Kinematic Design of a Lighting Robotic Arm for Operating Room

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Abstract. This paper deals on the design method applied to create a new useful robot for a lighting operating room. We present the specifications for this particular medical application, the proposed kinematic solutions as well as the topological and dimensional syntheses performed to choice the optimal solution. The work presented in this paper was conducted with a closely industrial collaboration, and a patent application of the chosen kinematic solution has been filed.

Key words: medical design, kinematics, mechanism syntheses.

1 Introduction

A lighting for operating room is a poly articulated medical arm. During the surgical operation, the optical axis of the lighting must be focused towards the desired surgical zone. The lighting is pre-positioned by the surgeon (or medical staff) before starting the operation. When the operation begins, the surgeon must not move the lighting arm for aseptic reasons, i.e. he cannot accede to the sterile zone. Therefore, the surgeon must ask to a medical assistant to move the arm, which is much less optimal than in the case of direct manipulation.

The study presented in this paper is developed in the context of the SMILE[1] French regional project, whose goal is to design a lighting robotic arm and control them using a touchless system based on hand gesture recognition [3-6]. The project is composed of two main parts: robotic and imaging parts, respectively. Moreover, only the robotic design study is presented here.

The paper is organized as follows. In section 2 we present the robotic and ergonomic specifications given by the industrial partner project Maquet SAS[2] to design the mechanism. The different topological solutions developed are presented and compared according to the industrial specifications in section 3. Then, a dimensional synthesis is described in section 4. Conclusions about the proposed approach are presented in the last section.

[1] SMILE: Sterile Manipulation Interface of Lighting Equipment
[2] http://www.maquet.com/fr/

2 Specifications

Maquet SAS Company builds manual lighting arms for operating room. For SMILE project, the company defined some specifications for a robot charged of positioning the lighting. Different criteria are specified: kinematic (DoF, workspace), dynamic, environment, aseptic, ergonomic, safety, cost, compatibility with existent system and so on.

For a first step, certain criteria are used to limit the kinematic solutions, e.g. the DoF of the robot for positioning the lighting. Moreover, in this step other specifications are qualitatively analyzed. For defined the specifications, several studies about the positioning of the lighting during surgeries are carrying out, as shown in [9,11].

2.1 Surgical scenes and movement

According to the type of surgery and the needs of the medical staff, it is necessary that the dome of lighting moves towards different positions around the medical scene. Generally three scenes were identified (Fig. 1 (a)). In the first scene, the dome is localized behind the surgeon's head, avoiding that the beams of light are pointed towards his eyes. A second scene exists when a vertical projection of the beams of light towards the patient becomes necessary. Finally, in some cases, the dome must turn around a target position, creating a remote center of motion.

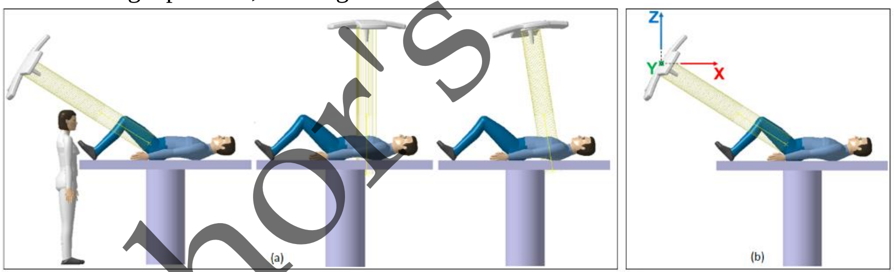


Fig. 1 (a) Operating scenes, (b) 3D movement

Moreover, the lighting dome must be capable to move in the horizontal plane (X, Y); movements in Z-axis are suitable but not mandatory (Fig. 1 (b)).

2.2 Medical gesture

From the observations made by the company, three medical cases of displacement of the dome are specified, denoted by C1, C2 and C3:

C1: the dome moves or turns following a desired surgical trajectory.

C2: the dome turns around a desired surgical position.

The third case (C3) is a combination between C1 and C2.

From precedent experiments conducted by the Maquet SAS Company, C1 represents 8% of medical surgery cases, C2 and C3 correspond to 36% and 56% of medical surgical procedures, respectively. After studying the specifications given by the company, the topological synthesis is carried out to propose kinematic structures adapted to the needs presented above.

