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A NEW SERIAL COMMUNICATION PROTOCOL FOR THE CONTROL OF A MEDICAL PARALLEL ROBOT

Doina PISLA, Florin COVACIU, Bogdan GHERMAN, Călin VAIDA, Nicolae PLITEA

Abstract: *The paper presents a new serial communication protocol which is used in the control of a parallel robot for brachytherapy. For safety reasons, the control system has been designed according to a specific protocol which covers the therapeutic aspects and safety issues, mentioned by the oncologists. The robotic system, called BR-1, has 5 degrees of freedom and was developed in two configurations: BR-1R (with rotational passive joints) and BR-1T (with translational passive joints), each one used for different brachytherapy procedures.*
Key words: *brachytherapy, parallel robot, serial communication protocol, user interface*

1. INTRODUCTION

A communication protocol is by definition: a set of rules needed to transmit information through a communication channel, and the rules are applicable for data representation, transmission, identification and detection of errors that may occur during transmission.
The serial communication protocol was built with the purpose of transmitting packages of information between the PC and microcontroller in the shortest amount of time. The microcontroller underlies the brachytherapy parallel robot that is the subject of this paper. Due to the brachytherapy therapeutic potential, a multitude of research centers around the globe try to provide solutions for minimally invasive treatment, thus developing robotic systems for brachytherapy.

Stoianovici developed MrBot [1]. This robotic system is used for prostate treatment and is designed as a platform that is supported by the joint linear motors in a parallel structure. All components are made from dielectric and nonmagnetic materials for multi-image compatibility. The robot is controlled by a control unit that is outside the imaging room. BranchyGuide[2] by Salcudean, was designed specifically for prostate and inguinal zone treatment, made of two-axis which are wrist-positioned. Actuators are used for this robotic system, in order to reach high speeds. Each axis uses one microcontroller. The microcontrollers are controlled by a motion planner using the computer (PC), through the user interface. Dubowski [3] has developed a MRI compatible needle manipulator for prostate treatment. The system consists of a parallel manipulator with two planes. Each plane has six bistable actuator elements that are symmetrically distributed around a radius. Because this manipulator will be mounted in the MRI, the room needs the minimal electronic hardware, this device is intended to be operated in "open loop" mode using real-time images. Another 3D ultrasound robotic prostate brachytherapy system was introduced by Nikolai Hungr [4]. A 4-DOF hybrid robot used for real-time transperineal prostate needle guided orientation under MRI guide was introduced by G. Fisher [5] and Basam [6], build a 5-DOF hybrid robotic system that could perform 3D ultra-sound guided percutaneous needle insertion surgery.

The paper is organized as follows: The second section presents the experimental model of the BR-1. Section 3 presents the new serial communication protocol continuing with the control and actuation system in section 4, followed by conclusions and references.

2. THE EXPERIMENTAL MODEL OF BR-1 PARALLEL ROBOT

Brachytherapy is an innovative method for advanced cancer treatment. This method consists in placing radioactive seeds or sources in or near the tumor itself. The radioactive seeds are delivered through brachytherapy needles. A major advantage in this procedure consists in the minimal irradiation of the healthy tissue [7], reduced patient trauma [8] and lower risks of side effects [9].

In the brachytherapy procedure, the robots task is to insert a rigid needle, which has a diameter between 1.6 mm and 2 mm, and the needle's length must be between 50 mm to 250 mm. The brachytherapy needle must be introduced inside the body of the patient using a linear trajectory. An experimental model of the brachytherapy parallel robot called "BR-1" has been developed[10] – figure 1. The control unit (13) has been developed with the purpose of controlling the robot, the motion of the robot is insured by five actuators (q_1, q_2, q_3, q_4, q_5), which are the stepper motors, that actuate three translation joints (3) and two rotational (2) joints. The switch sensors (s_1, s_2, s_3, s_4, s_5) are used both as stroke limits as well as to set the zero position of each axis of the robot.

