Design of a Biomechatronics Robot to Provide Therapy and to Remove Tumors

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Abstract This chapter presents the design of a biomechatronics device by means of a prototype that includes mechanical, electronic and computational design with biomedical applications. The robot design was done in SolidWorks 2009, and consists of a Cartesian robot with 3 degrees of freedom (RC3GL), whose pieces were fabricated using advanced manufacturing in a CNC machine.The objective of this design is that the robot is capable of moving in the x, y and z Cartesian axes controlled by a computer. Furthermore, its terminals should serve to perform functions to locate damaged tissue to provide microwave cancer therapy and remove

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tumors, with the purpose of contributing in the design of equipment that serves to make the manual labor that perform an oncologist with patients in Chihuahua, México.

Keywords Robot • Mechanical design • Electronic design • Programming • Heat transfer software • Advanced manufacturing • Therapy • Radiofrequency • Microwaves • Removal • Tumors • Electronic circuits • Bioheat equation

Abbreviations

RC3GL	Cartesian robot with 3 degrees of freedom
RF	radio frequency
LM35	temperature sensor
LCD	screen of liquid crystal

1 Introduction

This chapter is a contribution to the state-of-art-of robotics, which is the branch of technology devoted to the design, construction, operation, structural arrangement, manufacture and application of robots. Robotics combines various disciplines such as: mechanics, electronics, computer science, artificial intelligence and control engineering, among others [1, 2].

The aim of this work is the physical and experimental realization of a mechatronic robot with heat transfer functions [3–9] to remove tumors in therapy and to benefit the health sector.

Previously, a part of the robot (RC3GL, [11]) was designed in the software Solid Works 2009 [10], which were developed through advanced manufacturing in a CNC machine (mechanical design).

Recently, a part of the robot (RC3GL, [11]) was designed in the software Solid Works 2009 [10] and produces through advanced manufacturing in a CNC machine (mechanical design).

The actual focus is on the realization of the entire design: solid works, mechanical, electronic and computational designs to develop a robot that has two parts: (a) RC3GL [11] capable of moving in the three Cartesian axes and, (b) two terminals adapted to RC3GL to conduct cancer therapy in order to remove tissue damaged by microwaves and remove tumors, especially in human organs such as the liver.

In the framework of the computational design, three programming languages of high and intermediate level were used to write the software to control RC3GL: Flash CS5, Visual Basic.NET and Action Script 2.0. These tools were used to develop a power and control circuit to establish communication and to control the movements of the robot.

The results obtained so far in building the robot consists of two parts: (a) the designs: solid works, mechanical, electronic and computational; and (b) modeling and simulation.

Talking about the medical functions that the robot is supposed to perform, it must execute the work of radiosurgery, as the medical procedure of *radiotherapy* is called, where narrow beams of radiation in the megavoltage are administered by multiple convergent and formed fields. This allows having a high dose of irradiation which can be accurately located in an area or specific anatomical structure, avoiding toxic doses to adjacent tissues [12–16].

The terminals are expected to provide therapy to remove damaged tissue tumors, and to perform a precise function through the correct location of the affected tissue area as in radiosurgery. To do this, we modeled and simulated the functions of human tissue with the Comsol Multiphysics software [17–22]. The temperatures are expected to warm the terminals and the damaged tissue where the therapy and/or removal is undergoing, and reach the ideal temperatures to perform the medical tasks.

Despite all the wealth and new technologies in robot developments, there is no Cartesian robot that performs the heat transfer function with applications in oncology [12–16] at present in the market.

The first tests will be conducted with animal tissue during the II/2012 semester, and precision and refinement testing of the functions for which the robot was designed, is expected to be completed in the I/2013 semester with the conclusion of the student`s theses[1] that are working on this project.

The Solid Works design of the pieces of the robot is original, and all parts were machined with nylacero which is a modified copolymer lauryl lactam with greater tensile strength and impact resistance. This type of Cartesian robots tackles a lot of automation tasks such as handling and assembly of parts and performing reliably, quickly and cost-effective of several functions. This offers the enormous potential to use the same robot for various applications, thanks to the modular robotic systems.

The Solid Works 2009 design [10] for the robot without medical terminals has the copyright registration No. 03-2010-012012301500-01 and is entitled: Cartesian robot with three degrees of freedom.[2]

The software was chosen to simulate the mechanical design which is an easily readable model. Furthermore, it allows the simulation and optimization of the parameters using only standard values, such as number of teeth, diametral pitches, materials, among others, and presents results in a graphical and numerical form

[1] Scholarships DGEST: 03 2010-068, 069, 070, 071 and 072 ID of thesis project for: D. J. Camacho Medina, J. Ochoa Morales, O. G. Ochoa González, A. Ruiz Mendoza and D. A. Villalba Caraveo, respectively. Moreover, J. I. Loya Valladares, L. A. Rodríguez Gándara, W. Ceballos Castillo, A. E. Ledezma Lechuga, L. E. Torres González, I. Arias Chávez, D. A. Rodríguez García, M. A. Torres Navarro.

