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DESIGN OF A PARALLEL ROBOT FOR TRANSPERINEAL PROSTATE BIOPSY

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Abstract: *The paper presents the design of an innovative parallel robot used in transperineal prostate biopsy. Starting from a concept design and using the means of modern engineering, an experimental model has been developed. Special attention has been given to the achievement of the robot joints and links to obtain a maximum stiffness and reduce the dimensions and thus to avoid internal collisions and provide a maximum workspace.*

Key words: *parallel robot, design, prostate biopsy, kinematics, experimental model.*

1. Introduction

An increasing number of robotic systems designed for medical applications has been recorded lately [122], [13]. Due to their natural stiffness and position accuracy, parallel robots have been developed for medical applications [4], [5], [7-11]. Some solutions were design do assist the medical personnel [5], [8] while other were used in performing surgical tasks [4].

A prostate biopsy procedure involves the removal of a small piece of tissue from the volume of the prostate [12]. This procedure is the only one used to certainly detect prostate cancer [13] and it involves the use of two specific instruments: an ultrasound probe and a biopsy needle. The biopsy needle is embedded into a biopsy gun that uses a spring generated force to pierce the membranous surface of the human prostate while the ultrasound probe is used to achieve real time images of the prostate and the biopsy needle inside the patient. By using these two instruments, the biopsy can be performed in two modes: transrectal or transperineal. In the case of the transrectal procedure [14], the ultrasound probe is lubricated and inserted inside the patient via anus and the biopsy needle is guided towards the prostate through a channel embedded in the body of the ultrasound probe, the trajectory of the needle is computed by the control system of the ultrasound probe and the sampling points are identified using the same system. The transperineal approach [14] uses the same two instruments, only this time, the needle is inserted using an entry point on the perineum of the patient (not through the probe's embedded channel). The transrectal approach was the popular one, being used by the clear majority of the urologists. Unfortunately, it involves a high septic risk caused by the passing of the biopsy needle through the rectal wall and a small number of available sampling points accessible from the rectal channel. The transperineal approach became a

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safer (the needle passes only through the perineum) solution and because the entry point of the needle is on the perineum, a better access over the prostate is obtained [5], thus improving the cancer detection rate, reducing the false negative results and eliminating the septic risk. The transperineal technique has two main approaches: a) the use of the needle guiding template which allows the needles to be driven on parallel trajectories into the prostate; b) the use of a single-entry port, through a very small incision in the perineum, driving the needles on concurrent trajectories.

This paper focuses on design of an innovative parallel robot used to perform a targeted biopsy of the prostate using the transperineal approach. The robotic structure uses a previously established medical protocol [1] to perform a robotic assisted transperineal biopsy of the prostate.

2. Kinematics of BIO-PROS-1 Parallel Robot

BIO-PROS-1 is a parallel robotic system, developed following a patent application [8] specially designed to perform the transperineal biopsy of the prostate. The robotic system integrates two parallel robotic modules which collaborate in performing a complex medical act.

One robotic module manipulates the ultrasound probe in acquiring the optimal image of the targeted points inside the volume of the prostate (Figure 1).

