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SIMULATION AND CONTROL OF AN INNOVATIVE MEDICAL PARALLEL ROBOT USED FOR HCC TREATMENT PROCEDURE

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Abstract: *The paper presents numerical simulations and the modular control system of an innovative parallel robot designed for the targeted treatment of hepatic tumors. The robotic system is composed of two modules (one for needle insertion and the second one for ultrasound probe manipulation), therefore the input-output kinematic equations are optimized and used in the control strategies to ensure adequate control with respect to the medical procedure requirements. Numerical simulations are achieved showing optimal kinematic behavior, which in turn validates the robotic system for the medical procedure. The development of control system and the experimental model are also presented.*
Key words: *Parallel robot, simulation, kinematics, control, hepatocellular carcinoma.*

1. INTRODUCTION

Nowadays, hepatocellular carcinoma (HCC) has become one of the most spread type of cancer, with more than 800,000 cases diagnosed each year and nearly 750,000 deaths. [1, 2]. By the current medical standards, tumor resection, represents the best therapeutic method for HCC. However, close to 80% of the patients are diagnosed with unresectable HCC due to various factors such as: tumor location, tumor size, and poor health condition of the patient (making him unable to withstand the surgical procedure) [3]. Various targeted treatment are reported in the literature to show good results in the treatment of HCC, the most important ones being: percutaneous local ablation and transarterial chemoembolization. However each of these methods come with drawbacks and challenges: thermal ablation is not be fully exploitable on tumors proximal to large blood vessels (due to the heatsink effect), whereas chemoembolization has low levels of accuracy [4].

Recently, the question of using brachytherapy and intratumoral chemotherapy for the targeted treatment of HCC was investigated [3,5]. A technical solution was proposed in a form of a robotic system (ProHep-LCT) [5,6] that is designed to circumvent the main challenges that brachytherapy and intratumoral chemotherapy of HCC present: accuracy, patient safety and procedure ergonomics [3]. The kinematics, singularities and workspace of ProHep-LCT was studied [6,7] to ensure appropriate operational workspace and in turn patient safety and procedural ergonomics. The necessary automated medical instruments (in the form of end-effectors) [8, 9] were designed and studied to have a complete robotic system for HCC treatment. The control development of the ProHep-LCT was presented in [10], and the integration of image fusion technology for real time needle tracking was discussed in [5].

This paper studies the robotic system behavior in the active joint space during imposed (medically relevant) trajectories with respect to the needle tip and ultrasound probe transducer (both being commercially available medical instruments required in the procedure as illustrated in detail further in the paper). Numerical simulations are presented for the trajectories and the active joints, as well as the development of the robot control. The purpose of the study is to validate the ProHep-LCT robotic system for the targeted treatment of HCC.

Following the introduction section the paper is structured as follows: Section 2 presents the context of the state of the art in order to highlight necessity of the novel robotic system; Section 3 describes the ProHep-LCT robotic system and its kinematic behavior which is used further in the control; Section 4 presents the control of the experimental model, and Section 5 presents the conclusions.

2. BACKGROUND

Robotic structures have begun to be used more and more often in the medical field with an effective social impact in improving the quality of life. Some of the best known and most common are those in the field of rehabilitation of human movements, whether they are orthotic structures [11, 12], exoskeletons [13] or rehabilitation robots [14,15]. On the other hand, in recent years, various robotic structures have been designed and developed, for surgical procedures, most notably for minimally invasive surgery (MIS), one of the most prolific one being the da' Vinci system [16], however, other robotic systems for MIS exist, e.g. [17-20] which were developed, tested and validated in laboratory conditions. Moreover, there are several robotic systems used in various needle based procedures such as: i) therapeutic procedures, e.g. prostate brachytherapy [21], lung brachytherapy and breast brachytherapy [22], liver tumors radiofrequency ablation [23]; ii) diagnosis, e.g. transrectal prostate biopsy [21], breast biopsy [22]. Furthermore, many robotic systems were developed, tested and validated in laboratory conditions for cancer treatment of cavitary organs [24], for prostate cancer diagnosis (via transperineal prostate biopsy) [25].

The robotic systems used in medical applications were chosen as technical solutions in order to overcome some limitations of humans especially regarding dexterity, accuracy, safety, fatigue and ergonomics.

Recent studies proposed the use of robotic systems for the targeted treatment of HCC using either brachytherapy or intratumoral chemotherapy [3]. Moreover, in [5] the authors discussed the possibility of developing targeted treatment of HCC with brachytherapy and intratumoral chemotherapy, with real time image tracking (using US fused with CT). The proposed approach is to provide a safe and accurate solution for inserting therapeutic needles within HCC, under continuous image guidance using intraoperatory ultrasound (I-US) fused with preparatory CT. Since there are limitations of image fusion, in [5] the authors propose the continuous master slave control of a US probe to correct any positioning errors in situ (patient relative to robot or errors that may occur due to the patient positioning CT relative to operating table). Indeed, there exist various robotic systems that also use image fusion such as: [26] for endomicroscopy, [27] for prostate interventions. However, despite the recent advancements in medical robotics, a robotic system designed for the HCC targeted treatment is novel. Such robotic system may offer a window of opportunity in implementing targeted treatments for HCC which in turn may downstage the HCC (such that the resection may become a viable therapeutic method or the patient life spam is extended until a transplant is available), or maybe even cure it.