[2] Degree Theses of Emmanuel Núñez Jáquez.

and has substantial improvements over previous versions. Solid Works is a program for 3D mechanical design that uses a graphical environment based on Microsoft Windows, intuitive and easy to handle. The main features that make Solid Works a versatile and accurate tool is its ability to create assemblies from parts, the fact that the parts can be easily modified and uses standard measures in a bidirectional way with all applications. Also it uses the layout manager (Feature Manager) that facilitates the rapid change in three-dimensional operations sketch without having to redo the design already reflected in the rest of their associated documents. Along with the part design tools, assemblies and drawings, SolidWorks [10] includes productivity tools, project management, presentation, analysis and simulation in its mechanical design.

2 Nomenclature

C	tissue's specific heat (J kg^{-1} K^{-1})
C_b	blood's specific heat (J kg^{-1} K^{-1}), 3639 [J kg^{-1} K^{-1}]
C_p	heat capacity at constant pressure for the biological tissue (J kg^{-1} K^{-1}), 3600 [J kg^{-1} K^{-1})]
J^e	externally generated current density (A m^{-2})
P_{av}	time-averaged power flow in the cable
Q_j	current source (A m^{-3})
Q_{met}	heat source from metabolism (W m^{-3})
Q_{ext}	external heat source from spatial heating (W m^{-3})
r_{inner}	dielectric's inner radii (m)
r_{outer}	dielectric's outer radii (m)
t	temporal coordinate (s)
T	temperature (°C or K)
T_b	arterial blood temperature (°C), 37 [°C]
V	potential
z	cylindrical coordinate centered on the axis of the coaxial cable
Z	wave impedance in the dielectric of the cable

Greek letters

δ_{ts}	time-scaling coefficient
ε	relative permittivity
κ	thermal conductivity (W m^{-1} K^{-1})
λ	wavelength in the medium (m)
φ	cylindrical coordinate centered on the axis of the coaxial cable
ρ	tissue density (kg m^{-3})
ρ_b	blood's density (kg m^{-3}), 1,000 [kg m^{-3}]
σ	electric conductivity (S m^{-1})
ω	angular frequency
ω_b	perfusion rate (1/s), 0.0036 [s^{-1}]

3 Modeling

Modeling of the robot functions was performed by the Comsol Multiphysics software [17–22], which makes use of the heat transfer capacity [3–9] to simulate therapy and the removal of damaged tissue cells. The human tissue is modeled as a cylindrical geometry to which a conductive heat is applied to burn the cancer cells. The module of heat transfer in biological tissues uses the bioheat transfer interface of Comsol and plays an important role in technology for medical purposes. Comsol uses the approximation of Penne [4] to represent the heat sources from metabolism and blood perfusion. The equation for heat transfer by conduction with this approach is

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met} \tag{1a}$$

The terms on the left-hand side of Eq. (1a) belong to the model of biological tissue, while the terms on theright-hand side provide; provide the bioheat model [3].

Tumor ablation involves passing of four electrodes at a given temperature through the affected tissue. The method involves inserting a tube in which electrical current flows through four electrodes leaving a plunger, to the well localized cancerous tissue. Radio frequencies are used to heat these electrodes due to heat transfer [3–9] up to a temperature between 45 and 50 °C in the tissue. This method serves to increase the cell temperature above 45–50 °C, resulting in protein denaturation with coagulation that is the ultimate cause of cell death and tissue necrosis. RF tumor ablation could be implemented in patients with liver tumors [23, 24], kidney, lung [25], prostate and breast, among others. Currently, a radiation oncologist [12–16, 25] performs this function by hand as far as information is available in the State of Chihuahua.

The probe is a needle (main bar) and four electrode arms as shown in Fig. 1. The needle is electrically isolated, except near the electrode arms. An electric current through the probe creates an electric field in the tissue. The field is the strongest in the immediate vicinity of the probe and generates resistive heating, which dominates around the arms of the probe electrode due to the strong electric field.