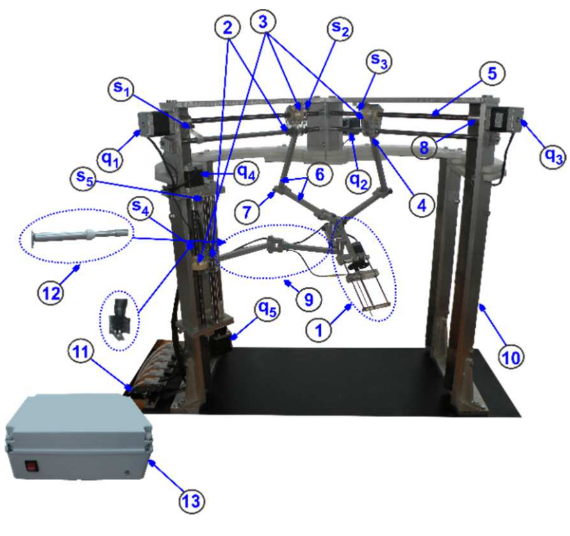

Fig. 1. Experimental model of BR-1

The robotic system is able to insert the brachytherapy needle by using a needle insertion module (1) on a linear trajectory, all other motors being held in position – figure 2.

The needle insertion module (1) used for placing the needle (6) into the tumor is actuated by using a screw mechanism (5). Motor q_6 is used to drive the screw mechanism and the link between motor (q_6) and screw is made through two gear wheels (3) (4). The needle insertion module integrates a resistive force sensor (S_F) which can monitor the force (on the user interface can be seen monitoring the force). The force sensor is used to avoid deformations or deviations of the needle from the imposed trajectory. If the force exceeds a certain level during the needle insertion, the needle stops and retracts.

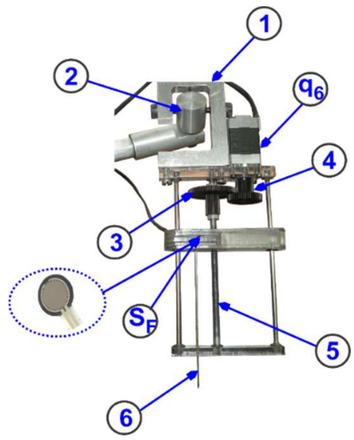

Fig. 2. Needle insertion module

3. DEVELOPMENT OF THE NEW SERIAL COMMUNICATION PROTOCOL

An efficient protocol for communication between the PC application (master) and the microcontroller (slave) via USB has been developed.

Thus, the communication is based on the master-slave technology. All the packets follow a general format, as described in Table 1.

Table 1. General packet structure

Field	Size (bytes)	Details
Command ID	1	Unique command ID
Command parameters/ response data	n	Variable length, specific to each command or response
CRC	2	16-bit CRC, assures

Field	Size (bytes)	Details
		integrity of delivered packet

Error-detection is ensured by a 16-bit cyclic redundancy check (CRC) field.

The packets are broadly categorized into:

- ✓ Motor specific packets
- ✓ Sensor specific packets

Motor specific packets include the commands and responses designed to control the behavior of the six motors by the PC application. This means setting the direction, speed, acceleration, position, resolution (microstep) for a subset or for all the motors. Also, the PC application issues requests to the microcontroller to obtain the current value of the motor related parameters. A few examples of commands are presented in Table 2.

Table 2. Motor specific command examples

Command ID	Brief description
MSG_ID_SET_DIR	Set the rotation direction for a number of motors.
MSG_ID_SET_SPEED	Set the speed for a number of motors.
MSG_ID_SET_POSITION	Set the position for a number of motors.
MSG_ID_SET_ACCELERATION	Set the acceleration for a number of motors.
MSG_ID_SET_MICROSTEP_REZ_M	Set the microstep resolution for a number of motors.
MSG_ID_REQ_POSITION	Request the position of a number of motors.
MSG_ID_RSP_POSITION	Response issued by the microcontroller, contains the current position for a number of motors.
MSG_ID_SET_HOMING	Send motors to predefined default position.

The PC application requires information from the sensors connected to the microcontroller board. For that purpose, sensor specific packets were designed. These general message types are used to collect data from all the sensors connected to the microcontroller.

