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Biomimetic approach to design and control mechatronics structure using smart materials

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1. Introduction

Life's evolution for over 3 billion years resolved many of nature's challenges leading to solutions with optimal performances versus minimal resources. This is the reason that nature's inventions have inspired researcher in developing effective algorithms, methods, materials, processes, structures, tools, mechanisms, and systems.

Animal -like robots (biomimetic or biomorphic robots) make an important connection between biology and engineenng.

Biomimetics is a new multidisciplinary domain that include not only the uses of animal-like robots – biomimetic robot as tools for biologists studying animal behavior and as research frame for the study and evaluation of biological algorithms and applications of these algorithms in civil engineering, robotics, aeronautics.

The biomimetic control structures can be classified by the reaction of living subject, as follows:

- reactive control structures and algorithms
- debative control structures and algorithms
- hybrid control structures and algorithms
- behavior control structures and algorithms.

Reactive algorithms can be defined, regarding living subject reaction, as being characterized by the words : "React fast and instinctively". This kind of control is specific to reflex reactions of the living world, fast reactions that appear as reply to the information gathered from the environment that generate reactions to variable conditions like fear, opportunities, defense, attack. For such algorithms there is available a small number of internal states and representations with the advantages (fast answer time, low memory for taking decisions) and disadvantages (lack of ability to learn from these situations, implicit repetitive reaction) that goes with them. Studies regarding this kind of control were started by Schoppers 1987 and Agre and Chapman 1990 that have identified the strong dependence of this control by

the environment and evolutive situations. In robotics, alternatives for this control are applicable in mobile structures that work in crowded places.
Debative algorithms can be defined by the following words: ”Calculate all the chances and then act”. This kind of control is an important part of artificial intelligence. In the living world, this type of control is specific to evolved beings, with a high level of planned life. For example, man is planning ahead its route, certain decisions that must be taking during its life, studies possible effects of these decisions, makes strategies. From a technological point of view, this kind of control has a complicated internal aspect, internal representations and states being extremely complex and very strong linked by predictive internal and external conditions with a minor or major level of abstract. Consuming a lot of memory and calculus, this kind of control doesn’t fit, for now, to real time control, the technological structures that benefit from such control might suffer decisional blocks or longer answer times. Even the solution given by this algorithm is optimal, the problem of answering in real time makes alternatives for this control to be partly applied, less then optimal solutions being accepted.
Hybrid algorithms can be defined by the phrase “Think and act independently and simultaneous”. Logical observation that living world decisions are not only reactive or debative has led to hybrid control. The advantages of reactive control – real time answers – together with the complexity and optimal solutions provided by debative control has led to a form of control that is superior from a decisional and performance point of view. The organization of control architecture consists of at least two levels: the first level – primary, decisional – is the reactive component that has priority over the debative component due to the need of fast reaction to the unexpected events; the second level is that of debative control that operates with complex situations or states, that ultimately lead to a complex action taking more time. Due to this last aspect, the debative component is secondary in importance to the reactive component. Both architectures interact with each other, being part of the same system: reactive architecture will supply situations and ways to solve these situations to the debative architecture, multiplying the universe of situations type states of the debative component, while the last one will create new hierarchic reactive members to solve real time problems. There is the need for an interface between the two levels in order to have collaboration and dialogue, interface that will lead to a hierarchy and a correspondence between members of the same or different levels. That’s why this system is also called **three levels of decision system.** In robotics this system is used with success, the effort of specialists is focused on different implementations, more efficient, for a particular level, as well as for the interactions between this levels (Giralt 1983, Firby 1987, Arkin 1989, Malcolm and Smithers 1990, Gat 1998).
Behavioural algorithms can be defined by the words: ”Act according with primary set of memorized situations”. This type of system is an alternative to the hybrid system. Thou the hybrid system is in permanent evolution, it still needs a lot of time for the decisional level. The automatic reactions identified when the spinal nervous system is stimulated have led to the conclusion that there is a set of primary movements or acts correspondent to a particular situation. This set is activated simultaneously by internal and external factors that leads to a cumulative action (Mataric 1990). This type of architecture has a modular organization splitted in behavioral sets that allows the organization of the system on reactive states to complex situations, as well as the predictive identification of the way that bio-mimetic system responds (Rodney 1990). This response is dependant of the external stimulations and the internal states that code the anterior evolution and manifests itself by adding

contribution of the limited number of behavioral entities (Rosenblatt 2000). The complexity of this approach appears in situations in which, due to internal or external conditions, are activated more behavioral modules that interact with each other and that are also influenced differently by the external and internal active stimulations at a specific moment in time. (Pirjanian 2002).