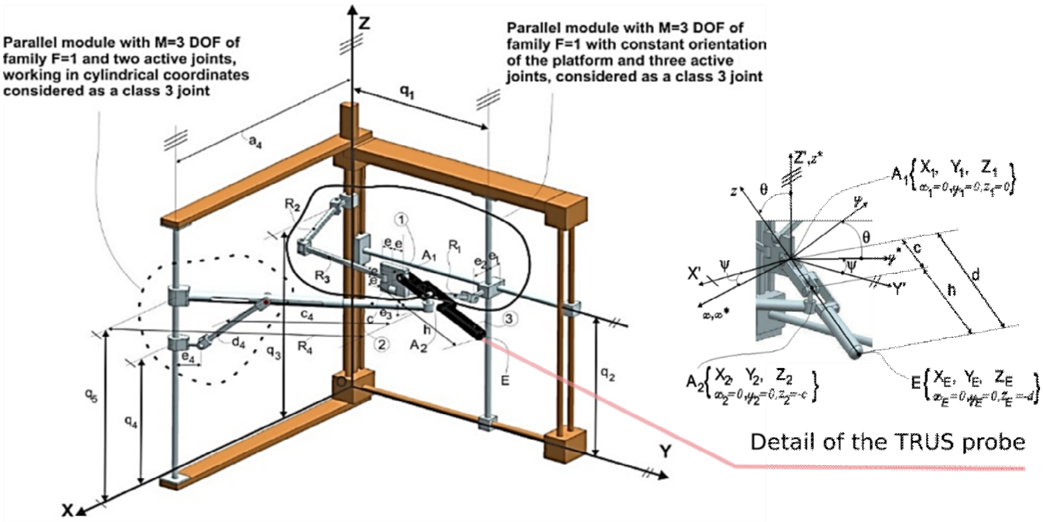

Fig. 1. *Ultrasound probe guiding module*

The transrectal ultrasound probe (TRUS) is a necessary device in performing the prostate biopsy, being the only one that can provide a real-time image of the prostate and of the needle motion. This robotic structure uses a fusion system to accurately locate the target points through a previously acquired MR image to identify the target points on the prostate. At the beginning of the biopsy procedure the MRI containing the sampling points is locked on the user interface. The ultrasound probe uses a pair of points to acquire the optimal image of the prostate. First is the insertion point; this point is the entry point inside the patient body and it is placed on the anus of the patient. The second point is the target point and it offers the optimal view upon the sampling points. Starting from insertion point, the ultrasound images provided by the probe are consecutively superposed over the MR image, if the target point does not offer the best image of the sampling points, a fine tune of the probe position is allowed through the user interface.

The second robotic module (Figure 2) is the one that performs the biopsy procedure. This module manipulates the biopsy gun with respect to the medical protocol for robotic assisted biopsy of the prostate. The motion of the biopsy gun starts, after the probe has reached the target point. This module also uses a pair of insertion and target points, only this time the insertion point is placed upon the perineum of the patient and the target point is the sampling point.

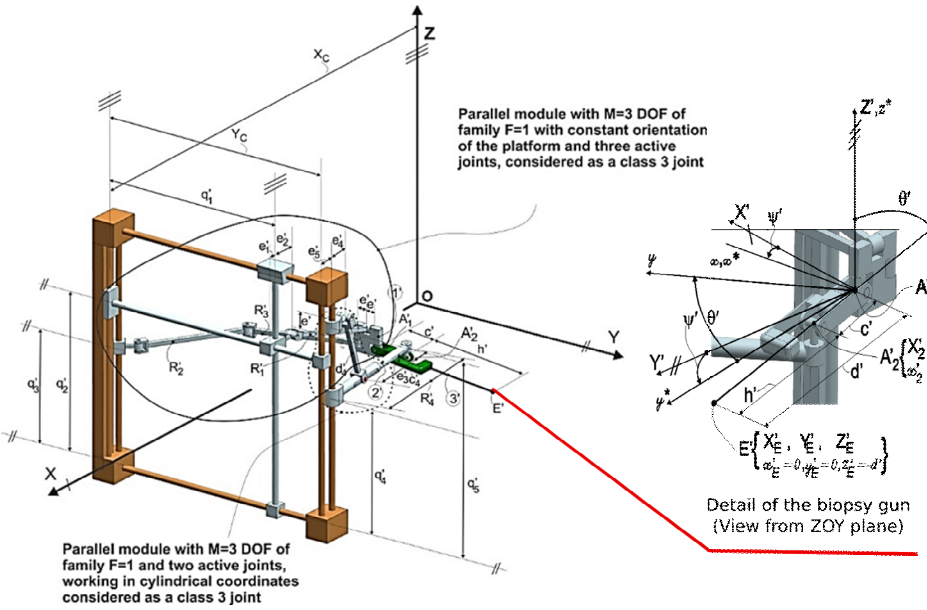

Fig. 2. *Biopsy gun module*

Each robotic module has 5 DOF (degrees of freedom) and the kinematic models of both robotic structures have been previously analysed and published [6], [7], [9].

Following the flowchart of the development process (Figure 3) after developing the kinematics, the next step is the design process of the virtual model. The achievement of the active and passive joints, as well as the links between these joints is detailed in the following sections.