As pointed out in detail in [3] there are certain aspects to be regarded in developing such robotic system, which in summary are: i) the robotic system must independently guide and insert therapeutic needles and an I-US probe (the robotic system is developed with two independent modules); ii) the robotic system must have good stiffness, high accuracy, and appropriate operational workspace. The two parallel modules have 5 DOF (positioning) with end effectors with: a) 3 DOF (fine tuning and needle insertion) + 1 (DOF needle gripping); consequently, b) 4 DOF (transducer orientation and insertion); iii) the master-slave control of the robot must incorporate image fusion technology for real time image tracking (the control architecture of the proposed robotic system contains modules for image fusion integration). All these technical requirements were established by a multidisciplinary team composed of engineers form the Technical University of Cluj-Napoca and medical experts from "Iuliu Hatieganu" University of Cluj-Napoca.

3. ProHep-LCT - AN INNOVATIVE ROBOTIC SYSTEM FOR HCC TREATMENT

To achieve the requirements imposed by the medical procedure, ProHep-LCT was designed as a modular parallel robotic system with two independent identical robotic modules, operating in mirror (Fig. 1) each having 5 DOF (Fig. 2) [28].

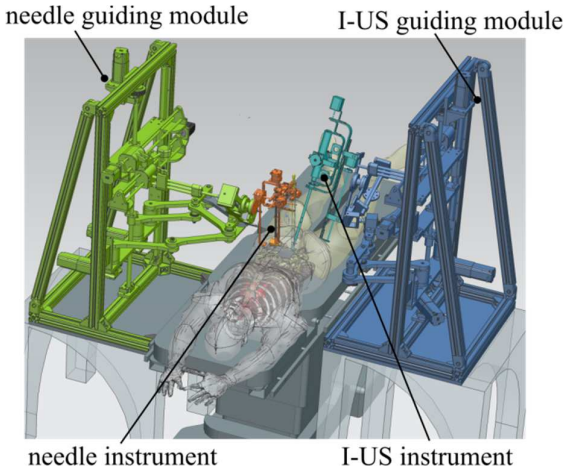


Fig.1. ProHep-LCT in simulated medical environment (CAD).

Furthermore, each module is equipped with one of the two automated medical instruments (serving as end-effectors): i) needle insertion instrument with 3 Cartesian DOFs plus a needle gripping DOF (Fig. 3.a) [29], and ii) Intraoperatory Ultrasound (I-US) Probe manipulation instrument with 4 DOF (Fig. 3.b) [30].

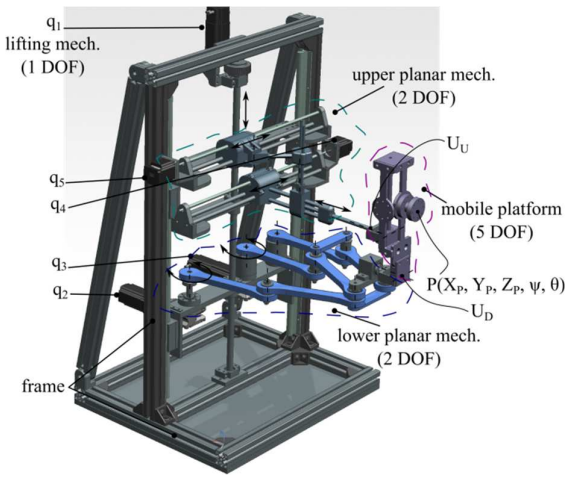


Fig.2. ProHep-LCT parallel module with 5 DOF (CAD).

Consequently, the ProHep-LCT system (as a whole) has 8 DOF for the needle insertion with 3 redundant ones and the rotation about the needle longitudinal axis being suppressed (and 1 DOF for needle gripping), and 9 DOFs for probe manipulation with 3 redundant ones where the rotation about the longitudinal axis being allowed.

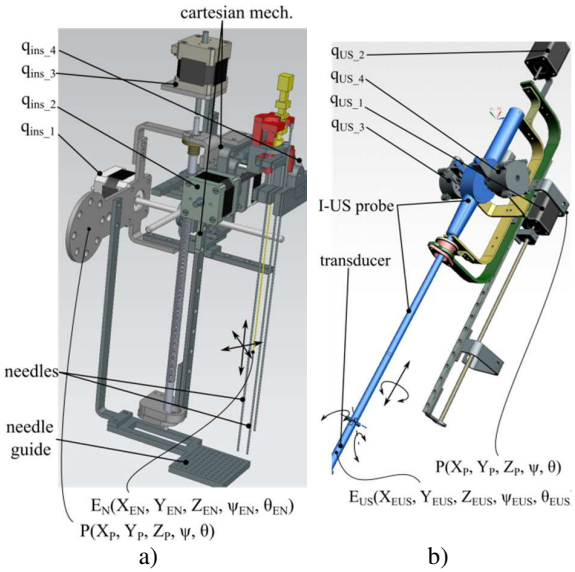


Fig.3. Automated medical instruments for ProHep-LCT (CAD): a) needle insertion instrument; b) I-US probe guiding instrument.