This model uses the bioheat equation and the continuous current mode to implement a transient analysis

$$\delta_{ts} \rho C \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \tag{1b}$$

where,

$$\nabla = \hat{\rho} \frac{\partial}{\partial t} + \frac{\hat{\phi}}{\rho} \frac{\partial}{\partial \phi} + \hat{z} \frac{\partial}{\partial z}$$

and,

$$-\nabla \cdot \left(\sigma \nabla V - \mathbf{J}^e\right) = Q_j \xrightarrow{\mathbf{J}^e = Q_j = 0} -\nabla \cdot (\sigma \nabla V) = 0 \tag{2}$$

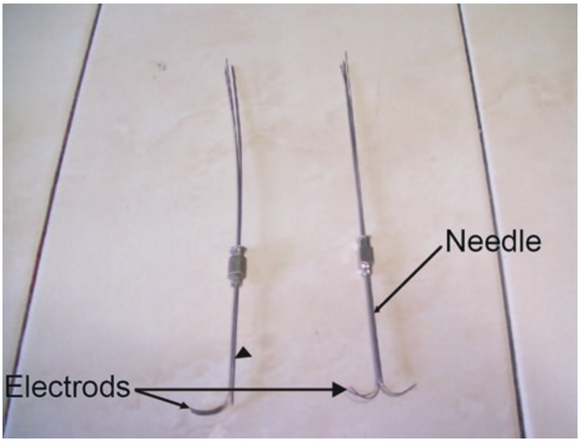


Fig. 1 Electrodes inserted into a needle to remove tumors

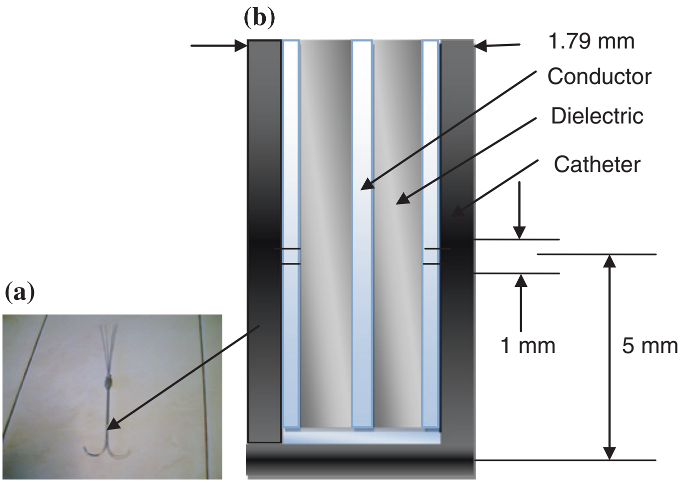


Fig. 2 Antenna geometry for microwave coagulation therapy. **a** A coaxial cable with a ring-shaped slot cut in the outer conductor which produces a short circuit at the tip. **b** A plastic catheter surrounding the antenna

It is assumed in the computational model that the body tissue is a cylinder and its temperature remains at 37 °C during the entire process. The model locates the probe along the centerline of the tissue such that its electrodes cross the region where the tumor is located.

The terminal to perform the cancer therapy by microwave consists of the following elements (see Fig. 2a): an instrument that converts electrical energy to electromagnetic energy by a coaxial antenna that emits a microwave.

The main instrument is a physical device that carries electrical energy to a very small antenna which emits microwaves onto a piece of human tissue.

The top of the antenna with a load of 128–1,300 milli volts is introduced to the center of the tumor, emitting microwaves, creating friction in the tissue of the molecules, generating heat transfer (electromagnetic field modeled by Eq. (1a, b) to a temperature of 50 °C to kill cancer cells.

The innovation that is intended to provide is to control three fundamental aspects: the induced voltage and time per session controlled by microcontrollers and temperature in order to achieve a good therapy.

The modeling of the microwave cancer therapy is done in two-dimensions with cylindrical coordinates as the problem is of rotational symmetry (see Fig. 2b).

An electromagnetic wave propagating in a coaxial cable is characterized by transverse electromagnetic fields (TEM). Assuming harmonic time fields with complex amplitudes containing the phase information, the appropriate equations are:

$$\mathbf{E} = \mathbf{e}_r \frac{C}{R} e^{j(\omega t - \kappa z)} \tag{3}$$

$$\mathbf{H} = \mathbf{e}_\varphi \frac{C}{Z} e^{j(\omega t - \kappa z)} \tag{4}$$

$$\mathbf{P}_{av} = \int_{r_{inner}}^{r_{outer}} \mathrm{Re}\left(\frac{1}{2}\mathbf{E} \times \mathbf{H}^*\right) 2\pi r dr = \mathbf{e}_z \frac{C^2}{Z} \ln\left(\frac{r_{outer}}{r_{inner}}\right) \tag{5}$$

The propagation constant κ is related to the wavelength in the medium λ as

$$\kappa = \frac{2\pi}{\lambda} \tag{6}$$

In tissue, the finite axial component of the electric field, and the azimuthal component of the magnetic field allow to model the antenna to a transverse magnetic axial symmetry (TM) and the wave equation becomes scalar $\mathbf{H}_\varphi$ as in

$$\nabla \times \left(\left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}\right)^{-1} \nabla \times \mathbf{H}_\phi\right) - \mu_r \kappa_0^2 \mathbf{H}_\phi = 0 \tag{7}$$