Table 3. Sensor specific command examples

Command ID	Brief description
MSG_ID_REQ_DATA	Request data from a number of sensors.
MSG_ID_DATA	Data response issued by the microcontroller, containing data collected by the sensors.

The message requests are interpreted and processed by the microcontroller firmware as soon as possible.

To assure the microcontroller responsiveness, the communication mechanism does not make use of message queues. Once a request has been issued, the PC application will wait for the response from the microcontroller before issuing another request. Besides responsiveness, this simplifies the communication mechanism, allowing for simpler error handling in case of failures.

On the microcontroller side, the firmware parses the incoming requests via a state machine that takes individual bytes from the stream as input. The authors opted for this approach because it has been considered to be flexible and efficient as compared to other implementation alternatives. The state machine receives and processes each individual byte from the stream as soon as it is available.

The state machine handles the message identification, parsing and error detection. If the request is valid, the appropriate routine is executed, a response is generated and sent back to the PC application. If the request is not valid (unknown request ID, CRC error, wrong packet size, etc.) the request is dropped and a NAK (negative acknowledgement) response is generated and sent to the PC application.

On the PC application side, classes are defined for each request and response. For the requests, the classes provide methods for CRC calculations, parameter checking (for the data field in the requests) and composition of the message as a byte array.

The responses received from the

microcontroller are processed on the PC side by a state machine that handles each incoming byte. The state machine checks for packet errors such as unknown request ID and packet size. In the case of an invalid ID or wrong size, the response is dropped. Otherwise, CRC is calculated and compared against the CRC field in the received response. Next, the data parameters are extracted, verified and the values passed to the data structures used by the algorithms implemented by the PC application.

4. THE CONTROL AND ACTUATION SYSTEM

In order to enable non-specialists (e.g. physicians) to use safely the BR-1 robotic system a brachytherapy protocol has been defined [10] and illustrated in figure 3. The protocol has been developed for one needle, for more needles, steps 5 and 6 will be repeated for each needle.

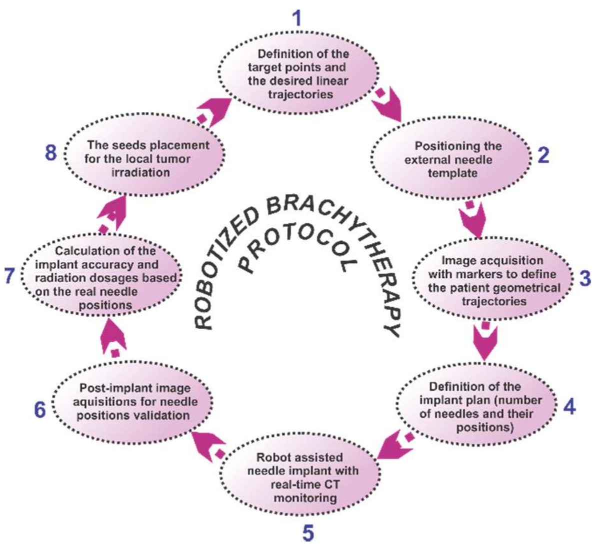

Fig. 3. Protocol defining the needle insertion in robotic brachytherapy

The geometrical model (inverse kinematics and direct kinematics) are needed for control of the robotic system. The information read from the motors are impulses, but the calculations from the geometrical models have units in “mm” and “radians”. To convert the motors pulses in "mm" and "radians" are required some transformations for each motor in part, which are described in the following equations: (1), (2), (3), (4), (5), (6).

Δq - advance the screw nut;
$stepS$ - step of the screw;
$gradNr$ - position in degrees;
$stepM_1 ... stepM_6$ - steps of the stepper motor;

$$q_1 = \frac{\Delta q}{stepS} \cdot stepM_1 \tag{1}$$

$$q_2 = \frac{stepM_2}{360} \cdot gradNr \tag{2}$$

$$q_3 = \frac{\Delta q}{stepS} \cdot stepM_3 \tag{3}$$

$$q_4 = \frac{\Delta q}{stepS} \cdot stepM_4 \tag{4}$$

$$q_5 = \frac{stepM_5}{360} \cdot gradNr \tag{5}$$

$$q_6 = \frac{\Delta q}{stepS} \cdot stepM_6 \tag{6}$$

For the robot actuation, three types of stepper motors have been used, as follows:

1. Motor model: Nema 17 gearless 42BYGHM809[12], with the following characteristics:
   - ✓ motor type: bipolar;
   - ✓ phase: 2 phases;
   - ✓ step angle: 0.9^0 (400 pulses per revolution);
   - ✓ voltage: 3V;
   - ✓ current: 1.7 A/phase;
   - ✓ holding torque: 0.48N;
   - ✓ Shaft Diameter: 5 mm;
2. Motor model: Nema 17 Planetary Gearbox, 36JX30K5.2G[13], with the following characteristics:
   - ✓ motor type: bipolar;
   - ✓ phase: 2 phases;
   - ✓ step angle: 0.35^0 (1028 pulses per revolution);
   - ✓ holding torque: 1.8N;

- ✓ voltage: 12V;
- ✓ current: 1.7 A/phase;
- ✓ Shaft Diameter: 8 mm;

3. Motor model: Nema 8, gearless ST2018S0604[14], with the following characteristics:

- ✓ motor type: bipolar;
- ✓ phase: 2 phases;
- ✓ step angle: 1.8^0 (200 pulses per revolution);
- ✓ holding torque: 0.018N;
- ✓ voltage: 3.9V;
- ✓ current: 0.6 A/phase;
- ✓ Shaft Diameter: 5 mm;

A representation of the electric block diagram of the parallel robotic system BR-1 is presented in figure 4 [15].

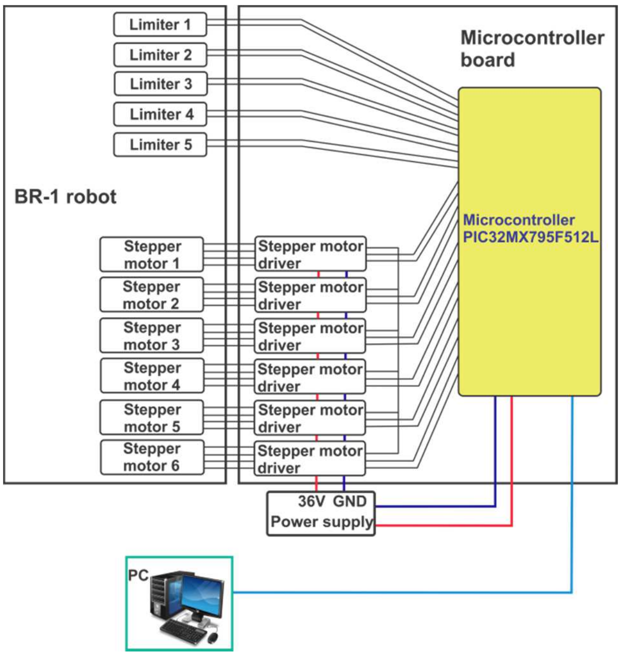

Fig. 4. Electrical scheme of the robotic system BR-1

The Brachytherapy parallel robot control is made via a command and control unit, composed of several modules that are mounted in an electrical panel which shows in figure 5.

The robotic system's command and control unit connects the BR-1 computer (PC) and robot. In Figure 5 we can identify these components as follows:

1 - stepper motors drivers;
2 - PIC32MX795F512 microcontroller;
3 - for micro switch and force sensor circuit;
4 - power supply for stepper motors coils;
5 - the signal for stepper motor drivers; (direction, number of steps);
6 - driver configuration steps for division of stepper motor;
7 - power supply for the control panel;
8 - power supply for stepper motor drivers;
9 - Power Supply for fans;
10 - fans;
11 USB port.