The main mechanical components of the ProHep-LCT parallel robotic system (illustrated in Figs. 1-3) are detailed in Tab 1.

Tab. 1. ProHep-LCT robotic system components.

Annotation	Description
ProHep-LCT parallel robotic system	
needle guiding module	5 DOF parallel robot guiding an automated instrument for needle insertion.
I-US guiding module	5 DOF parallel robot guiding an automated instrument for I-US probe.
Needle insertion instrument	4 DOF automated instrument for multiple needle insertion (on parallel trajectories); the therapeutic needles are commercially available and manually mounted in the needle rack.
I-US probe guiding instrument.	4 DOF automated instrument for I-US probe manipulation (orientation of the transducer about 3 rotational axes and transducer insertion); the I-US probe is commercially available and manually mounted in the instrument.
Parallel module with 5 DOF	
q_i (i=1..5)	Active joints of the 5 DOF parallel robot.

lower planar mech.	Parallel planar mechanism (6 bar linkage – 6R type) with a platform with constant orientation; optimised for the mobile platform positioning and stiffness.
upper planar mech.	Parallel planar mechanism with 2 prismatic active joints (PRR-RR type) and optimised for mobile platform accurate orientation.
mobile platform	Platform with modular flange for instrument mounting; guided by the upper and lower mechanisms via 2 Cardan joints and a prismatic one (UPU type).
M_P	Mobile coordinate system point; for a clear definition of instrument mounting.
Needle instrument	
q_{ins_i} (i=1..4)	Active joints of the needle insertion instrument.
Cartesian mech.	Gantry type mechanism (PPP) with a needle gripper; optimised for accurate needle insertion.
needle guide	Matrix type element to constraint the needle insertion on parallel trajectories and reducing needle bending.
P	Mobile coordinate system point; for a clear definition of instrument mounting.
E_N	Needle tip coordinate system point; for a clear definition of needle insertion.
I-US instrument	
Q_{US_i} (i=1..4)	Active joints of the I-US guiding instrument.
I-US probe	Commercially available I-US probe.
transducer	Physical element that converts soundwaves into medical images.
P	Mobile coordinate system point; for a clear definition of instrument mounting.
E_{US}	transducer coordinate system point; for a clear definition of transducer position.

3.1 Kinematic input output equations

This section presents the general input-output equations (the mathematical detail was presented in [6]) and the manner in which they can be used in the robot control. One important note is that the two modules of the ProHep-LCT parallel robotic system work in different manners:

1. The **needle guiding module** works using a **sequential** approach: **a)** first, the parallel module guides the automated instrument near the patient abdomen such that all the target points (within the tumors) can be reached by the therapeutic needles with given trajectories (defined pre-operatory); **b)** second, while the robot is stiff (active joints are not actuated). Mathematically these steps may be generally represented as:

Step **a**; based on the inverse kinematic models, where the position of the point M_P is given, the values of the active joint have the form:

$$\begin{cases} q_i = f(P, E_N, J), \;\; q_{ins\_i} = ct.; \\ \dot{q}_i = f(\dot{P}, \dot{E}_N, P, E_N, J); \\ \ddot{q}_i = f(\ddot{P}, \ddot{E}_N, \dot{P}, \dot{E}_N, P, E_N, J); \end{cases} \quad (1)$$

with $q_i = [q_1, q_2, q_3, q_4, q_5]$ (the active joints position of the parallel robotic system), $\dot{q}_i = [\dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5]$ (the velocity vector of the active joints), $\ddot{q}_i = [\ddot{q}_1, \ddot{q}_2, \ddot{q}_3, \ddot{q}_4, \ddot{q}_5]$ (the acceleration vector of the active joints), J the set of geometric parameters of the parallel robot (see [6]), $q_{ins\_i} = [q_{ins\_1}, q_{ins\_2}, q_{ins\_3}, q_{ins\_4}]$ (the active joints position of the needle insertion instrument, which is constant during this stage). The term P = [X_P, Y_P, Z_P, ψ, θ] represents the trajectory (of the mobile platform), $\dot{M}_P$ its velocity and $\ddot{M}_P$ its acceleration, E_N = [X_{EN}, Y_{EN}, Z_{EN}, ψ_{EN}, θ_{EN}] represents the trajectory of the needle tip.