3 Topological synthesis

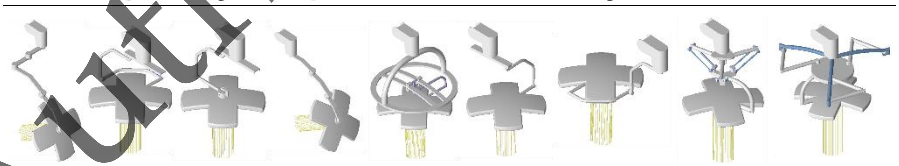
In this part, we present the topological synthesis of mechanism carried out in the project context. In literature, there are few papers on topological robotics. There are often focused on specific kinematic structures and not linked to a particular application. Tuttle et al. [10] proposed a method of topological synthesis based on finite symmetry of group theory, Mitrouchev [7] used combinatory analysis for topological robotic parallel mechanisms. This method allows to obtain all the possible solutions to the position end-effector and actuators in parallel kinematic chains. Laribi [12] used a method based on a genetic algorithm for the synthesis of plane, spatial and parallel robots. We choose a multi criteria analysis based on a decision matrix to obtain the optimal solution, allowing to include quantitative but also qualitative industrial expert reviews.

3.1 Kinematic structures

In order to accomplish the overall specifications given by the company, the robot should have at least 4 DoF: 2 DoF for the translation allowing to move the lighting in the horizontal plane and 2 DoF allowing the orientation of the lighting dome. It is important to note that the existent non-robotized arm has only 3 Dof [9].

Based on the specifications presented above, nine kinematic structures have been proposed, as presented in Table 1.

Table 1. Kinematic structures proposed

Solution								
A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***
								
4 DoF	4 DoF	3 DoF	3 DoF	3 DoF	3 DoF	4 DoF	5 DoF	4 DoF

Certain of these solutions have only 3 DoF, limiting the robot movements but giving the advantages of lightweight of the overall structure as well as in terms of price. This step of seeking solutions allows us to propose two structures based on parallel chains. In terms of manufacturing, the parallel robot is more complex than the serial one but it offers a better mechanical balancing, a great accuracy and it guarantees a higher velocity of the manipulated tool [2]. Even if the velocity criterion is not essential for our application, the control of the mechanical balancing is a point of great importance. Nevertheless, the workspace/compactness ratio is often less important than in the case of serial solutions.

3.2 Decision matrix

After having proposed different kinematic structures, we have compared them to find the optimal/more adapted robot based on the specifications defined by the company. Thus, we defined a decision matrix to classify the kinematic solutions, an example is presented in Table 2 for Solution A (The reference frame is the same used in Figure 1(b)). This decision matrix is composed of two parts. First, all the solutions are evaluated qualitatively from the criteria defined in the specifications. There are three possibilities of qualification: Yes (if the robot always verify this criterion) or Possible (if the robot comply the criterion under conditions) or not possible (the robot has not level of flexibility). If the last qualification is given, the solution is then penalized for the second part of the decision matrix. Moreover, if a solution obtain "Not possible" for a criterion flexibility "none", then the solution is automatically annulled.

Table 2. Comparison of proposed solutions – first part

Criterion[1]	*Criterion flexibility*	*Required value*	*Solution A*
Maximum displacement of the center of mass (CoM) of the dome in the (X, Y) plane along X-axis and Y-axis	None	30cm	Possible
Maximum rotation of the dome around the two directions of the horizontal plane (X, Y)	Possible	± 90°	Not possible
Maximum rotation of the dome around the vertical axis (Z-axis)	Possible	360°	Possible
Number of links	None	Unlimited	Yes
At least one posture must allow the coincidence between the CoM and the first vertical axis	None	Yes	Possible
The supporting link designed by the company can attach the solution	None	Imperative	Yes
The solution must not disturb the lighting functionalities	None	Imperative	Yes

In the second part, see Table 3, the performance criteria are defined to differentiate the solutions validated in the first part.

Each criterion has a weight-coefficient characterizing the priority scale. Each kinematic solution is evaluated by assigning a grade between 0 and 1.