The boundary conditions on the metal surfaces are

$$\mathbf{n} \times \mathbf{E} = 0 \tag{8}$$

The feed point is modeled with a boundary condition of a source with 10 W. This is a reflection boundary condition of first order with an input field $\mathbf{H}_{\varphi 0}$

$$\mathbf{n} \times \sqrt{\varepsilon}\mathbf{E} - \sqrt{\mu}\mathbf{H}_\phi = -2\sqrt{\mu}\mathbf{H}_{\phi 0} \tag{9}$$

$$\mathbf{H}_{\phi 0} = \frac{\sqrt{\frac{\mathbf{P}_{av} Z}{\pi r \ln\left(\frac{r_{outer}}{r_{inner}}\right)}}}{r} \tag{10}$$

to an input power of W $\mathbf{P}_{av}$ as shown in the average power flow in time. The antenna radiates in the tissue where a damped wave propagates: (1) an absorption boundary condition at some distance from the antenna, without excitement, in all the external borders, and (2) A symmetry boundary condition at the boundaries $r = 0$, namely

$$E_r = 0 \tag{11}$$

$$\frac{\partial E_z}{\partial r} = 0 \tag{12}$$

The domain and boundary equations of heat transfer are satisfied by the bioheat equation which describes this phenomenon in steady state as

$$\nabla \cdot (-\kappa \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \tag{13}$$

$$Q_{met} = 0 \tag{14}$$

$$Q_{ext} = \frac{1}{2} \mathrm{Re}\left[(\sigma - j\omega\varepsilon) \mathbf{E} \cdot \mathbf{E}^* \right] \tag{15}$$

The model assumes that the rate of perfusion of blood is $\omega b = 0.0036\ s^{-1}$, and that the blood enters the liver at a body temperature of $T_b = (37 + 273.15)$ K and is heated up to a temperature T. The heat capacity of the blood is $C_b = 3{,}639$ J/kg K. These data are used to model the heat transfer only in the domain of the liver. Where this field is truncated, the insulation is used, namely:

$$\mathbf{n} \cdot \nabla T = 0 \tag{16}$$

4 Results and Discussion

This section presents the results of this work by Figs. 3, 4, 5, 6, 7, 8 and 9. Figure 3 a shows the parts that make up the prototype which were developed through advanced manufacturing in a CNC machine, (b) the CNC machine and (c) the Solid Works design of RC3GL.

This robot designed in 2009 by Solid Works [10, 11] is able of moving in three axes, driven by motors of five steps that are managed through a USB port of a computer, with the use of microcontrollers (PIC 18F4550 and PIC16F84A) so that it can be positioned accurately in a Cartesian space. The movement in two axes is assisted by bands, while the other axis is driven with the aid of nuts and bolts [11].

The results of the electronic design were based on a previous analysis that was done on the shape memory material to construct the electrodes of the end piece that must be adapted to RC3GL in order to remove tumors.

The heat transfer behavior of the shape memory materials was studied in order to know in which way the high frequency waves must flow through the material (see Fig. 4).

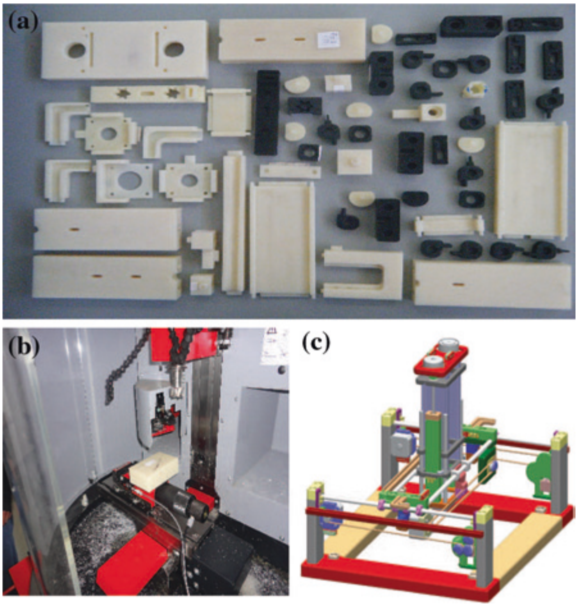


Fig. 3 **a** Some parts of RC3GL were made with advanced manufacturing in a **b** CNC machine. **c** Solid Works design of RC3GL

Based on another study [26] on the thermo mechanical characterization of the *Ni–Ti* alloy to change its original shape by applying heat to the electrodes prior to its yield point, a circuit was developed to induce high frequency electrical waves in the electrodes, that would not risk the the recovery of the material. Furthermore, the process of shape change (reshaping) of the *Nitinol* was studied.

Finally, the terminal was developed in order to remove tumors with four electrodes of *Nitinol* with the required shape memory effect and a search was performed ti find a way to insert the electrodes in liver tissue (Figs. 1 and 2a).