Step **b**; based on the inverse kinematic models, where the target points are known the laws of motion of the needle tip point E_N may be computed, therefore, the length and trajectories (which are parallel) of the needle insertion are determined using:

$$\begin{cases} q_{ins\_i} = f(E_N, J_N), \;\; q_i = ct.; \\ \dot{q}_{ins\_i} = f(\dot{E}_N, E_N, J_N), \;\; |\dot{q}_{ins\_i}| = 10mm/s \\ \ddot{q}_{ins\_i} = f(\ddot{E}_N, \dot{E}_N, E_N, J_N), \;\; |\ddot{q}_{ins\_i}| = max \end{cases} \quad (2)$$

with $q_i = ct.$ (the active joints position of the parallel robotic system being constant), $\dot{q}_{ins\_i} = [\dot{q}_{ins\_1}, \dot{q}_{ins\_2}, \dot{q}_{ins\_3}, \dot{q}_{ins\_4}]$ (the velocity vector of the active joints of the needle instrument), $\ddot{q}_{ins\_i} = [\ddot{q}_{ins\_1}, \ddot{q}_{ins\_2}, \ddot{q}_{ins\_3}, \ddot{q}_{ins\_4}]$ (the acceleration vector of the active joints of the needle instrument), J_N the set of the geometric parameters of the needle insertion instrument. One important aspect is that the needle insertion velocity is set to 10 mm/s and the acceleration is the maximum allowed by the actuator.

Note: for the needle guiding module the orientations ψ and θ of M_P and T_P are the same

The **I-US probe guiding module** works using a **continuous** approach: the I-US probe is guided

in real time with both the parallel module and the automated instrument. This approach may be generally describer by finding the active joints position, velocity and accelerations when the laws of motion of the I-US probe transducer are known:

$$\begin{cases} q_i = f(P, E_{US}, J_{US}); \\ \dot{q}_i = f(\dot{P}, \dot{E}_{US}, P, E_{US}, J_{US}); \\ \ddot{q}_i = f(\ddot{P}, \ddot{E}_{US}, \dot{P}, \dot{E}_{US}, P, E_{US}, J_{US}); \end{cases} \quad (3)$$

with q_i the active joints position of the parallel robotic system, $\dot{q}_i$ the velocity vector of the active joints, $\ddot{q}_i$the acceleration vector of the active joints, P the trajectory of the mobile platform and E_{US} = [X_{EUS}, Y_{EUS}, Z_{EUS}, ψ_{EUS}, θ_{EUS}, φ_T] the trajectory of the transducer with respect to the mobile platform.

Note: the insertion point of the I-US probe is a pivot point which constraints the motion in a Remote Center of Motion (RCM), constraint which is also accounted in the control after the I-US probe insertion.

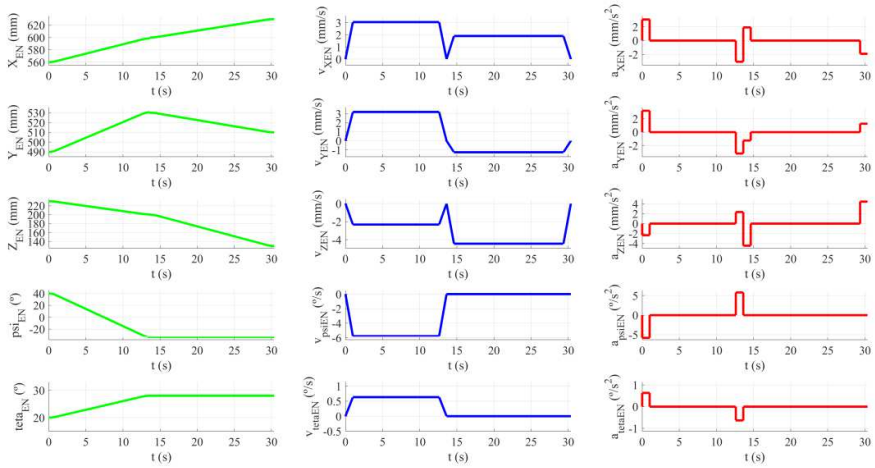
3.2 Motion simulations

Based on the kinematic models presented generally in Eqs. (1) – (3) several motion simulations were performed in Matlab environment. Since the parallel robotic system has singularities only at the boundaries of the operational workspace (task related workspace) [7] there was no need to make computations to determine whether or not an imposed trajectory passes through a singularity. The laws of motion were defined (with medical experts guidance) as following:

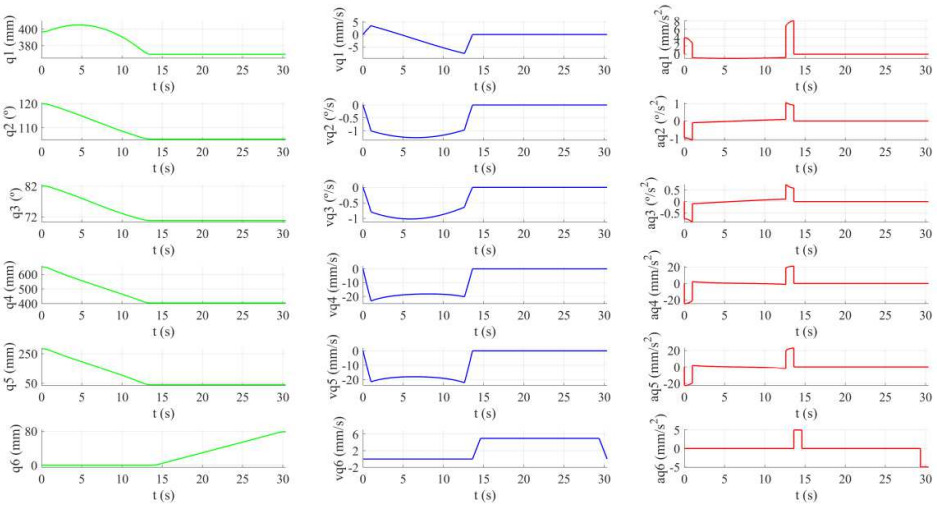
For the **needle insertion module**:

- The initial position of the needle tip was E_N(X_{EN}=560 mm, Y_{EN}=490 mm, Z_{EN}=230 mm, ψ_{EN}=40°, θ_{EN}=20°), which describes the robot above the patient such that the medical personnel is able to check or load the therapeutic needles within the instrument rack;
- The target point was chosen E_N(X_{EN}=630 mm,Y_{EN}=510 mm, Z_{EN}=130 mm, ψ_{EN}=-33°, θ_{EN}=28°) to define a tumor within the liver, which resulted in a needle insertion depth of 80 mm;

Fig. 4 shows the numerical results obtained (using Matlab software) for the two sequence medical procedure. First, the parallel robot guides the medical instrument towards a predefined (preoperatory) position (t = 0 – 15 s), and then the needle is inserted while the robot actuators are constant (t = 15 – 30 s). Fig. 4.a illustrates the time history diagram of the imposed trajectory (at the needle tip) whereas Fig. 4.b illustrates the time history diagram of the active joints (position, velocity and acceleration).



a)

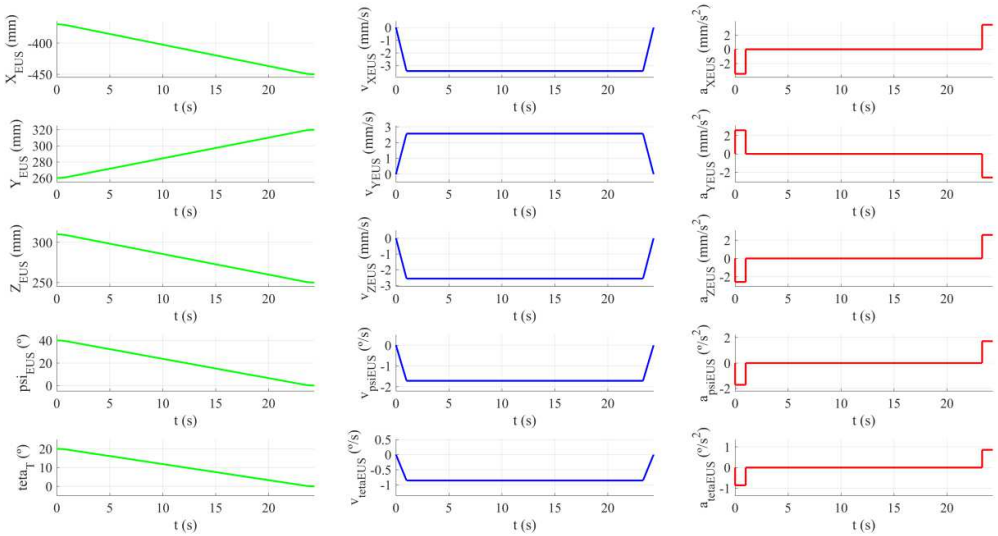


b)

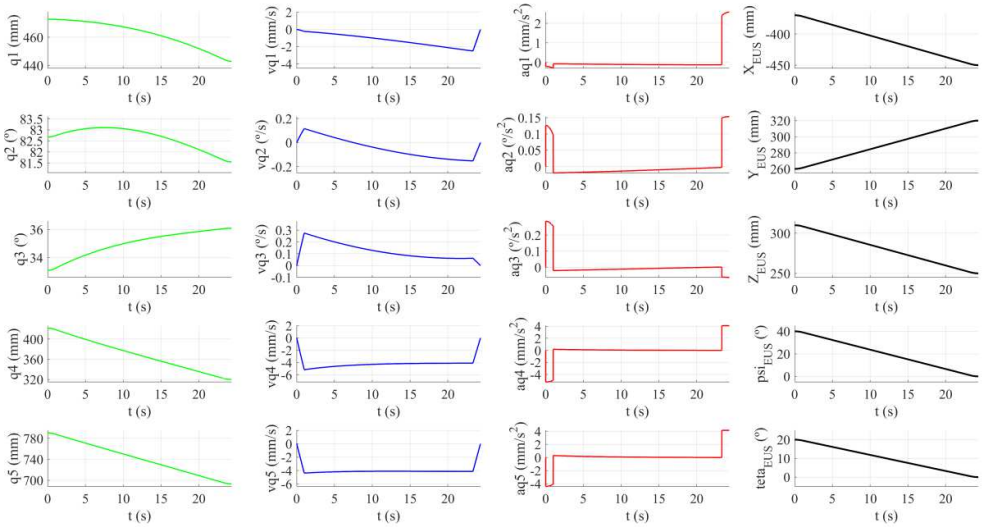
Fig. 4. Needle insertion simulation in to stages (0-15 sec - stage 1 – instrument guidance; 15-30 sec – stage 2 needle insertion): a) imposed trajectory with respect to the needle tip; b) active joint space (5 DOF parallel module + 4 DOF automated instrument).