Table 3. Comparison of proposed solutions – second part

Criterion	*Weight*	*Quantification*	*Grade (Solu. A)*
Number of DoF lost in case of motor failure	2	<=1 (1) / >=1 (0)	1
Possibility to control the vertical translation of the lighting dome	1	Yes (1) / Not (0)	0
Possibility to control the movement of the lighting dome along the horizontal plane while focusing on the target zone	1	Yes (1) / Limited (0.5) / Not (0)	0.5
Similarity with the existent non-robotized system	2	Yes (1) / Not (0)	0
Kinematic complexity (number of links, type of joints, number of actuators) [10]	4	Between 0 and 1	0.27

The total score of a solution is defined by adding all the weight-grade products. The ranking of the solutions is presented in Table 4.

Table 4. Final ranking of the proposed solutions

					Solution				
	A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***
Score	5.39	8.07	7.69	5.25	5.69	7.69	8.12	2.64	3.12
Rank	6	2	3	7	5	3	1	9	8

From these results, the solution G can be defined as the optimal kinematic solution. Nevertheless, in agreement with Maquet SAS Company, a further analysis will be performed for the parallel solutions H and I, considering their performance in terms of mechanical balancing and accuracy.

3.3 Comparison of parallel solutions

We compare the two parallel solutions in four criteria: presence or not of singularity in the workspace (circle with R = 30mm), forces supported by the robot (the light has a mass of around 20 kg), frictions in joints, and workspace/compactness relation. The Solution H is based on a Delta-robot kinematics with 5 DoF [2] whereas the Solution I is based on a 3RRR planar robot with 4 DoF [1,8].

3.3.1 Singularities

Usually parallel kinematics have more singularity cases than serial solutions [1]. Singularities are positions where the robot cannot be controlled. From the specifications given above, the workspace can be considered like a disk with 30 mm radius. For the two parallel solutions, singularity positions must be localized outside the disk. By adjusting some geometric parameters, singularities can be moved outside of the workspace in both cases.

3.3.2 Forces

An analysis concerning the forces supported by the robots was carried out. Delta-robot (Solution H) was typically designed for “pick-and-place” tasks [2]. It uses one DoF for a vertical movement carrying the load and two DoF to move in the horizontal plane. Thus, the configuration of the actuators on the Delta-robot allows to support the weight load naturally. On the other hand, the 3RRR robot (Solution I) is a planar robot designed for horizontal displacements [1,8]. In this case, the actuators are not positioned to move a weight along the horizontal plane or even to support a weight with natural movement of joints. From this point of view, the Solution H looks more adapted for our application.

Finally, some joint frictions are produced when supporting the weight of the lighting dome. Furthermore, these frictions damage passive joints (without actuators). In the case of Solution H, joint movements are naturally generated by the direction of the lighting weight force, transmitting that force to the actuators and generating low passive joint frictions. However, the Solution I is the opposite case, because the weight force is not transmitted to the actuators, producing higher passive joint frictions. A summarized table of this analysis is presented below.

Table 5. Comparison of the two parallel kinematics

Model	***Singularities***	***Forces axis***	***Friction***
Solution H	Outside of the workspace	Torques from weight force are transmitted to the actuators	Low passive joint frictions
Solution I	Outside of the workspace	Torques from weight force are not transmitted to the actuators	High passive joint frictions

A last analysis of the parallel solutions was performed comparing the workspace/compactness relation. For the two robots, an adjustment of geometrical parameters was made to obtain the necessary workspace (disk/cylinder of radius 30 mm). CATIA software was used to reproduce all the possible robot movements into the workspace, determining their compactness. The workspace of the Solution H is a cylinder of ratio 30 mm. Figure 2 shows the compactness superposition of the two robots. It is clear that Solution H is more compacted than Solution I.

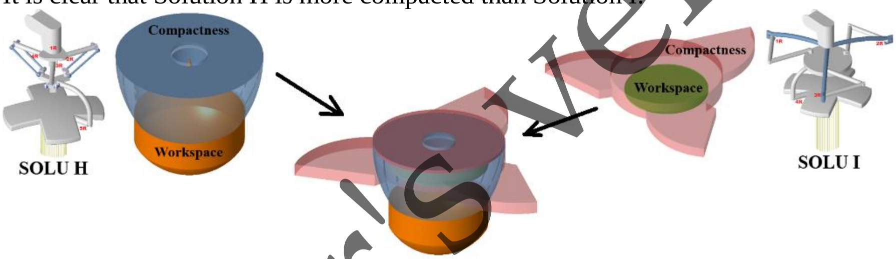


Fig. 2 Comparison of workspace/compactness relation for Solution H and I

To conclude, the analysis presented above allows to conclude that Solution H is the more adapted parallel solution to satisfy the specifications of the application.