To prevent the electrodes to lose their shape and to penetrate liver tissue removing the tumor, a circuit for controlling the temperature with a 16F873A microcontroller and a temperature sensor LM35 was designed.

A value is assigned to the maximum and minimum temperature and the emission of a pulse to the main circuit obtained, showing the temperature on LCD display (see Fig. 4a).

Figure 4b–e show the circuit board, the soldier components, the full box, the terminals and box components. The electronic design is controlled by an electronic circuit that transmits and receives signals such as radiofrequencies, with buttons, displays, LCDs, indicators, etc. The results are obtained as described below.

A block diagram of the complete circuit for electronically controlling the function of the terminals of the robot is shown in Fig. 5, whose design has been finalized by:

1. Power supply: (a) Voltage source of 5 V and 30 V. (b) Physical voltage source. For the treatment of tumor removal, which is based on the emission of RF through titanium-nickel electrodes, which are introduced into damaged tissue, the RF causes the tumor to be heated and to be burned.

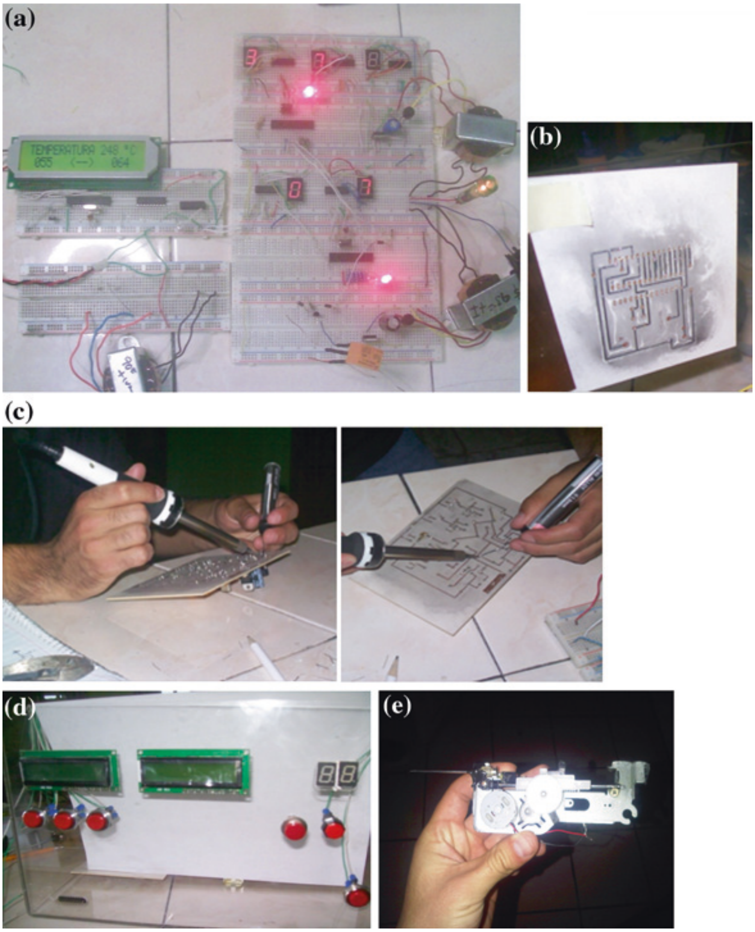


Fig. 4 Electronic design and analysis of shape memory material: (**a**) the temperature controller circuit, (**b**) printed circuit board, (**c**) soldier components, (**d**) full box (Push button, indicators, LCD displays, switch and connection to electrodes) and (**e**) terminals and box components (terminal stripping of liver tumors: shortest amount of time and high accuracy to improve security of the process)

2. Control circuit.

Receives signals from the majority of the circuits.

Controls output to the electrodes.

Gives way to the RF to the electrodes when the start button is pressed and it does not emit this signal when the device is not operating or when the process ends. This signal is received from the timing circuit.

Receive signals from the circuit of the electrode to maintain its temperature at 55 and 65 °C.

Control the input and output or the electrodes on the needle.