Cognitive model refers to essential aspects of the level of intelligence associated with a living or bio-mimetic system. The main models involved in this assembly are associated with **visual attention, motivation and emotions. Visual attention** is achieved in two stages (Chun 2001): first stage is a global, unselected, acquisition of visual information – **prefocus period** – and the second stage is **selective focus** that identifies a center of attention, a central frame in which the objective is found, objective that corresponds to the target image stocked in system memory.

Motivational model (Breazeal 1998) identifies all internal and external stimulations that trigger a basic behavior (movement, food, rest, mating, defense, attack). If animals are thought to have only one behavior at a certain moment in time because they receive only one primary motivational stimulation at a time, in humans this system must be extended. This extension results from numerous internal variables that are taken into account in human motivational analysis, external stimulations might be interpreted differently related to the internal states. Inside this motivational molding one must take also into account the complexity of reactions of different groups of people. These situations mustn't be looked like a sum of factors, the group reactions being, at least in most cases, a motivational reactions that neglects the individual (the survival of the group might accept the loss or disappearance of an individual or of a group of people, a fact that is practically impossible for an individual).

Emotional model is considered to be an identification system for major internal and external stimulations, as well as system to prepare the reaction response of the global system. Thus, based on low level entries and beginning initial states, the emotional model is activated in a different degree of excitation that will lead to a response of the global system correspondent to the generated states by the model, response different by the major actions with which the global system answers to emergent situations.

Fig. 1. Android robot Repliee R1 – Osaka University

The way that emotional system manifests itself is very different with every biological system: changing skin color, changing feathers arrangement, repeated movements that do not generate movement indicating fear or trying to intimidate, different sounds, changing face physiognomy. This last aspect was studied mainly in the last years, to achieve a

humanization of the technological environment that is evermore present (Pioggia 2006, Goetz 2003).
The androids made in Japan, the researches in USA, pet animals are only few examples for the evermore increasing interest for this type of research.
A promising field in practical implementation of biomimetics devices and robots is the domain of intelligent materials. Unlike classic materials, intelligent materials have physical properties that can be altered not only by the charging factors of that try, but also by different mechanisms that involve supplementary parameters like light radiation, temperature, magnetic or electric field, etc. This parameters do not have a random nature, being included in primary maths models that describe the original material. The main materials that enter this category are iron magnetic gels and intelligent fluids (magneto or electro-rheological or iron fluids), materials with memory shape (titan alloys, especially with nickel), magneto-electric materials and electro-active polymers. These materials prove their efficiency by entering in medical and industrial fields, a large number of them, due to their biocompatibility, being irreplaceable in prosthesis structures. Electro-active polymers, due to the flexibility of the activator potions, are a perfect solution for the implementation of animatronic projects. A special attention deserve the researches made by NASA, Jet Propulsion Laboratories – project Lulabot, Dept. of Science and Technology, Waseda University in Tokyo – project Humanoid Cranium, Cynthia Breazeal MIT (Cambridge, Mass.) – Kismet.

Fig. 2. Lulabot -David Hanson, NASA, JET Laboratory

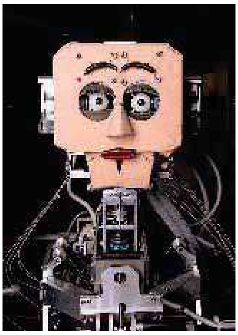

Fig. 3. Humanoid Cranium - Prof. Takanishi Atsuo, Waseda University in Tokyo

Fig. 4. Robotul Kismet dezvoltat de Cynthia Breazeal, MIT (Cambridge, Mass)

2. Fundamental characteristics of shape memory alloys

The unique behavior of SMA's is based on the temperature-dependent austenite-to-martensite phase transformation on an atomic scale, which is also called thermoelastic martensitic transformation. The thermoelastic martensitic transformation causing the shape recovery is a result of the need of the crystal lattice structure to accommodate to the minimum energy state for a given temperature [Otsuka and Wayman 1998].
The shape memory metal alloys can exist in two different temperature-dependent crystal structures (phases) called martensite (lower temperature) and austenite (higher temperature or parent phase).