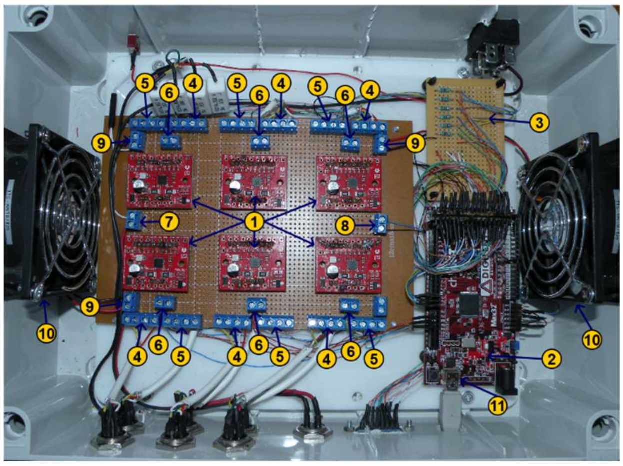

Fig. 5. Command and control unit

From software point of view, it is divided into two control system levels (fig. 6)

□ **PC level**, this level controls the commands and has included the user interface;
□ **Microcontroller level**, contains the software to the hardware, drivers and stepper motor control unit with PIC32MX795F512.

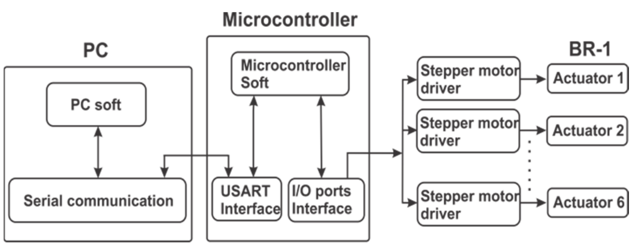

Fig. 6. Command system structure in terms of the software

The two levels that divide the robots command are:

The first level, which in terms of software contains the man-machine interface, allows the data input by users. User commands are processed, analyzed, verified by BR-1 program, and then the program computes the motion parameters after which they are sent to the microcontroller.

The second level achieves the motor positioning. Electrical signals to control the motors are generated at this level, depending on the input data that is received by the PC via the serial communication line.

The input data is processed by a microcontroller and then is sent to the motor driver. The control driver uses three signals:

- The **enable** signal activates the driver;
- The **step** signal, giving momentum to the execution of a step;
- The **dir** signal defines the sense of motor rotation;

Then the signal from the driver reaches the stepper motor through output ports. In order to initialize the motors and set the zero position, stroke sensors have been mounted on the robotic structure. These sensors signals reach the microcontroller digital entry ports.

On this level there are 3 main components:

- PIC32MX795F512 microcontroller program;
- USART interface (serial communication);
- I / O (input / output);

4.1 The user interface

In order to be able to interact with the robot, a user interface is needed, detailed in figure 6, which enables a simple and precise control of the robot.

The user interface allows selection between five control options of the robot, as follows:

- **Test Motors & Check Kinematics& Serial Communication;**
- **Manual Control;**
- **Continuous Path Set;**
- **Parametric Control;**
- **Continuous Path points;**

Test Motor & Check Kinematics & Serial Communication – By using this option the developer can test the robot kinematics, with different motion parameters (acceleration, speed, displacement).

Manual Control – the user can actuate individually each motor or a selected number of motors on the structure of the robot (between one and six motors), and set the working speed, without predetermined coordinates.

Continuous Path Set - The continuous path waypoints of positions and velocities arising from the calculation of motion control algorithm called "Continuous Path" are shown.

Parametric Control - This is the main interface through which the user controls the robotic system BR-1 in brachytherapy procedures, figure 6.

4.2 Performing the steps to control the robotic system via the user interface

Since the beginning of the procedure, the power supply for the motor drivers must be set on by the user by clicking the "Stepper Motors On" button. From that moment the "k_translation / k_rotation" selection becomes active allowing choosing the kinematics of the robot, depending on the used configuration of the robot, (rotational mode / translational mode), turning into a properly led chosen configuration.