Nevertheless, in order to reduce the prototype cost and to produce a structure close to the already existent arm, the company decides to develop the serial solution G, whose dimensional phase is presented in the next section.

4 Dimensional synthesis (Dynamics analysis)

A dynamic analysis has been performed in Solution G, in order to know the motor characteristics needed in each actuated joint, as well as the torsional and bending forces applied in every link. The goal of this analysis is to find the joint configurations for which the motor torques are maximum. The Newton-Euler algorithm [7] was applied to the Solution G for every possible joint combination. In order to take into account inertial effects, joint velocities and accelerations were considered maximum.

The Solution G presents 4 DoF, two mobility in the horizontal plane (X and Y) and two rotations mobility. Therefore, this solution has 4 revolute joints (q_4, q_5, q_6, q_7), as shown in Figure 3.

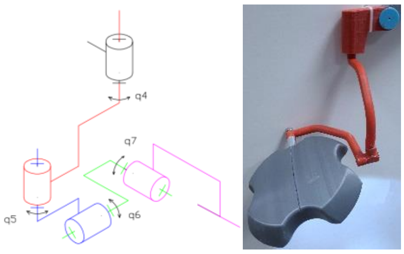


Fig. 3 Solution G – kinematic chain and 3D printed prototype

The dimensions, velocities and accelerations of links used for the dynamic analysis are presented in Table 6. Moreover, a maximum joint speed $\dot{q}_i = \pi/32\,[rad \cdot s^{-1}]$ and acceleration $\ddot{q}_i = \pi/32\,[rad \cdot s^{-2}]$ for $i = 4\ to\ 7$ were used.

Table 6. Details for dynamic analysis

	S4	***S5***	***S6***	***S7 (Lampe)***
Material	Aluminum ($\rho = 2710\ Kg \cdot m^{-3}$)			Plastic ($\rho = 1050\ Kg \cdot m^{-3}$)
Section	$\emptyset_{ext} = 50\ mm, \emptyset_{int} = 45\ mm$			-
Weight	0.926 Kg	0.351 Kg	1.094 Kg	20.16 Kg

The Newton-Euler's algorithm is applied for all the articular combinations according to the robot workspace: $q_4 = 0°$, $0° \le q_5 \le 31°$, $-90° \le q_6 \le 90°$ and $-90° \le q_7 \le 90°$. The obtained results don't take into account motor weights because they are not chosen yet. Thus, we must apply the algorithm two times, the first one to obtain the characteristics of the motors and choose them, and the second one to include the motor weights. If the results of motor torque and axial forces found in the second step exceed the motor capacities, we must choose another actuator.

For the first step of calculation, the results are summarized in Table 7. The second step is omitted in this paper, further details of this analysis will be provided in a next paper.

Table 7. Results obtained in the first step (without motor weights)

	Joint 4	***Joint 5***	***Joint 6***	***Joint 7***
Maximum Radial force [N]	1.2356	1.2464	208.33	197.60
Maximum Axial force [N]	220.85	211.77	0.82	197.61
Maximum Bending moment [Nm]	46.86	85.79	73.73	69.98
Maximum Motor torque [Nm]	0.49	0.61	4.44	3.71

5 Conclusions

In this paper, we present the design method applied to create a lighting robotic arm for operating room. This study was carried out in the context of the SMILE regional project in collaboration with Maquet SAS Company. Some kinematic solutions were proposed based on the specifications of the industrial partner. A topological synthesis was then carried out through a decision matrix, combining quantitative and qualitative criteria. A particular analysis was made to the parallel solutions, even if a serial solution was resulted as the optimal in the decision matrix. The chosen solution was then defined in dimensional synthesis, where the maximum torque motors were provided. A patent application [14] for the chosen solution was filed, in order to protect the kinematic design of this robotized lighting arm for operating room. Moreover, a scaled 3D printed prototype was first built and some experiments in operating room using pigs are planned once a motorized real-scale prototype will be produced.

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