Fig. 5. Shape memory alloy phase transformation

When martensite is heated, it begins to change into austenite and the temperatures at which this phenomenon starts and finishes are called austenite start temperature (A_s) and respectively austenite finish temperature (A_f). When austenite is cooled, it begins to change into martensite and the temperatures at which this phenomenon starts and finishes are called martensite start temperature (M_s) and respectively martensite finish temperature (M_f) (Buehler et al. 1967).

Several properties of austenite and martensite shape memory alloys are notably different. Martensite is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned.
Austenite is the stronger phase of shape memory alloys, which exists at higher temperatures. In Austenite phase the structure is ordered, in general cubic.
The thermoelastic martensitic transformation causes the folowing properties of SMA’s (Waram, 1993, Van Humbeeck, 1999, Van Humbeeck, 2001).

- *One-way shape memory effect* represents the ability of SMA to automatically recover the high temperature austenitic shape upon heating, but it is necessary to apply a force to deform the material in the low temperature martensitic state.
- *Two-way shape memory effect* or *reversible shape memory effect* represents the ability of SMA's to recover a preset shape upon heating above the transformation temperatures and to return to a certain alternate shape upon cooling.

Note that both the one-way and two-way shape memory effects can generate work only during heating (i.e. force and motion).

- *All-round shape memory effect* is a special case of the two-way shape memory effect (Shimizu et al. 1987). This effect differs from the two-way effect in the following ways:
  (I) a greater amount of shape change is possible with the all-around effect,
  (II) the high and low temperature shapes are exact inverses of each other, that is a complete reversal of curvature is possible in the case of a piece of shape memory strip.
- *Hysteresis behavior*. Due to processes which occur on an atomic scale, a temperature hysteresis occurs. In other words the austenite to martensite transformation (the “forward reaction”) occurs over a lower temperature range than the martensite to austenite transformation. The difference between the transition temperatures upon heating and cooling is called hysteresis. Most SMA’s have a hysteresis loop width of 10-50°C.
- *Superelasticity* can be defined as the ability of certain alloys to return to their original shape upon unloading after a substantial deformation has been applied.
- *Vibration damping capacity*. Due to the special micro structural behavior, SMA’s exhibit the highest vibration damping property of all metal materials. The damping is non-linear and frequency independent, but it’s sensitive to temperature variations and the antecedents of thermal cycling.

3. Design strategies for SMA elements

The first step an engineer should take when undertaking a design involving shape memory material is to clearly define the design requirements. These usually fall into one of the following interrelated areas: operating mode, mechanical considerations, transformation temperatures, force and/or motion requirements, and cyclic requirements.

3.1 Operating modes of SMA’s

The most used operating modes of SMA's are:

- *Free recovery* which consists of three steps: shape memory material deformation in the martensitic condition at low temperature, deforming stress release, and heating above the A_f temperature to recover the high temperature shape. There are few practical applications of the free recovery event other than in toys and demonstrations.

▪ *Constrained recovery* is the operation mode used for couplings, fasteners, and electrical connectors.

▪ *Work production – actuators*. In this operation mode a shape memory element, such as a helical springs or a strip, works against a constant or varying force to perform work. The element therefore generates force and motion upon heating.

3.2 Mechanical considerations and design assuptions

The most successful applications of shape memory alloy components usually have all or most of the following characteristics:

- A mechanically simple design.
- The shape memory component "pops" in place and is held by other parts in the assembly.
- The shape memory component is in direct contact with a heating/cooling medium.
- A minimum force and motion requirement for the shape memory component.

The shape memory component is isolated ("decoupled") from incidental forces with high variation.

The tolerances of all the components realistically interface with the shape memory component.

3.3 Transformation temperatures

The force that a spring or a strip of any material produces at a given deflection depends linearly on the shear modulus (rigidity) of the material. SMA's exhibit a large temperature dependence on the material shear modulus, which increases from low to high temperature. Therefore, as the temperature is increased the force exerted by a shape memory element increases dramatically [Dolce, 2001]. Consequently the determination of the transformation temperatures is necessary to establish the shear modulus values at these functional temperatures for a high-quality design.

This section presents the transformation temperatures obtained for the studied SMA elements (strip and helical spring) using Thermal Analysis Methods. Ni-Ti-Cu (Raychem proprietary alloy) is the material used for the two SMA elements.