After choosing the configuration, the user can click on the "Add Value" to insert a set of values for the insertion point and the target point, values that are found in a text file. After inserting the sets of values, by clicking on the "Homing" positioning, the motors are sent in zero position and all the active joints of the robotic system are sent to the their respective stroke limits. After this operation ends, the "Origin" button becomes active, sending the needle in the workspace of the robot. The next step consists in pressing the "Go to insertion point" in order to calculate the trajectories of the robot, after which a workspace check is performed. If the needle is in the robot workspace, the "Validate" button becomes active and a message appears on the user interface. In this moment the robot moves on the calculated trajectories. After the robot has reached the target point, the five motors of the robot are blocked and the interface buttons for handling the needle insertion module brachytherapy become active. By clicking "Automatic Forward" the brachytherapy needle will advance from the actual position of the needle (usually the insertion point) up to the target point in the patient tumor. By pressing "Automatic Backward", the needle starts to retract. For manual control of speed and distance traveled by the needle the "Manual Insertion" button can be used. The force with which the needle penetrates the tissue of the patient can be observed on a real time graph that displays the force on 3 color levels, red color representing the point where the force of the advancing needle is too large and the brachytherapy needle should stop and retreat. After the needle insertion procedure is over, pressing the "C_P-Origin" button the robot moves back on the trajectory to the point of origin.

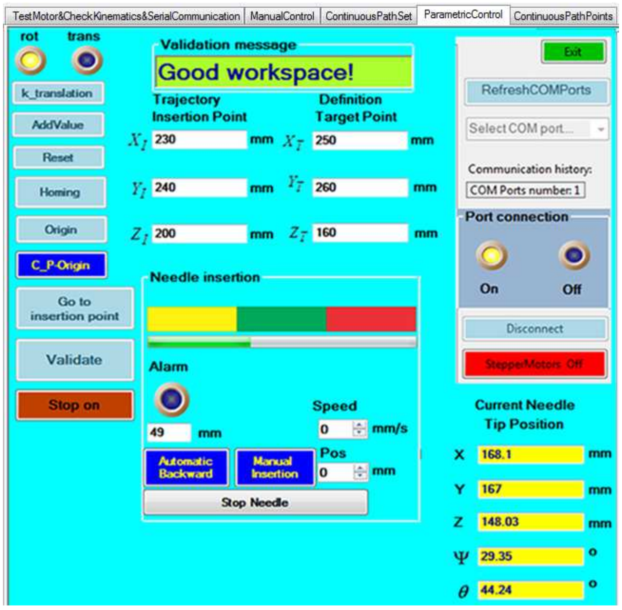

Fig. 6. The main User Interface

4.3 The experimental tests performed with the parallel robotic system BR-1

Laboratory tests have been performed in order to assess the robots functionality. For experimental tests, ballistic gel has been used to simulate human tissue; a few target points (the opaque area in the ballistic gel form) have been set. Once the pattern position has been defined by using ballistic gel, the tumor coordinates were determined and introduced in the PC robot application.

These experimental tests have been achieved with two configurations of the BR-1 parallel robot. The first configuration has a rotational passive joint called BR-1R and the other one is called BR-1T, having a translational passive joint. The BR-1R configuration has been conceived for the use of treatment of localized tumors at the thyroid and the lung level; the second one (BR-1T) has been conceived for the use of treating localized tumors at the kidney and liver level. In figure 3 is represented the experimental model of the BR-1T parallel robot for brachytherapy and in figure 4 the experimental model of the BR-1R.

4.3.1. Tests performed with the parallel robot BR-1R:

For the experiments to be validated, a set of six measurements were performed (see Table 4) with the following pairs of points:

Table 4. Experimental measurements

Nr. Crt.	**Insertion point coordinates [mm]**	**Target point coordinates [mm]**	**Target organ**
1.	$X_I = 230$, $Y_I = 240$, $Z_I = 200$	$X_T = 250$, $Y_T = 260$, $Z_T = 160$	Lungs
2.	$X_I = 280$, $Y_I = 250$, $Z_I = 250$	$X_T = 330$, $Y_T = 300$, $Z_T = 200$	Thyroid
3.	$X_I = 250$, $Y_I = 260$, $Z_I = 240$	$X_T = 265$, $Y_T = 275$, $Z_T = 225$	Lungs
4.	$X_I = 300$, $Y_I = 270$, $Z_I = 230$	$X_T = 330$, $Y_T = 300$, $Z_T = 190$	Lymph nodes
5.	$X_I = 280$, $Y_I = 260$, $Z_I = 200$,	$X_T = 300$, $Y_T = 290$, $Z_T = 160$	Thyroid
6.	$X_I = 270$, $Y_I = 270$, $Z_I = 270$	$X_T = 300$, $Y_T = 300$, $Z_T = 250$	Lungs

The 6 sets of points were relatively defined to the robots coordination system where the patients position on the CT-SIM table had been taken into account.

