure 1: Tele-echography robot principle.

2.2 Minimally-invasive surgery (MIS) robot

The practice of surgery has progressed in the last two decades from an invasive paradigm to a primarily minimally invasive paradigm. Surgeons now use several long, thin tools, including a camera, to perform many different types of abdominal surgery. Robotics can be applied to MIS to enable expert telesurgery, remove tremor, provide motion scaling, and so forth. Therefore, the objective is to create a compact telesurgical robot which conforms to the constraints imposed by the MIS paradigm.

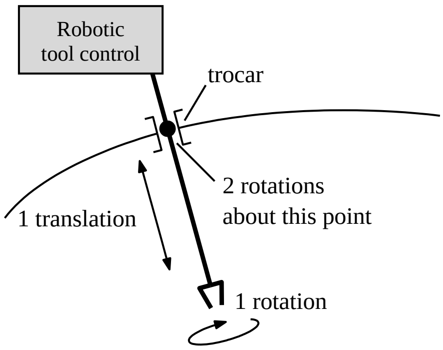


Figure 2: Minimally invasive robot principle

2.3 Medical act requirements

After having studied the medical gestures with different methods and different medical experts [8-10], the specifications of the two medical robots are established. They are summarized in Table 1.

Table 1: Tele-echography robot and minimally-invasive robot specifications.

	Tele-echography robot	MIS robot
Kinematic	4 DoF (3R with RCM+T) conical workspace θ=35° avoid singularities	4 DoF (3R with RCM+T) conical workspace θ=60° avoid singularities
Forces and Torques	F=20N	F=20N
Safety constraints	no collision between the moving parts of the robot no collision with the patient's body (θ_s<75°)	no collision between the moving parts of the robot no collision with the patient's body
Specific constraints	transportable to isolated sites, body mounted	transportable to different operating rooms
Dimensions	lightweight: mass less than 3 kg, compact: width < 45cm	compact and lightweight

The specifications describing kinematics, forces and torques, safety constraints, dimensions and specific constraints are detailed. Many common points between the two medical specifications can be mentioned as follows. The kinematic specifications are similar. The robots need 4 DoF, 3 rotations with a remote centre of motion (RCM) and one translation to exert a force along the tool axis. The RCM is the contact point between the probe and the patient skin for the tele-echography robot and the trocar for the MIS robot. The workspace is conical. The vertex angle of the cone depends on the application (about 35° for tele-echography, 60° for MIS). This value is a fuzzy limit, which is expert dependent determined by the analysis of medical gestures. Singularities inside the workspace must be avoided to obtain good path following of medical gestures. The force exerted by the effector is fixed at 20N for the two robots, one for using the MIS tools, the other to push the probe to obtain a better echography image of the organ. The safety constraints are very important in medical robotics. The robot must have no collision with the patient's body. A safety angle has been defined to respect this condition ($\theta_s = 35°$).

The robots present specific needs which depend on the application. The tele-echography robot must be transportable to different sites and supported by the patient. These needs lead to dimensional constraints. The tele-echography robot must have a mass less than 3kg. It must be compact; its width must be less than 45cm so as to not be in the way of the patient. The MIS robot must be transportable to different operating rooms, so it must be compact and lightweight as well. So, the specifications are very similar, with only the limit of the conical workspace being significantly different. The first specification we must respect is the robot mobility. The kinematic structure chosen allows satisfaction of this constraint.

2.4 Topology Specifications

The robots must both have 3 rotations with a RCM. The naturally suited structural candidate is the serial spherical wrist. However, we also consider the parallel spherical wrist for the tele-echography robot because this structure has no singularity in the workspace. The kinematic structures which are to be dimensionally optimized are presented in Figure 3.