Thermal Analysis Methods comprises a group of techniques in which a physical property of a sample is measured as a function of temperature, while the sample is subjected to a controlled temperature program.

Thermo**g**ravimetric Analysis (**TGA**), **D**ifferential **T**hermal **A**nalysis (**DTA**) and **D**ifferential **S**canning **C**alorimetry (**DSC**) methods were used to determine the required parameters.

TGA is a technique which relies on samples that decompose at elevated temperatures. The **TGA** monitors changes in the mass of sample on heating.

In **DTA**, the temperature difference that develops between a sample and an inert reference material is measured, when both are subjected to identical heat-treatments. **DTA** can be used to study thermal properties and phase changes.

The related technique of DSC relies on differences in energy required to maintain the sample and reference at an identical temperature.

The **DTA** and **DSC** curves use a system with two thermocouples. One of them is placed on the sample and the other on the reference material.

In this paper, both isothermal and non-isothermal regimes combined with heating-cooling experiments, were used in order to characterize SMA test samples.
The measurements were carried out on a Perkin Elmer Thermobalance in dynamic air atmosphere, in the aluminium crucible.
The test sample's phase transitions were identified by analyzing their behavior at programmed heating up to 200°C and cooling at ambient temperature. In addition we can notice that the sample's mass does not undergo any changes at heating and cooling. In consequence, the TGA curves are ignored in further measurements.

3.3.1 SMA strip transformation temperature

The temperature-control program used for SMA strip measurements contains the following sequences:

- heating from 30°C to 160°C at 5°C/min;
- holding for 10 min at 160°C;
- cooling from 160°C to 20°C at 5 °C/min.

The measurements were carried out in dynamic air atmosphere. The results are presented in Fig. 6.
By analyzing Fig. 6 we can observe two phase transitions. The first occurs during the heating process while the second one appears during the cooling process. The details of these thermal effects are presented in Fig. 7 and Fig. 8 (reported from the DSC curve). Figure 6 shows that the determined transformation temperatures at heating (martensite to austenite) are A_s=80°C and A_f=111°C. The enthalpy of the endothermal transition process is ΔH_h = 36.8858 J/g. The temperature corresponding to maximum transformation speed is 98.79°C.
The transformation temperatures at cooling (austenite to martensite) result from Fig. 8: M_s=69°C and M_f=48.25°C. The enthalpy of the exothermal transition process is ΔH_c=-28.7792 J/g and the temperature corresponding to maximum transformation speed is 59.75°C.

3.3.2 SMA helical spring transformation temperature

The transformation temperatures of SMA helical spring are obtained by similar measurements as in the case of SMA strip, using the following temperature-control sequences:

- heating from 30°C to 100°C at 5°C/min;
- holding for 10 min at 100°C;
- cooling from 100°C to 20°C at 5 °C/min.

The form of DTA and DSC curves is similar to the ones represented in Figure 5, for 6.849 mg SMA spring sample.
The determined transformation temperatures at heating (martensite to austenite) are A_s=58.89°C and respectively A_f=67.93°C. The enthalpy of the endothermal transition process is ΔH_h=9.2 J/g and the temperature corresponding to maximum transformation speed is 60.42°C.
The transformation temperatures at cooling (austenite to martensite) are M_s=45°C and M_f=33°C, the enthalpy of the exothermal transition process is ΔH_c = -5.03 J/g and the temperature corresponding to maximum transformation speed is 39.07°C.