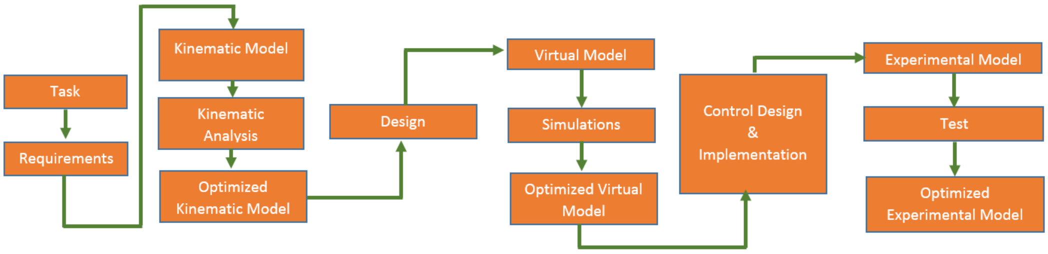

Fig. 3. *Flowchart of the development process*

The control design has been achieved using MATLAB, in which the inverse and direct kinematics have been programmed. To achieve a robust control of the robot trajectory, a “continuous path” algorithm has also been implemented in MATLAB, mainly because a linear trajectory is needed both for the ultrasound probe insertion as well as for the biopsy needle. The MATLAB function have been written in Simulink and using the Automation Studio Target for Simulink tool, the functions have been exported to be used with the Automation Studio developed control software. The motor control has been achieved using the X20CP1584 PLC from B&R Automation and ACOPOSmicro drivers. The actuation has been achieved using stepper motor featuring brakes and encoders for precise positioning.

3. Design of the Active Joints

All the active joints are prismatic ones, the optimal solution to design these joints was using ball screws. Since the momentum needed to perform the designed task was close as value for each active joint and in respect to the modularity requirement of the robotic structure the same type of ball screw was selected for every motion axis only the length of the screws being different. The diameter of all screws is 20 mm and the step of the thread is 5 mm. In Figure 4, the connection between the motion axis (ball screw) and the other elements of the robot is represented. As it can be seen q1 axis (A) is parallel with the OY axis while q2, q3, q4 and q5 (B, C, D and E) are parallel with the OZ axis. The connection between the screw nut sliding on the ball screw and the driven link is made using the fixture element. This element is different for each driving link.

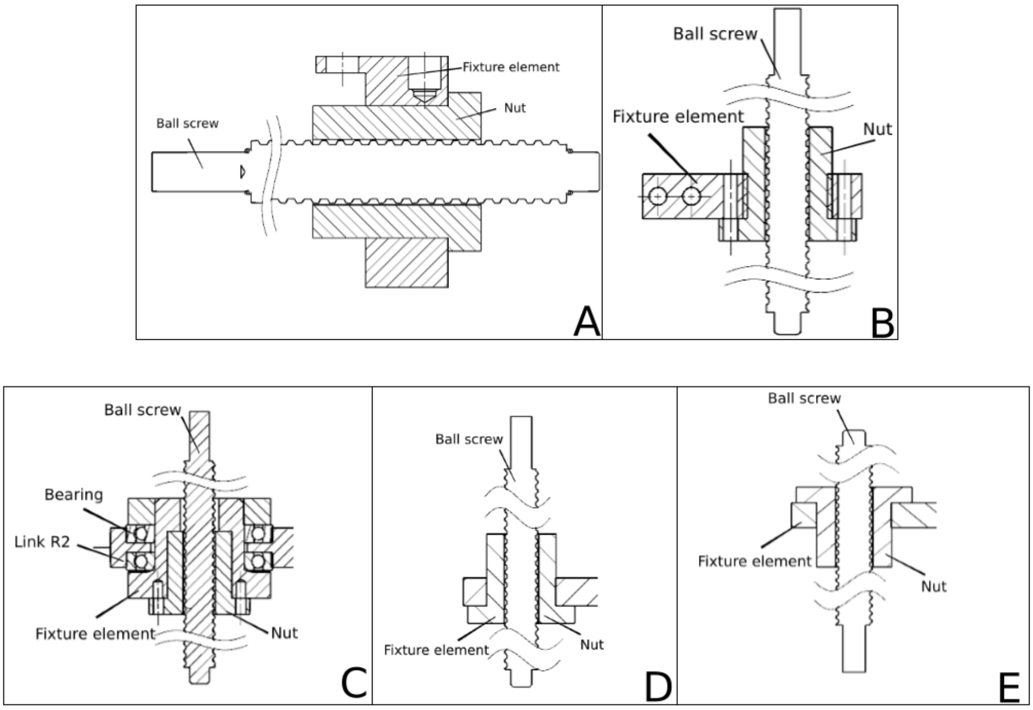

Fig. 4. *Active joints of the robot*

4. Design of the Mobile Platform and the Orientation Mechanism

An important element in the construction of the robotic structure is the platform having a constant orientation (element 1 in Figures 1 and 2). This platform connects the positioning mechanism of the robot (the links driven by q1, q2 and q3) and the orientation mechanism (q4 and q5). Figure 5 illustrates the solution chosen to connect these 2 modules. Each module is plugged into the mobile platform using a partially threaded pin. To reduce the radial backlash between the threaded pins and the inner diameters of the platform holes, cage bearings have been used, while to reduce friction along axes, needle bearings have been chosen. Aside from the pins and the bearings, all the links are made of aluminium.