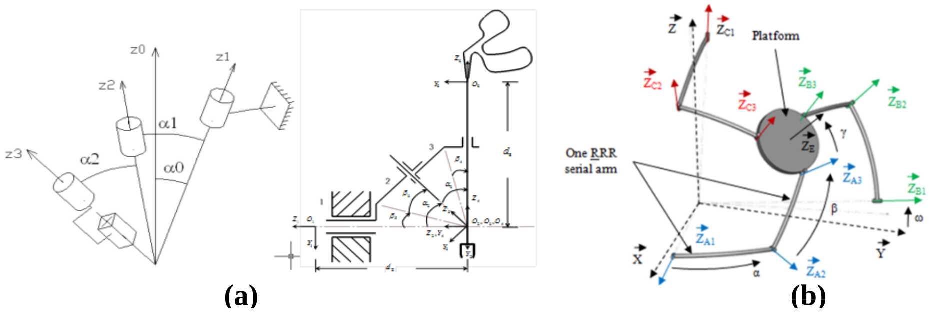


Figure 3: Kinematical sketch and parameters of tool-guidance robots: (a) serial wrist; (b) parallel wrist

The kinematic structure design parameter vectors, I, are:

- $I = [\alpha_0 \quad \alpha_1 \quad \alpha_2]^T$ for the serial tele-echography robot
- $I = [\alpha \quad \beta \quad \gamma \quad \omega]^T$ for the parallel tele-echography robot
- $I = [\beta_3 \quad \beta_5 \quad r \quad L]^T$ for the minimally invasive surgery robot

3 Dimensional synthesis

3.1 Formulation

The aim of this section is to develop and to solve a multidimensional, nonlinear optimization problem of selecting the geometric design variables for the tool-guidance robot. The robot must be compact and describe a desired workspace with a good kinematic performance.

The optimal dimensional synthesis of the tool-guidance robot can be defined as follows:

Given: a specified volume in space,

Find: the optimal parameters of the tool-guidance robot describing the workspace with a good kinematic performance while remaining compact.

If the desired volume is a cone, then the workspace of the tool-guidance robot has to include the given conical volume.

The general associated optimization approach, with n parameters for a suitably chosen objective function $F(I)$, can be stated as:

$$\begin{aligned} &\text{maximize } F(\mathrm{I}) \\ &\text{subject to } \begin{array}{l} g_i(\mathrm{I}) \leq 0, i = 1,..,n \\ h_j(\mathrm{I}) = 0, j = 1,..,m \end{array} \end{aligned} \quad (1)$$

where I is the unknown vector of parameters, and $\mathrm{g_i}(\mathrm{I})$ and $\mathrm{h_j}(\mathrm{I})$ represent respectively inequality and equality constraints of the problem. By convention, the standard form defines a minimization problem. A maximization problem can be treated by negating the objective function.

The identified specifications in the previous section can appear in the problem formulation as constraints or criteria. In the next section, we detail the formulation of the optimization problem for serial and parallel wrists. The formulation differs from one structure to another and from one application to another but the approach remains the same. The difference between the methods used for each robot optimization rests on the criteria and the constraint choices.

3.2 Serial spherical wrist

3.2.1 MIS application

The robot must describe a conical workspace with good kinematic performance and must be compact. A positive objective function F is proposed to linearly combine all criteria and is used to evaluate candidate solutions. The overall objective function to evaluate the performance is:

$$\mathrm{F(I)} = \mathrm{k_1} \cdot \mathrm{W} + \mathrm{k_2} \cdot \mathrm{K_g} + \mathrm{k_3} \cdot \mathrm{S} \quad (2)$$

where $\mathrm{k_i}$ is the weight of the $\mathrm{i^{th}}$ criterion and $k_1 + k_2 + k_3 = 1$. The considered criteria, including workspace (W), consistent manipulability $(\mathrm{K_g})$ and size (S), are minimized to achieve desirable performance. Each of these criteria is expressed such that the values can range from 0 to 1, with 0 being optimal. By changing the priorities of each criterion, various desirable performances with different emphases can be achieved. The optimization goal is then to find a set of design parameters which minimizes the objective function according to the priorities expressed by the weights.

3.2.2 Echography application

The kinematic structure adapted for tele-echography is the serial spherical wrist. This structure presents a singularity located at the center of the workspace. To displace the central singularity of the classic structure outside the most frequently used portion of the workspace, an incline offset of an angle α_0 from the normal direction to the patient's skin is proposed in Figure 2.

The dimensional synthesis is carried out via an optimization procedure. The aim is to determine the design vector, I, of the inclined structure to produce good kinematic performance near the singularity to offer better medical gesture following, as well as a compact structure. The choice of the design criteria is very important for respecting the tele-echography robot specifications.