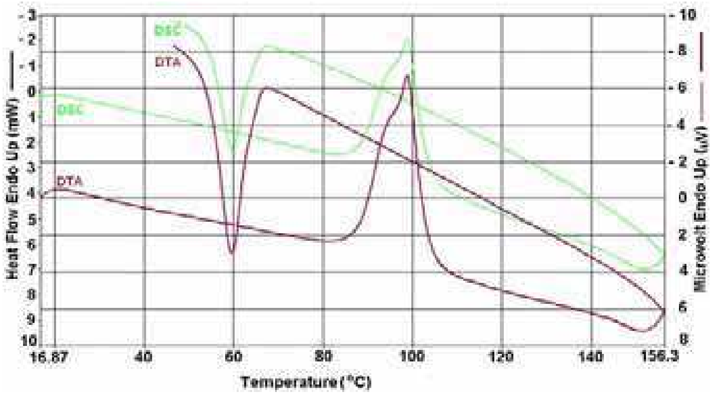

Fig. 6. DTA and DSC curves for 18.275mg SMA strip

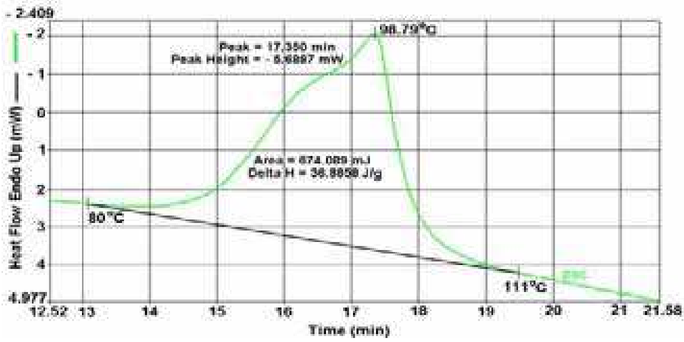

Fig. 7. Detail of DSC curve for computation transition at heating of SMA strip.

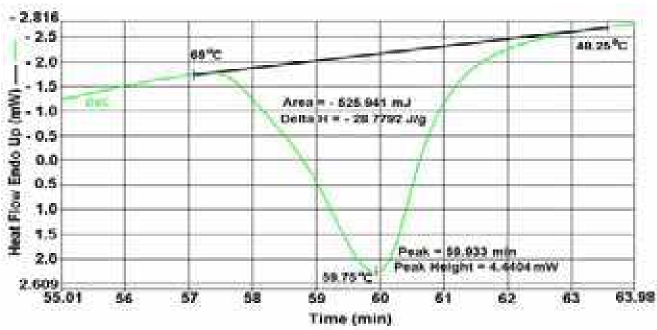

Fig. 8. DTA and DSC curves for 18.275mg SMA Detail of DSC curve for computation transition at cooling of SMA strip.

3.4 Mathematical model of constitutive behavior of shape memory alloy

A variety of mathematical models describing the constitutive behavior have been proposed over the past 15 years, which has not made it an easy for the designer to select. The frequently used SMA constitutive laws are:

- The Landau-Devonshire theory
- The mathematical model of Graesser and Cozzarelli
- The model of Stalmans, Van Humbeeck and Delaey

The Landau-Devonshire (Devonshire,1940) theory is one of the early models introduced. The free energy Ψ of SMA is a function of temperature T and strain ε with positive constants a_i:

$$\Psi(T,\varepsilon) = a_0 + a_1 T \log(T) + a_2 (T - T_1)\varepsilon^2 - a_4\varepsilon^4 - a_6\varepsilon^6 \quad (1)$$

The $\sigma(T,\varepsilon)$ stress reaction of the material system, with ρ - material density, in varying the order parameterε, is proportional to the partial derivative of equation with respect to ε:

$$\sigma(T,\varepsilon) = \rho \frac{\partial \Psi(T,\varepsilon)}{\partial \varepsilon} = \rho\left[2a_2(T - T_1)\varepsilon - 4a_4\varepsilon^3 + 6a_6\varepsilon^5\right] \quad (2)$$

Unfortunately the Landau Devonshire theory can only reproduce the isothermal constitutive behavior of SMA. Neither the constant-stress transformation nor the free or constrained memory effect can be modeled.

The mathematical model of Graesser and Cozzarelli (Graesser & Cozarelli, 1994) uses for one dimensionality case only two basic equations. First equation is related to the stress rate $\dot{\sigma}$ and the second equation determinates so-called one dimensional back stress β:

$$\dot{\sigma} = E\left[\dot{\varepsilon} - |\dot{\varepsilon}|\left|\frac{\sigma - \beta}{Y}\right|^{n-1}\left(\frac{\sigma - \beta}{Y}\right)\right] \quad (3)$$

$$\beta = E\gamma\left[\varepsilon - \frac{\sigma}{E} + f_T|\varepsilon|^c \operatorname{erf}(a\varepsilon)\right] \quad (4)$$

Three model parameters are directly related to material (elasticity modulus E, the slope of inelastic region γ, the threshold stress Y) while the others have to be determined empirically (f_T controls the type and size of the hysteresis, c is assumed zero, *n* depends on influence in forming the stress strain hysteresis, a describes the transition from the linear-elastic to the inelastic region and the other way around).

The numerical stability of the model is the main advantage, but the model does not consider the difference between martensite and austenite elasticity modulus.

