A novel Kinematic structure for Tele-echography Application

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Abstract
In this paper, a novel six degrees of freedom that are five degrees of rotational freedom and one degree of translational freedom, hybrid robot is proposed. The robot is used in tele-echography application. It main task is to hold and place a probe on the patient's skin during an examination. The robot structure consists of two modules: The first one is the translation module which is consists of a five bar linkage, enabling the probe to move on the horizontal plan of the body, the workspace for this module is analyzed and the manipulability measure is presented to evaluate the best postures and the singularities positions. The second one is the orientation module; it is used to obtain a spherical motion around the point of contact with patient’s body. A serial kinematic of this module is proposed which are three revolute joints with concurrent axes.

Keywords: Tele-echography; five bar linkage; kinematic model; workspace; maipulability

1. Introduction
Robots are widely used in medical field for Tele-echography efficiently and accurately. Tele-echography is a medical examination that allows a medical expert to examine internal organs of a patient from a distant site. The major motivation of this technique is the lack of medical assistance in isolated sites or for emergency cases. As means of addressing this problem, an alternative way is proposed by using robotic system to enable specialists to remotely perform ultrasound diagnosis [1-4].

Around the world, different kinematic structure for robotized tele-echography have been developed. Masuda et al. [1] designed a robot with 6 degrees of freedom that consists of an unsymmetrical parallel mechanism with three legs fixed to the bed side.

Najafi and Sepehri [2] developed a spherical serial wrist with parallelogram structures in 2008. In Japan, FASTele was proposed by Keiichiro et al [3], it is a portable and attachable tele-echography robot system based on gimbals mechanisms. In France, several robots were designed by the Vision and Robotics Laboratory, OTELO, ESTELE and PROSIT-1, having a serial kinematic structure with three revolute joints in which all the joint axes intersect at a common point [4].

Our aim, therefore, is to propose a tele-echography system, consisting of two modules, one parallel five bar linkage and one serial, described in detail in this paper.

The paper is structured as follows: Section 2 is dedicated to the presentation of echography concept. Sections 3 deal with system overview of the new proposed robot, in this section we have two main parts, the first one is about a positioning module which is a five bar linkage, workspace visualization and manipulability measure of this mechanism are presented in order to evaluate kinematic performance of this module. The second one presents a three serial revolute joints for orienting module. Finally, conclusions of the study are given in Section 4.

2. Echography concept
The abdominal examination requires two principal tasks: the first one is focused on determining the organ to be examined, and the second one is focused on finding the best incidence between the organ and the ultrasound waves of the probe. The specialist moves the probe in a circular motion around a contact point with the patient’s body. This point is the center of motion and the workspace produced is a conical space Fig1. During the examination, the contact between the patient’s body and the probe is required with an appropriate contact force applied to the skin in order to obtain clearer ultrasound image. Hence a robot should be able to perform both tasks.

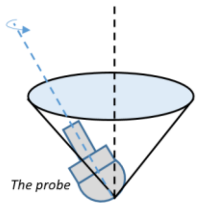


Figure 1: conical space of the probe

3. System overview
The main requirements for the design of the robot are the following: the robot should occupy the abdomen space of the patient in the operating room, not to interfere with the patient or the expert medical in the operating area, to be simple and lockable at any desired position. In addition, the rigidity and safety features are an important factor to be taken into consideration.

The kinematic configuration of the proposed system is comprised of two main parts, the arm (for positioning) and the wrist (for orienting the tool). The major requirement of the wrist is to perform spherical movements around the contact point with the abdomen, a three degree of freedom serial link is proposed for the wrist mechanism [5].

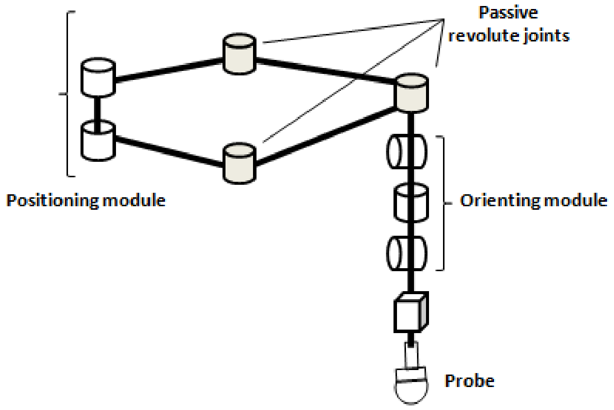


Figure 2: Kinematic structure of the proposed robot

3.1. Positioning module

There are several possibilities of mechanisms to perform the positioning motion. Generally to put the tool of a robot in a two dimensional space, at least 2 degrees of freedom is required. In this work we propose the use of a five-bar parallel linkage mechanism which can provide planar motions and cover required workspace Fig 3.