For the **I-US guiding module**:

- The initial position of the transducer tip was $E_{US}(X_{EUS}$=370 mm, Y_{EUS}=260 mm, Z_{EUS}=310 mm, ψ_{EUS}=40°, θ_{EUS}=20°, φ_{EUS}=0°), which describes the robot above the patient such that the medical personnel is able to check or load the I-US probe within the instrument, as well as make real time corrections for the instrument position;
- The coordinates of the RCM(X_{RCM}=630 mm,Y_{RCM} =510 mm, Z_{RCM} =130 mm, ψ=0°, θ=0°) and the insertion depth was chosen 70 mm;
- The orientation of the transducer (after the probe insertion) was (ψ_{EUS}=-13°, θ_{EUS}=13°, φ_{EUS}=26°).

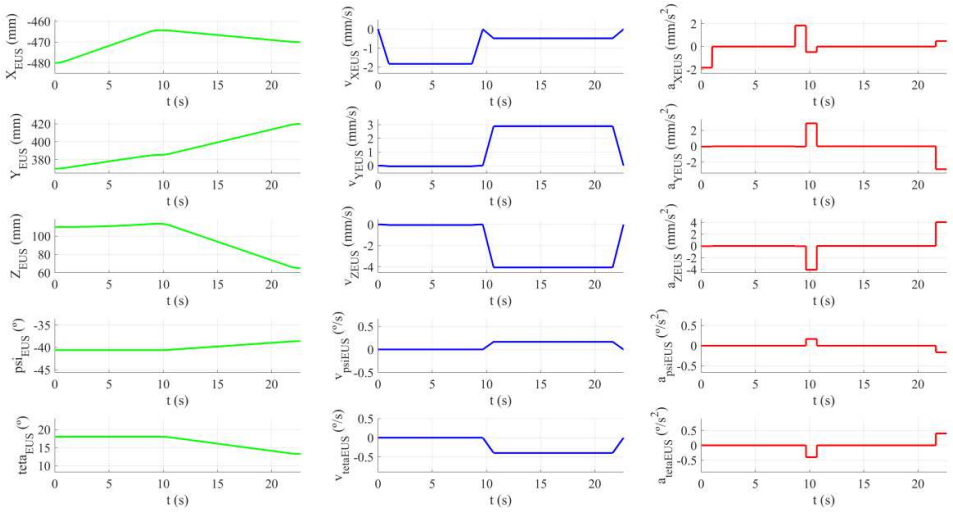


a)

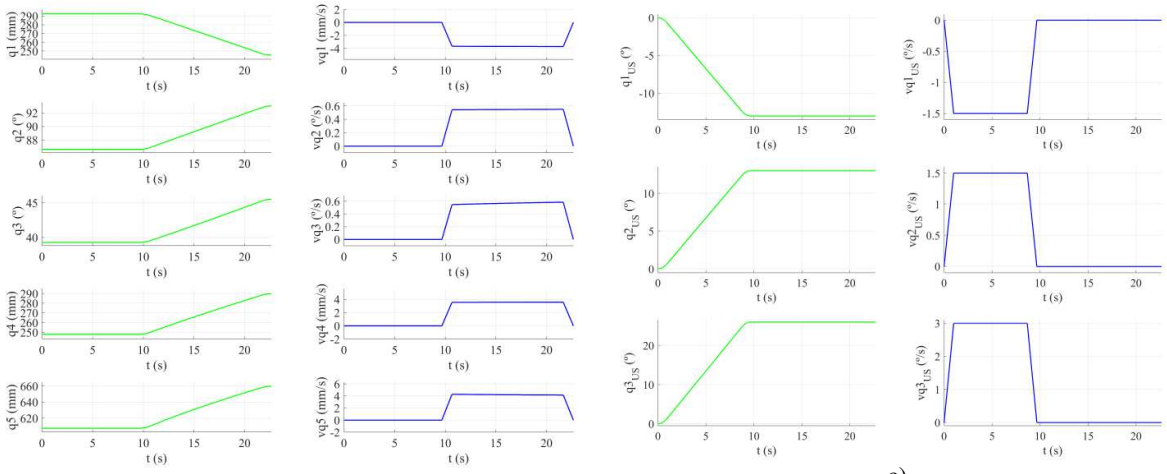


b)

Fig. 5. I-US guiding simulation where the I-US probe is guided and inserted: a) imposed trajectory with respect to the transducer position; b) active joint space (5 DOF parallel module).



a



b) c)

Fig. 6. I-US guiding simulation under RCM constraint: a) imposed trajectory of the transducer; b) active joint space (5 DOF parallel module); c) active joint space (4 DOF automated instrument).

Fig. 5 illustrates numerical results for time history diagram of the transducer motion (Fig. 5.a) during the I-US probe insertion stage. Fig. 5b. shows the time history diagram of the active joints (position, velocity and acceleration). Fig. 6 illustrates numerical result for the motion of the transducer after the probe was inserted. The time history diagram of the transducer motion are shown in Fig. 6.a, whereas the time history diagram of the active joints (position and velocity) are shown in Fig. 6.a.