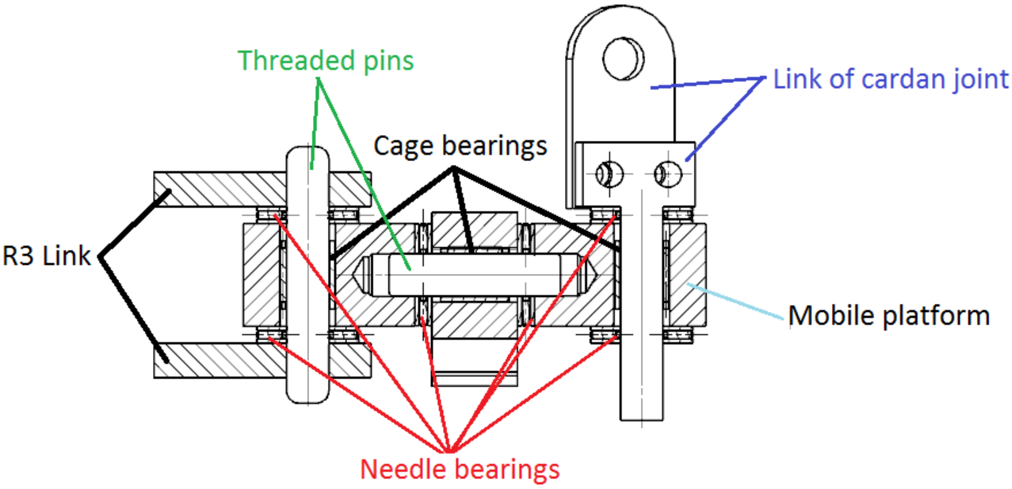

Fig. 5. *Mobile platform*

Another crucial part of the robotic structure is the orientation mechanism (Figure 6). This mechanism is driven using q4 and q5 active joints and it combines the motion of several rotational and translational passive joints.

In the Figure 6, element 1 represents the vertical sliding rod of the mechanims (25 mm diameter); elements 2 and 2b are fixture elements of q4 respectively q5; elements 3 and 10 are horizontal sliding rods; element 5 is a spacer (2 for whole mechanism); element 6 is the link sliding along horizontal sliding rods, it contains 2 sliding ball bearings (7) and the embeded rod 10; element 8 is the link containing the sliding bearing for the rod 10 and it is attached to rod 3; element 9 is the complementary fixture element of the cardan joint seen in Figure 5. Elements 11 and 18 are linking the fixture elements (2 and 2b) to the orientation mechanism using the bearings 13 and 19 to reduce friction and allow motion; elements 12 and 20 are washers and in the same support for the bearings 13 and 19; elements 14 and 16 are sliding axial bearings that alow motion along and around rod 1; link 15 contains the sliding rod 3 while link 17 is connected through link 4 to the sliding link 6.