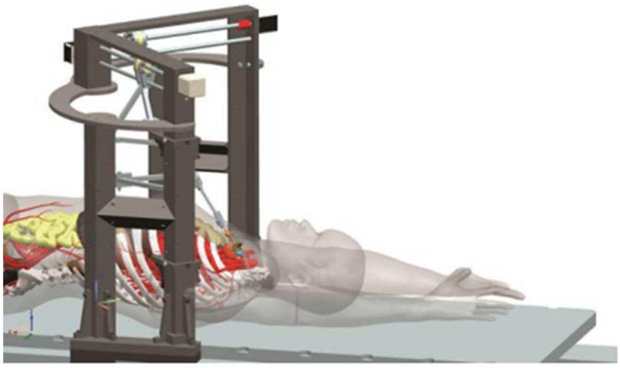

Fig. 7. Simulation treatment of a tumor in the thyroid

Figure 8 and figure 9 presents the experimental stand, the two sets of points are introduced in the command interface, according to the second position from the table which has experimental measurements and virtual simulation illustrated in figure 7.

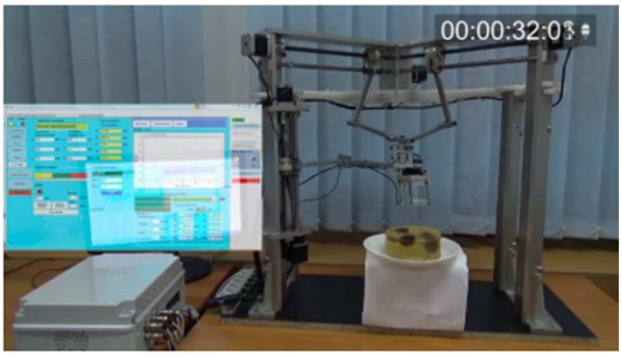

Fig. 8. Final guidance in positioning the needle with the insertion point

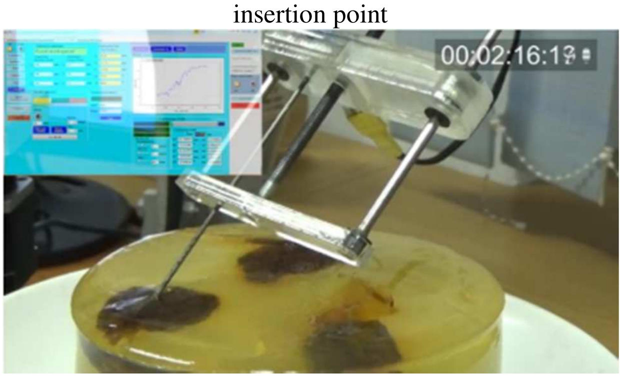

Fig. 9. The insertion needle reaching target tumor

4.3.2. Tests performed with parallel robot BR-1R:

A second set of experimental tests (see Table 5) was done with the BR-1T robotics configuration, fitted with passive translational coupling (item 9 in figure 1 is replaced with the module 12). In this case we defined a series of pairs with representative points.

Table 5. Experimental measurements

Nr. Crt.	**Insertion point coordinates [mm]**	**Target point coordinates [mm]**	**Target organ**
1.	$X_I = 310$, $Y_I = 260$, $Z_I = 220$	$X_T = 330$, $Y_T = 270$, $Z_T = 190$	Liver
2.	$X_I = 330$, $Y_I = 290$, $Z_I = 230$	$X_T = 350$, $Y_T = 320$, $Z_T = 200$	Liver
3.	$X_I = 340$, $Y_I = 290$, $Z_I = 220$	$X_T = 360$, $Y_T = 295$, $Z_T = 200$	Kidney
4.	$X_I = 240$, $Y_I = 290$, $Z_I = 220$	$X_T = 260$, $Y_T = 295$, $Z_T = 200$	Kidney

Figure 10 and figure 11 presents the experimental stand; in the command interface two sets of points are introduced as the first experimental measurements of the table position. In this case the robot was able to successfully achieve the target tumor.