4. ProHep-LCT CONTROL AND OPERATION

4.1 Control system architecture

Starting from the medical protocol described in [6], the control system of the robot has been developed to fully comply with the medical task. Fig. 7 presents the schematic representation of the control setup and the possible interactions between the control system main components: PC, PLC, I-US Module (including the I-US Tower) and the Needle Module and the input devices: Joystick, Mouse and Keyboard. The first step of the procedure consists in analyzing the input data collected during the initial investigation and preplanning (mainly CT scans), which help to locate the tumors and estimate the brachytherapy needles trajectory. Based on the location, position and size of the tumor, up to six needles may be used, all being charged in the instrument needles magazine (the needles rack). As a rule, the first needle targets the middle of the tumor (being located in a central position relative to the other needles) and is the most important needle.

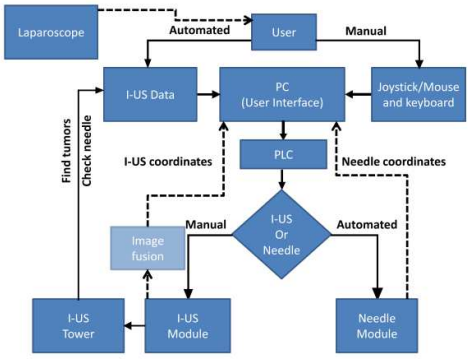


Fig.7. Schematic representation of control methodology.

All other needles are inserted on a linear trajectory parallel to the first one, in a matrix arrangement, using the custom developed sieve, which plays a double role: guide the needles on a linear trajectory and ensure the proper distance between needles, accurately determined and used to compute the power of the radiation seeds.

The main steps of the procedure, implemented into the control system are:

- Chose the insertion point of the I-US into the patient's abdomen. Perform the incision and place the 10mm trocar.
- Insert the I-US using the I-US robotic Module. Outside the body, the robot will use its 5 DoF to position and orient the I-US probe guiding it up to the insertion point and save the insertion point - RCM (Remote Center of Motion). From this moment on, the RCM acts as a class two joint (having 4 DoF) which changes the robot control which will have 3 DoF inside the body (two rotations and one translation along the longitudinal axis of the instrument) the other 2 DoF being used to preserve the RCM.
- Guide the I-US on the liver surface. In this instance of the procedure, the I-US module (equipped with 4 additional motors) can also be used. Through the combined motion of all the actuated joints the probe transducer is positioned on the liver parenchyma and used to locate the targeted tumor(s). The I-US Module is guided remotely, with the help of the Joystisk of the 3DCONNEXION SpaceMouse Enterprise, which is a 6 DoF device. The Joystick's coordinates are read using the developer's API and are further used to position the probe's head.
- Use the image fusion module to compare the real-time images with the previously obtained CT scans to precisely locate the tumors and thus the brachytherapy needles target points and finally their insertion trajectories.
- Choose the first needle's insertion point into the patient's body.
- Insert the first needle using the Needle Module into the abdominal cavity of the patient until it reaches the liver parenchyma (visual confirmation using a laparoscope

placed into the patient's abdominal cavity so that the surgical field is always visible).

- Start inserting the needle further and constantly check (using the I-US probe) the needle's trajectory.
- If corrections are required, the needle is removed from the liver, the corrections are applied and a new insertion point into the liver is chosen. If this is not possible (because the new insertion point is too far from the current position to maintain the insertion point into the patient's abdominal cavity – using visual confirmation), the needle is completely removed from the patient's body and reinserted using a new insertion point.
- The procedure is repeated until the first needle reaches its target point.
- The other needles are inserted in a similar way, having as reference the position of the first needle.

4.2 Implementation

The control system's hardware is classified into three categories as follows: user level, command and control and physical level. The **user level** consists of all devices with which the user interacts directly: PC – user interface, US Tower and all input devices.

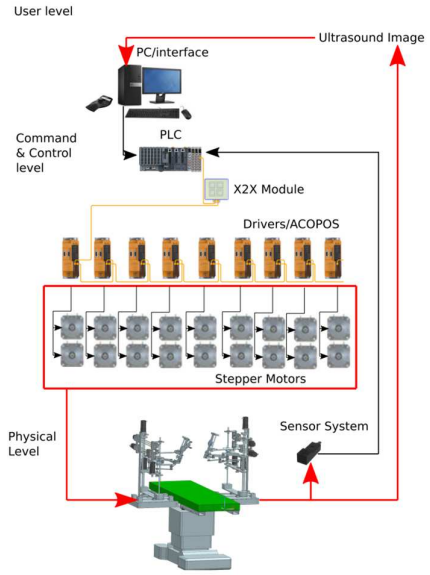


Fig.8. Hardware configuration of the system [10].

The **command and control** level integrates the PLC (X20CP3586 from B&R), motor drivers (80SD100XD.C044-01) – 9 pieces, one to drive two motors. The **physical level** consists of sub-components: the mechanical structure (presented in Fig. 8), 10 stepper motors (5 on each robotic module) and four stepper motors actuating the two instruments (with encoders brakes) and 18 proximity sensors mounted on the mechanical structure and used to perform the homing initialization procedure of the robot. Furthermore, at the user level a Graphical User Interface (GUI) was developed with multiple tabs (each with specific functionality to facilitate operation as well as maintenance [10]).