These mechanisms attract more attention from researchers thanks to its high stiffness, rigidity and accuracy.

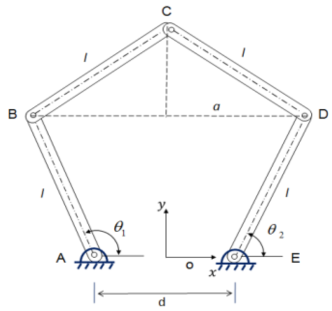


Figure 3: Five-bar linkage

It is composed of four arms, five revolute joints, two active joints and three passive joints. The pivot joints at A and E are motorized. All four links have equal lengths.

Forward Kinematics:

The direct kinematic model of the mechanism is:

$$x=\frac{1}{2}(-d+l\cos\theta_1+l\cos\theta_2)+\frac{1}{2}\chi\frac{\sqrt{l^2-a^2}}{a}(l\sin\theta_1-l\sin\theta_2) \quad (1)$$

$$y=\frac{1}{2}(l\sin\theta_1+l\sin\theta_2)+\frac{1}{2}\chi\frac{\sqrt{l^2-a^2}}{a}(d-l\cos\theta_1+l\cos\theta_2) \quad (2)$$

Where:

l is the lengths of the links

$p=[x\ y]^T$ is the position of C with respect to the base coordinate system.

$\chi=+1$ if C is on the right side of vector BD

$\chi=-1$ if C is on the left side of vector BD

From the above equations, there are two solutions for the forward kinematic problem of the mechanism illustrated in Fig4.

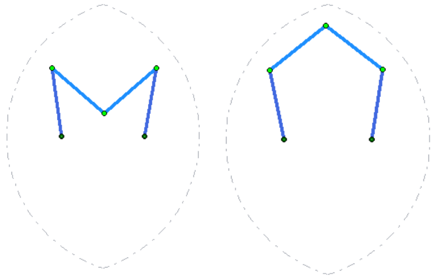


Figure 4: The two forward kinematic solution

Theoretical workspace:

Theoretical workspace is defined as the region that the end effector can reach of set values of the joints angles without taking into consideration the interference between links and the singularity positions.

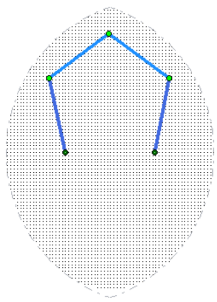


Figure 5: workspace of five bar linkage

Based on the workspace obtained, this mechanism can cover the space required by the application.

Manipulability Analysis:

To evaluate the performances of a mechanism several criteria could be involved, for such a reason, the manipulability measure is the most studied issue in the field, which is the ability of changing the position and orientation of the end effector that allows to ensure that a robot stay away from singular configuration.

An important way to determine that a singular position is not reached is to use the determinant of the Jacobian matrix by verifying it is far away from zero as possible.

The manipulability for redundant robot is defined as:

$$w=\sqrt{\det(JJ^T)} \quad (2) \quad (3)$$

For nonredundant robot manipulators:

$$w=\left|\det J\right| \quad (4)$$

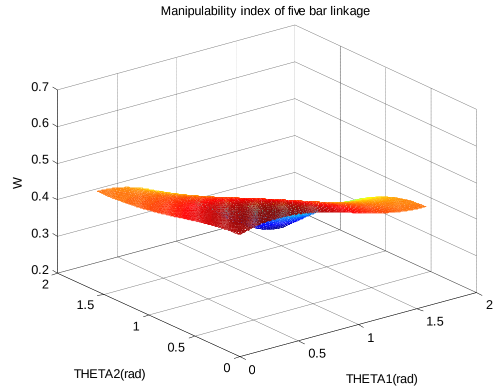
Where J is the Jacobian of the mechanism.

W represent the manipulability measure at the configuration specified by the set of values for joints angles. The representation of this criterion allows us to show how far the robot is from singularities positions.