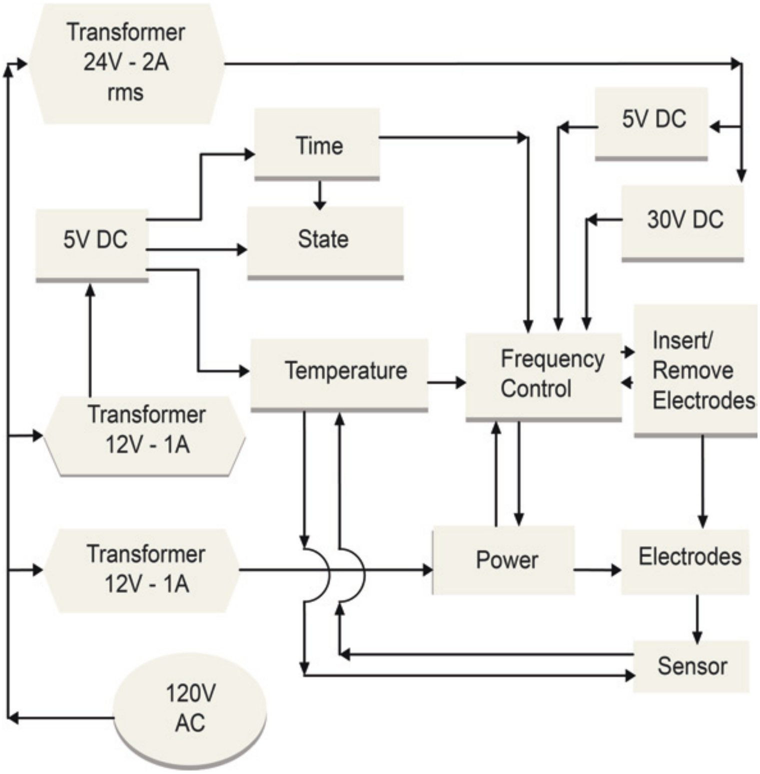


Fig. 5 Block diagram of the complete circuit for electronically controlling the function of the terminals of the robot

3. The frequency-control blocks (Fig. 6). The circuit function is to emit a radio frequency (RF) of 8 MHz with amplitude of about 7 Vpp taking 12.5 V as the basis around this voltage is the oscillation from 9.5 to 15.5 V. It is connected to the electrodes. It is powered by the 24 V supply to 2 A, and converted to direct current. The output goes to the power circuit.

4. Adaptation of the microcontroller to the physical prototype.

The machine has a temperature sensor (LM35) in the electrodes. Range: 55–65 °C.

The sensor sends its signal to the PIC16F873A, this interprets the signal and sends it to an LCD screen which displays the temperature value by sending a signal to the control circuit.

5. Electronic design. Figure 7 shows (a) Physical circuit of temperature, (b) Timing circuit (PIC16F873A), (c) Process State circuit (d) all of the breadboard circuit (LCD screens, displays of the timing circuit, the frequency—control circuit, power supplies, indicators, and all circuits).

6. Circuit for measuring the electrode temperature and to set the time of the process.

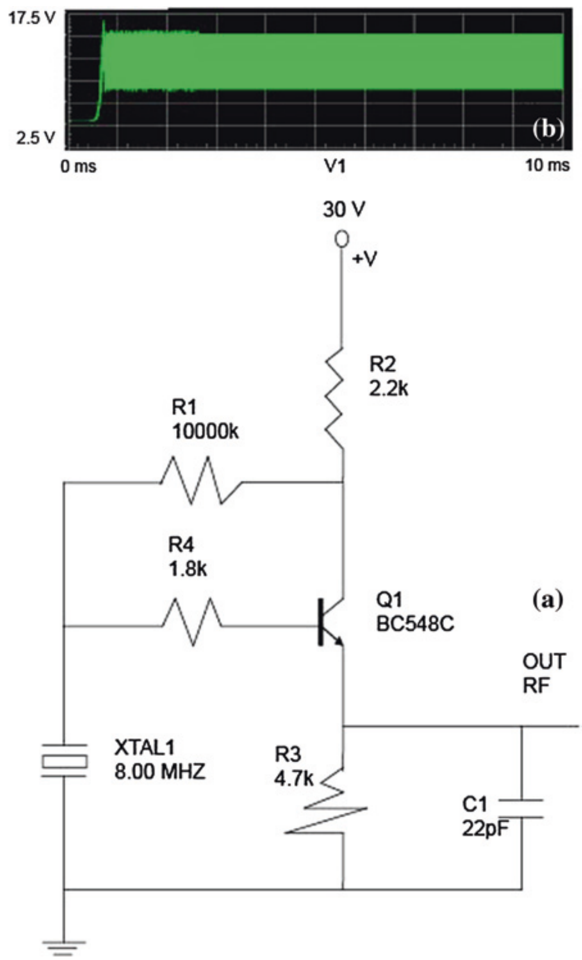


Fig. 6 Block control-frequency. **a** RF transmitter circuit. **b** Output signal RF circuit

7. The circuit for controlling the temperature of the terminal to provide cancer therapy by microwave emission.

With respect to the computational design, the micro controller programming was performed to play its role in the mechatronic prototype.

The control of the circuit through the micro controller (3 pieces) PIC16F873A, each was charged by separate programs according to their function in the circuit. Program for function 1: Controls the duration of the process, sends signals to insert and remove electrodes and emits signals to start or stop the process. For the program for function 2 there is a PIC that indicates the status of the process as waiting, treatment in process and treatment completed. Finally, the program for function 3 has a PIC to control the temperature (an input (sensor LM35) and an output).