For the **operation mode** the core functionality consists of tools for automatic positioning of I-US Module and the Needle Module. The required inputs are the coordinates of the insertion points for the intraoperatory ultrasound probe and for the tip of the needle respectively. The motions can be scaled up or down (increasing or decreasing the motion increment). Several tools and guidelines allow for an non-ambiguous operation of the robotic system to ensure patient safety and ergonomics (prompts to insert/retract/release needles, validation of the steps etc.).

For the **maintenance mode**, the tabs may only be accessed by authorized personnel (engineers with the admin levels). It is worth pointing that the robot may function either in operation mode or in maintenance mode. Furthermore, a technical documentation is provided in the as a PDF file which helps the user in both operation and maintenance mode.

5. THE EXPERIMENTAL MODEL

The experimental model of the ProHep-LCT is illustrated in Fig. 9. An initial set of laboratory experiments was performed by medical experts and engineers to study the robotic system behavior (robot motion based on imposed trajectories and control validation), and procedural ergonomics.

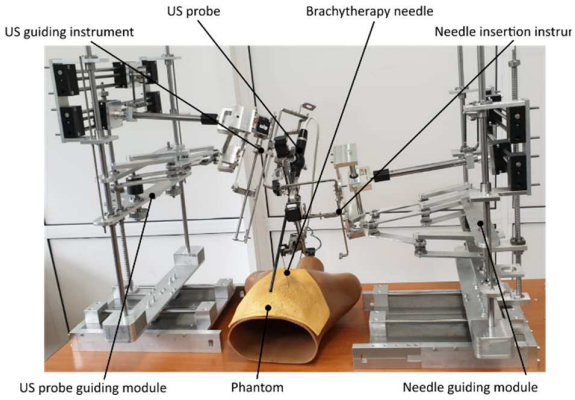


Fig. 9. Experimental model of the ProHep-LCT parallel robotic system for HCC treatment.

Fig. 10 shows a close view of the robotic system positioning the I-US probe on a simulated liver (manufactured from gel with objects that also simulate the hepatic tumors). Furthermore, a brachytherapy needle was inserted (within a simulated tumor) based on approximated coordinates (in the real procedure the target point coordinates and the insertion trajectories are computed using real CT images).

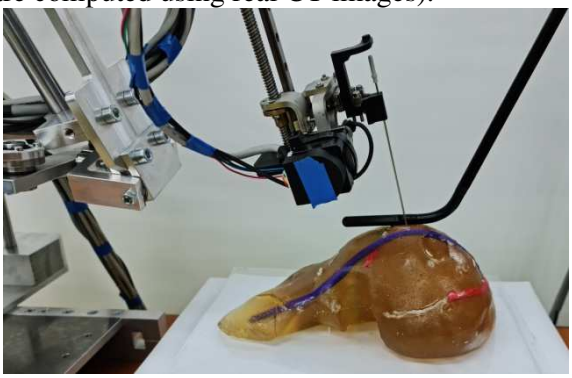


Fig.10. Positioning of the I-US and Needle modules on the liver parenchyma.

6. CONCLUSIONS

Although there are various therapeutic method available for the management HCC, nowadays this pathology has a relatively high mortality index. Despite all the recent advances in medical robotics, a robotic system designed for HCC brachytherapy and/or intratumoral chemotherapy is not available. The paper presented the ProHep-LCT parallel robotic system which was designed for the targeted treatment (brachytherapy of chemotherapy) of HCC guided by real time US. Results from numerical simulations (based on the robot kinematic models) defined appropriately for the medical procedure, were presented showing nu hazardous behavior such as high values of velocities and accelerations of the active joints. Furthermore, the control system of ProHep-LCT was developed and presented using specific control strategies for the two parallel modules: a sequential control strategy for the needle insertion to ensure accuracy and safety; a continuous master-slave control strategy for needle and tissue visualization using US.
Further work is required to implement image fusion tools into the robotic system user interface and control and for more experimental testing (in laboratory conditions) in order to validate the robotic system at a maturity level of TRL 5.

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SIMULAREA ȘI CONTROLUL UNUI ROBOT PARALEL MEDICAL INOVATOR UTILIZAT PENTRU TRATAMENTULUI HCC-ULUI

Lucrarea prezintă simulări numerice și sistemul de control al unui robot paralel inovator conceput pentru tratamentul țintit al tumorilor hepatice. Sistemul robotizat este compus din două module (unul pentru inserarea acului și cel de-al doilea pentru manipularea sondei cu ultrasunete), prin urmare ecuațiile cinematice de intrare-ieșire sunt utilizate în strategiile de control pentru a asigura un control adecvat în ceea ce privește cerințele procedurilor medicale. Sunt prezentate simulări numerice care arată un comportament cinematic optim, care la rândul său validează sistemul robotizat pentru procedura medicală. Sunt prezentate, de asemenea, dezvoltarea sistemului de control și modelul experimental.

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