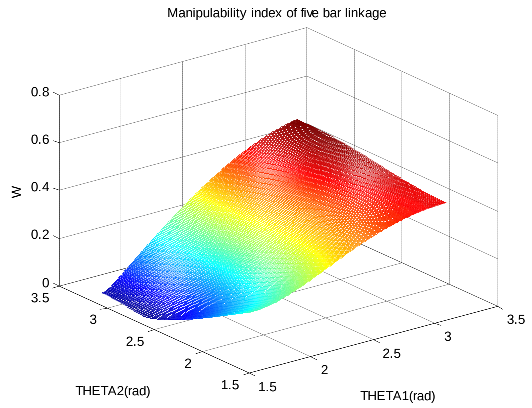
The Jacobian matrix of the mechanism is given by:

$$W=\left|\begin{matrix}(-\frac{1}{2}l\sin\theta_1+\frac{1}{2}\chi\frac{\sqrt{l^2-a^2}}{a}l\cos\theta_1)(\frac{1}{2}l\cos\theta_2-\frac{1}{2}\chi\frac{\sqrt{l^2-a^2}}{a}l\sin\theta_2)- \\ (-\frac{1}{2}l\sin\theta_2-\frac{1}{2}\chi\frac{\sqrt{l^2-a^2}}{a}l\cos\theta_2)(\frac{1}{2}l\cos\theta_1+\frac{1}{2}\chi\frac{\sqrt{l^2-a^2}}{a}l\sin\theta_1)\end{matrix}\right| \quad (5)$$

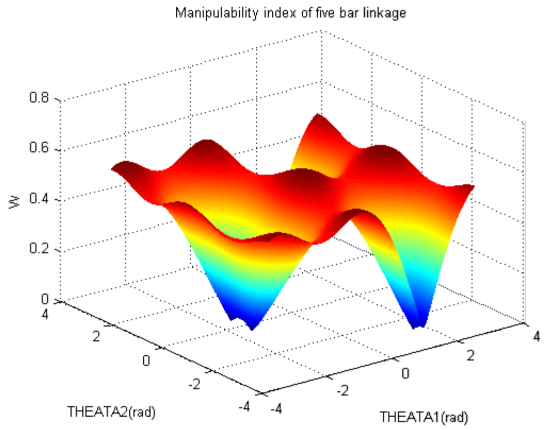
In this study we focus on the analysis of the manipulability index for different values of the joints angles.



(a) $\theta_1 \in [0, \pi/2]$ $\theta_2 \in [0, \pi/2]$



(b) $\theta_1 \in [\pi/2, \pi]$ $\theta_2 \in [\pi/2, \pi]$



(c) $\theta_1 \in [0, 2\pi]$ $\theta_2 \in [0, 2\pi]$

Figure 6: Manipulability measure of translation module

The Fig 6 illustrates the manipulability measure visualization, which indicates the maximum and minimum value of the manipulability on the workspace and the best postures of the mechanism.

In the case (a) the manipulability is maximum when $\theta_1 = 0(\text{rad})$ and $\theta_2 = 0.33(\text{rad})$ which represents the best region in which the mechanism achieve a complete motion.

The singularity is not reached in this case because the manipulability is as far away from zero.

In the case (b) the highest point of manipulability measure is reached by the mechanism when $\theta_1 = 3.0408(\text{rad})$ and $\theta_2 = 3.0408(\text{rad})$

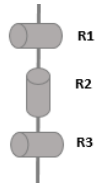
The singular configuration in this case appear when $\theta_1 = 0.38(\text{rad})$ and $\theta_2 = 3.1408(\text{rad})$

From the case (c) the singular positions is reached when $\theta_1 = 1.54(\text{rad})$ and $\theta_2 = 2.69(\text{rad})$

$\theta_1 = 4.71(\text{rad})$ and $\theta_2 = 0.38(\text{rad})$

3.2. Orienting module:

There are various mechanisms in literature that provide spherical motion of the end-point; in this paper we use a three degree of freedom revolute joint.



4. Conclusion

After having highlighted the concept of tele-echography application for medical examination, we presented a new kinematic structure for tele-echography application by using a five bar linkage. The two main parts which are the positioning and the orientation module of the mechanism are studied separately. Then we illustrated the workspace visualization. Also the manipulability of this mechanism is evaluated for different values of the joints angles and analyzed in order to determine the singularities localization on workspace.

further work will consist of determining the dimensions (link lengths) of the mechanism, which is suitable for the task to be performed.

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