The RC3GLcontrol software was developed in three programming languages of high and intermediate level: Flash CS5, Action Script 2.0 (Design of

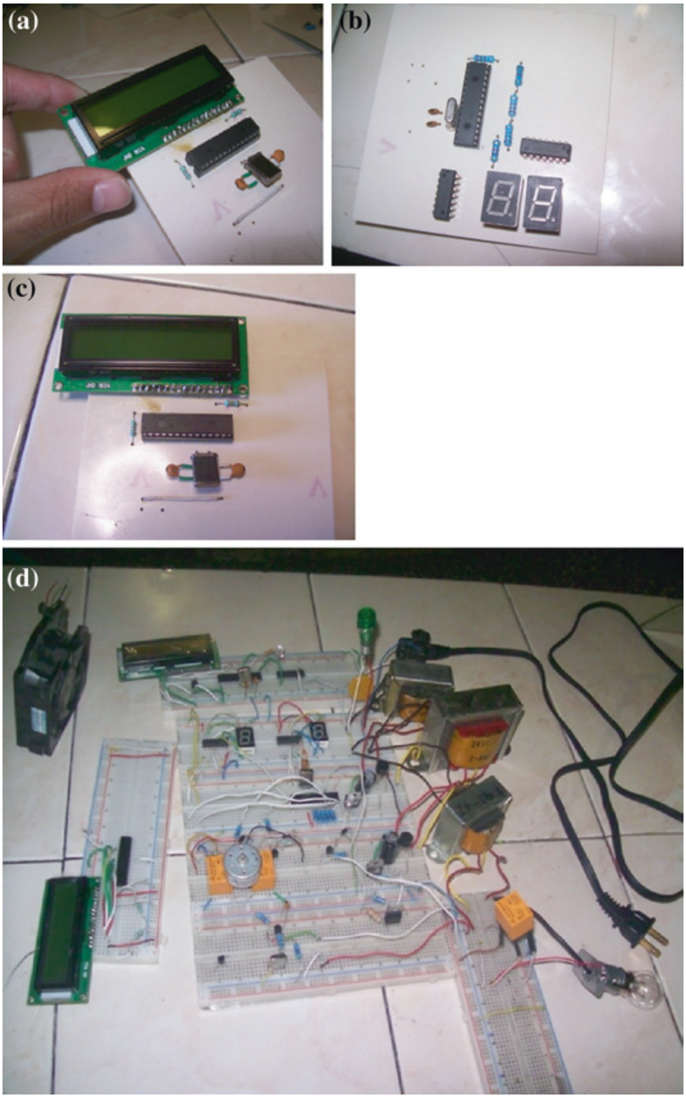
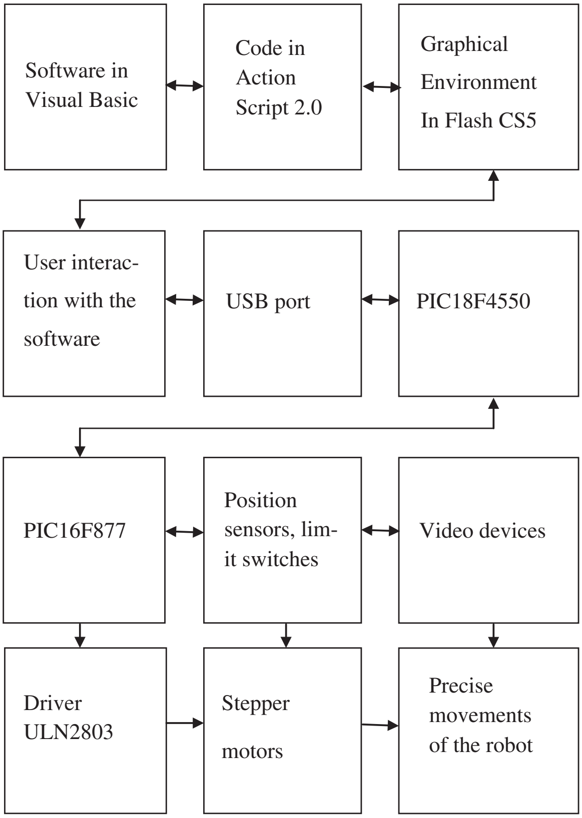


Fig. 7 **a** Physical circuit of temperature. **b** Circuit of time control. **c** Circuit of state of process. **d** All circuit in protoboard

the appearance of software in Flash CS5 using Action Script 2.0 code) and Visual Basic.NET. A video test was performed in the control software.

The simulation of the control of the stepper motor in Proteus 7.7SP2 with a PIC16 series microcontroller and the simulation in Proteus 7.7SP2 of the interaction between the PIC18F4550 and USB port of the computer and communication

Table 1 Process for the optimal control of RC3GL



with the control software: Circuit of control and power to establish communication and control the movements of the robot.