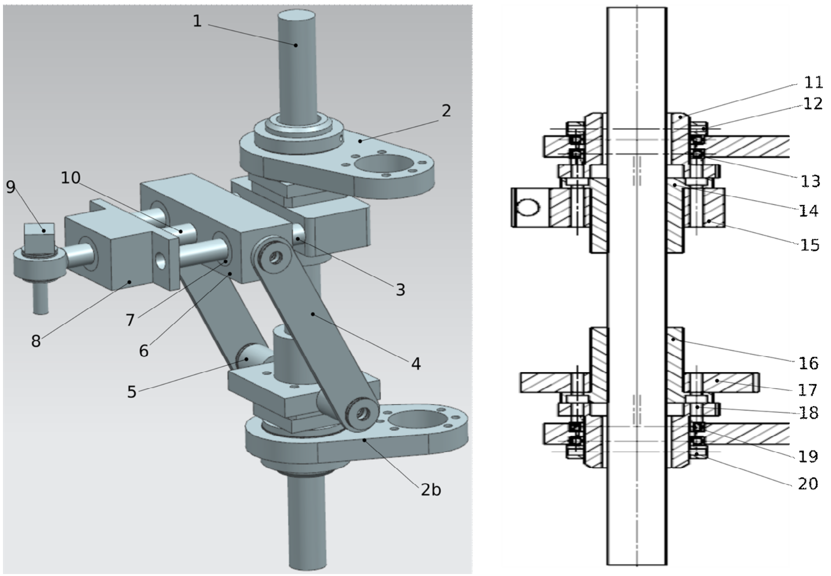

Fig. 6. *Orientation mechanism*

5. The Experimental Model

Prior to the development of the experimental model, several simulations using a virtual medical environment have been performed (Figures 7 and 8). Thus, Figure 7 illustrates the medical virtual environment with the patient being placed in gynaecological position on the table and the robot set up for the procedure. Figure 8 presents a close up of the procedure with probe inserted in the patient’s anus, the biopsy gun inserted through the perineum up to the prostate, ready to be fired (and achieve the sample).

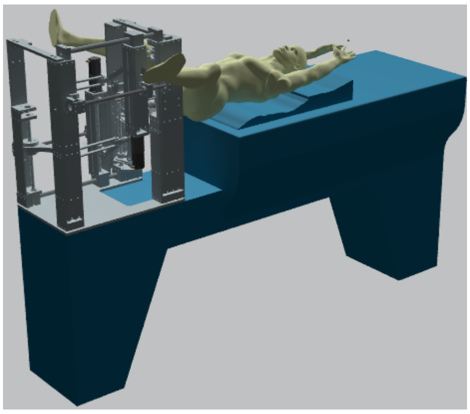

Fig. 7. *Prostate biopsy simulation in virtual environment using BIO-PROS-1*

The result of the design process is shown in Figure 9. A modular and robust robotic structure was obtained, which can manipulate both medical instruments (TRUS probe-light blue in the figure and the biopsy gun represented with green colour). To store the sampled tissue, which must be extracted from the needle, a special device was designed

[10]. This device allows the linear insertion of the needle, the firing of the biopsy gun, so that the biopsy gun can be easily extracted from the device after the biopsy.

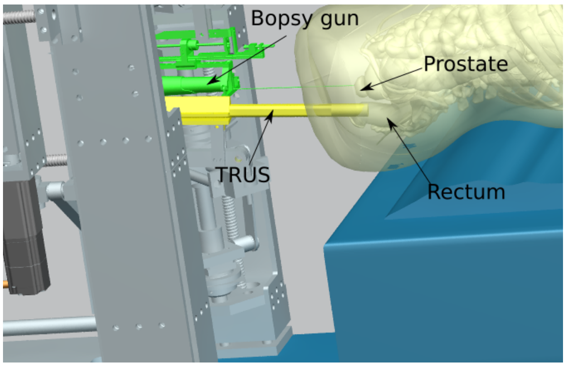

Fig. 8. *Close up of the robotic prostate biospy procedure using BIO-PROS-1*

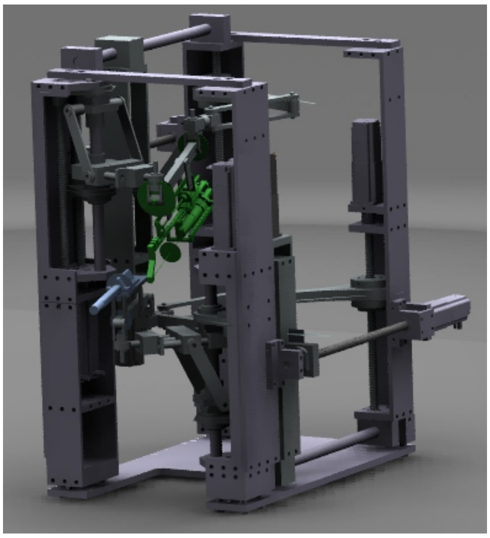

Fig. 9. *Experimental model*

6. Conclusions

The design of the parallel robot for transperineal biopsy of the prostate has been described. The steps from the concept to virtual model have been detailed. The design of the active joints and of some important elements from the configuration of the robot have been described and the final product of the design process was presented. Following the above implementation flowchart, the next step is building of the experimental model, the stage of the development has reached the test phase of the control of the robotic structure. Preliminary tests have proven a good positioning ability of the biopsy gun needle, correlated with a high stiffness of the robotic structure. Future work includes laboratory tests using specialized metrological equipment to accurately determine the positioning and orientation of the needle tip.

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