The optimal solution must have both good kinematic performance and compactness, respectively expressed using global dexterity η and global compactness C_g. The optimization problem for a suitably chosen objective function F is defined as:

$$\begin{aligned} &\text{maximize } F(I) = k \cdot C_g + (1-k) \cdot \eta_g \\ &\text{Subject to } \begin{array}{l} \alpha_1 + \alpha_2 - \alpha_0 \geq \theta_n \\ \alpha_1 + \theta_n \geq 75° \end{array} \end{aligned} \qquad (3)$$

The maximum of the objective function is sought, with the weighting factor k being a real number between 0 and 1. The set of solutions is limited by the tele-echography robot constraints. The first constraint enforces the necessary workspace:

$$\alpha_1 + \alpha_2 - \alpha_0 \geq \theta_n \qquad (4)$$

The second constraint equation represents the safety angle condition:

$$\alpha_1 + \theta_n \geq \theta_s \qquad (5)$$

The choice to take into account the necessary workspace and the safety angle as constraints and not as criteria is to guarantee these conditions are verified by the optimal structure. The conical workspace must have a minimal vertex angle $\theta_n = 35°$ and the robot arms must not be inclined more than $\theta_s = 75°$ to avoid collision with the patient.

3.3 Parallel spherical wrist

The architecture to be designed has to respond to several specifications: it has to be light and compact, and it has to be able to generate the minimal necessary workspace. Also, a good trajectory tracking is required.

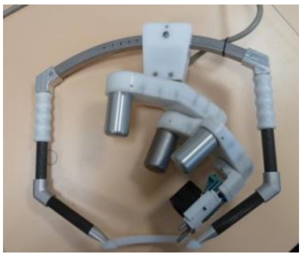
The aim of the dimensional synthesis is to identify the design vector that will generate the highest level of dexterity, considered as the criterion, while respecting the two selected constraints (workspace and compactness). The associated optimization approach, with four parameters for a suitably chosen objective function F, can be stated as:

$$\begin{aligned} &\text{maximize } F(I) = \eta_I^G \\ &\text{Subject to } \begin{array}{l} W_I = 0 \\ C_I = 0 \end{array} \end{aligned} \qquad (6)$$

Here, C_I represents the number of orientations of the end effector that generate external collisions. When C_I is zero, the entire workspace is free of external collisions. W_I gives the number of unreachable points in the necessary workspace. If W_I is zero, this means that the entire workspace is reachable.

4 Results

A Pareto front of only four solutions maximizing the objective function respecting tele-echography constraints is obtained. The solution retained, which is a compromise of the two opposing criteria of global dexterity and compactness, is the PROSIT 1 robot shown in Figure 4-a. This solution is the most compact with no singularity in the centre of the workspace. The prototype has been built and tele-echography visual servoing experiments have been carried out.



(a)

(b)

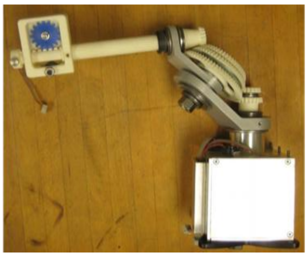


Figure 4 : (a) PROSIT-1 tele-echography robot; (b) Prototype MIS robot.

For the case of the MIS robot, the optimization led to a family of solutions which satisfied the objectives and constraints. Using a set of weights which gave similar emphasis to each of the three criteria, the solution shown in Figure 4-b was obtained. The prototype has undergone bench top and clinical experiments to validate its intended functionality.

5 Conclusions

This paper seeks to describe a dimensional synthesis process of spherical wrists for tool-guidance medical robots. Serial and parallel architectures were presented. Medical needs for two different applications (minimally invasive surgery and echography) were enumerated. Despite the differences between these applications in terms of medical needs, the mechanical specifications for different robots (kinematics, workspace, bulkiness) were the same or very similar. Multiple optimization criteria are combined linearly, as is presented for different examples, in the objective function to meet practical needs in realistic applications. It is known that the most difficult point is the choice of the design criteria. The difference between the methods used for each spherical wrist optimization rested on the choices of criteria and constraints. Even though these methodologies may not give unique solutions, additional constraints appropriate to other medical applications can be used, allowing extension of these methods to a variety of medical robot design applications.

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