Table 1 shows the process for optimal control by means of circuit of control and power of the RC3GL used to test with two of the four stepper motors.

The results we expect to obtain during the implementation of the mechatronic robot have been modeled only theoretically in the software Comsol Multiphysics [17–22] and the graphics are contained in its Model Library for: (a) removal of tumor and (b) microwave cancer therapy.

During the process of tumor removal, a temperature field in the intervals of 39–82.017 °C and/or 310 and 361 K is expected in the electrodes during a period of 60 s. It is also expected that the temperature at the tip of an electrode behaves as the graph of Fig. 8.

A localized region of human tissue must reach 50 °C within 8 min and must be swept by the electrodes [23].

During the process of cancer therapy by means of microwaves (for steady state and a microwave power input of 10 W), it is expected that the temperature field in

Fig. 8 Expected temperatures at the tip of an electrode

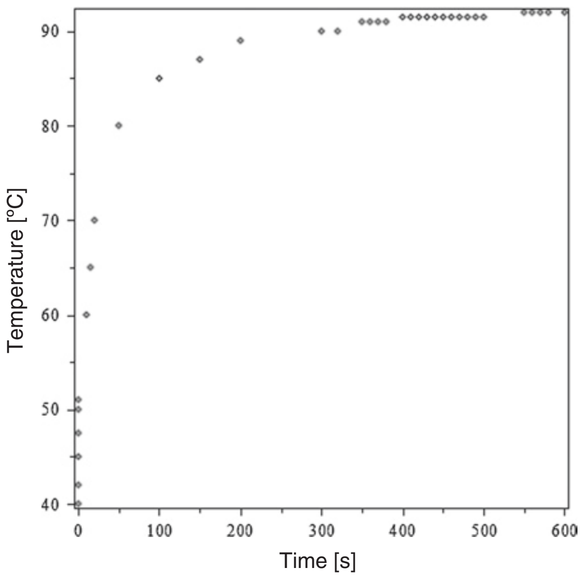
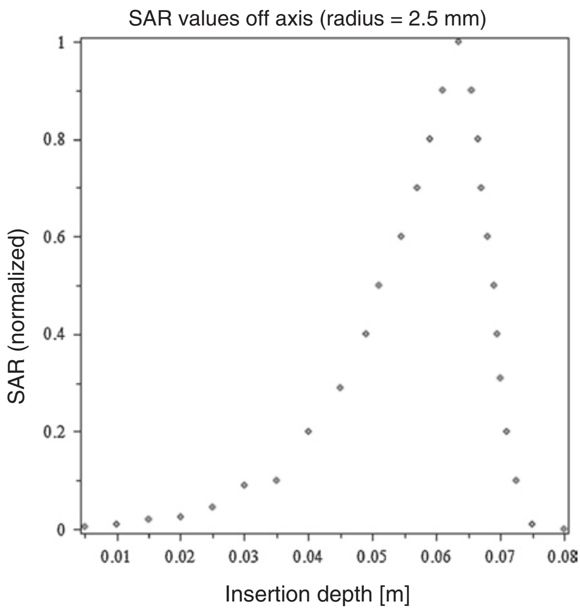


Fig. 9 Normalized specific absorption (SAR) value along a line parallel to the antenna and 2.5 mm from the antenna axis [27]. The tip of the antenna is located at 70 mm, and the slot is at 65 mm



the liver tissue raises in the range of 310.273–373.892 K, according to simulations in Comsol Multiphysics.

The computed microwave heat-source density must reach its highest values near the tip and the slot; to a scale that is cut into 1e6 W/m^3 (the field of microwave heat-source density oscillates between 0 and 10e5 W m^{-3}).

The blood perfusion which is relatively cold seems to limit the extension of the area that is being heated.

Close to the antenna, the heat source is stronger (see Fig. 2), and far from it, the heat source is weaker and the blood manages to keep the tissue at normal body temperature.

The normalized specific absorption (SAR) values along a line parallel to the antenna should show a behavior as the graph of Fig. 9.

5 Conclusions

The mechanical, electronic and computational design of a mechatronic robot with thermofluids application, that allows replacing the manual function that is done by a radio oncologist in order to remove tumors and give cancer therapy through microwaves has proven to be feasible and has been successfully completed. It only remains the pending implementation. The first tests are going to be conducted during the II/2012 semester and accuracy and refinement testing should be done to the end of the I/2013 semester.

It is expected that the tip of the antenna generates a heat transfer to a temperature of up to 50 °C in order to kill cancer cells by an excellent therapy via microwaves.

Likewise, it is expected that the radio frequencies heat the electrodes to a temperature between 45 and 50 °C in the tissue or above this temperature, for a suitable removal of tumors in human organs.

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