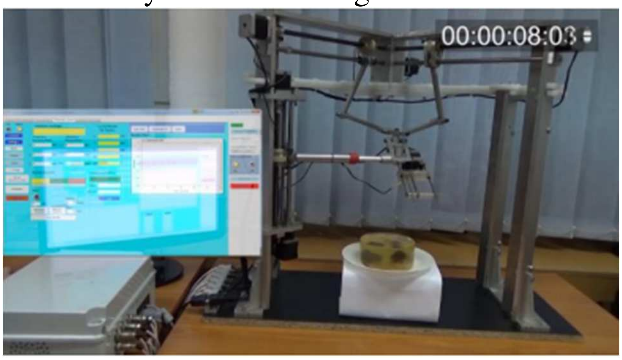

Fig. 10. Final guidance in positioning the needle insertion point

5. CONCLUSIONS

The paper presents a new serial communication protocol for commanding and controlling a parallel innovative structure suitable for brachytherapy applications. The most important advantages offered by this structure are:

The system will enable a minimally invasive approach for most tumors that can be treated using brachytherapy procedure.

The robotic control system was based on a protocol for achieving robotic brachytherapy procedure defined together with oncologists to ensure optimal results in maximum security conditions.

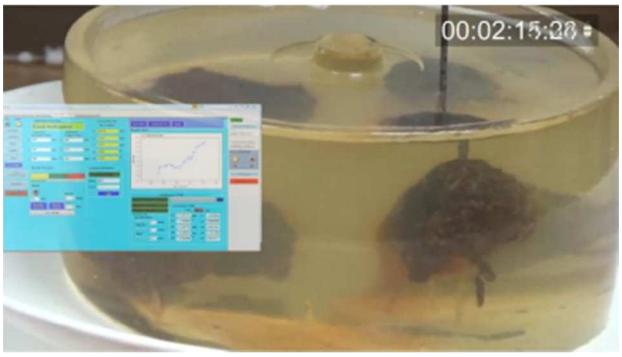

Fig. 11. The insertion needle reaching target tumor

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UN NOU PROTOCOL DE COMUNICARE SERIAL PENTRU CONTROLUL UNUI ROBOT PARALEL MEDICAL

Lucrarea prezintă un nou protocol de comunicare serial folosit în controlul unui robot paralel pentru brahiterapie. Din motive de siguranţă, sistemul robotic a fost proiectat după un protocol care acoperă atât aspectele terapeutice cât şi problemele de siguranţă punctate de către medicii oncologi. Sistemul robotic, numit BR-1, are 5 grade de mobilitate şi a fost construit în două configuraţii: BR-1R(cu cuplă pasivă de rotaţie) şi BR-1T(cu cuplă pasivă de translaţie), fiecare fiind folosit pentru procedure de brahiterapie specifice.

Doina PISLA, Prof. Dr. Ing., Technical University of Cluj-Napoca, Doina.Pisla@mep.utcluj.ro, Office Phone: +40 -264-401684, B-dul Muncii 103-105, Cluj-Napoca.

Florin COVACIU, Dr. Ing., Technical University of Cluj-Napoca, Florin.Covaciu@mep.utcluj.ro, Office Phone: +40 -264-401684, B-dul Muncii 103-105, Cluj-Napoca.

Bogdan GHERMAN, Dr. Ing., Lecturer, Technical University of Cluj-Napoca, , Bogdan.Gherman@mep.utcluj.ro, Office Phone:+40 -264-401684, B-dul Muncii 103-105, Cluj-Napoca.

Calin VAIDA, Dr. Ing., Associate Prof., Technical University of Cluj-Napoca, Calin.Vaida@mep.utcluj.ro, Office Phone:+40 -264-401684, B-dul Muncii 103-105, Cluj-Napoca.

Nicolae PLITEA, Prof. Dr. Ing., Technical University of Cluj-Napoca, , Nicolae.Plitea@mep.utcluj.ro, Office Phone:+40 -264-401684, B-dul Muncii 103-105, Cluj-Napoca.