The model of Stalmans (Stalmans,1994), Van Humbeeck and Delaey (Delaey,1987)0 was developed to describe the change of one-dimensional composite material with embedded SMA wires. Differentiation of the global equilibrium condition gives a generalized Clausius-Clapeyron equation:

$$\left\{\frac{d\sigma_{SMA}}{dT}\right\}_{\varepsilon,\nu=const} = -\frac{\rho_0 \Delta s}{\Delta\varepsilon_{tr\Sigma A}(\xi_V)} = C_A \quad (5)$$

The material constant Δs is the entropy change during transformation from austenite to martensite, ρ_0 is the mass density of SMA material in stress free condition and $\Delta\varepsilon_{tr\Sigma A}(\xi_V)$

is the transformation strain in dependence of the martensite volume fraction, C_A represent the gradient.
During transformation from martensite to austenite, the stress-rate is calculated during the following equation:

$$\frac{d\sigma_{SMA}}{dT} = \frac{(\alpha_{mar} - \alpha_{sma}) + \frac{(P_{sma} - E_{sma})\rho_0 \Delta s}{\Delta\varepsilon_{tr\Sigma A}(\xi_V) P_{sma} E_{sma}} - \frac{k_{spr}\alpha_{matr} l}{Q_{matr}E_{matr} + k_{spr} l}}{\frac{1}{P_{sma}} - \frac{Q_{mar}}{Q_{matr}E_{matr} + k_{spr} l}} \tag{6}$$

The parameters implied in the last equation are:
l – the SMA matrix beam, *P* - the initial pseudo plastic strain, the cross section of the SMA wire, *Q* - pseudo elastic modulus, α - the average values of the thermal dilatation coefficient, *E* - the elasticity modulus. The subscript *matr* represent the specific parameters of matrix beam to specific load or temperature.
The stress of the matrix material and the strain temperature can also be found out. However the model can so far only describe the transformation from martensite to austenite.
Comparing the different models (Schroeder & Boller,1998) shows that each model has its own characteristic. Each of the models still lacks the one or the other of the proprieties being mentioned. A combination of models, such as done with the models of Stalmans and Brinson leading to a new model called Stalman modified can result in an improvement of the model's proprieties.

3.5 Numerical tools for modelling shape memory alloy behavior

Based a description of shape memory alloy materials, a SMA Simulink block was developed. The characteristic of material is idealized, but the approximations made are suitable for an efficient simulation. The user can indicate the start and stop martensitic and austenitic temperature and the force, momentum evolution.

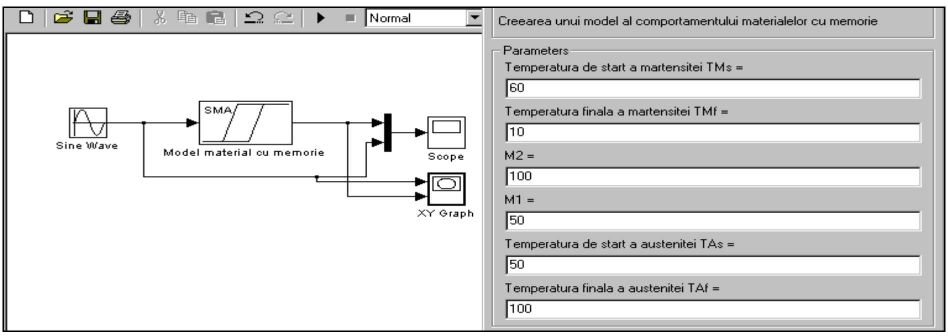

Fig. 9. Configurable Simulink block for SMA material

The numerical results respect the real comportment of the user specified shape memory alloy:

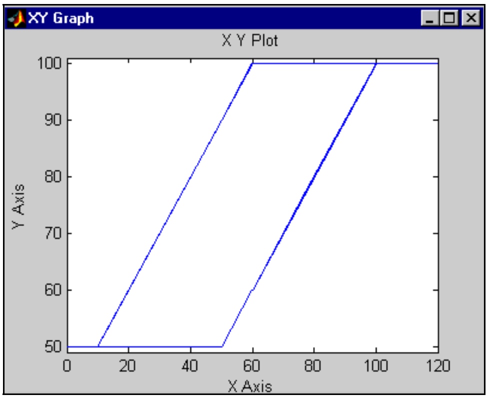

Fig. 10. The numerical simulation for Nitinol

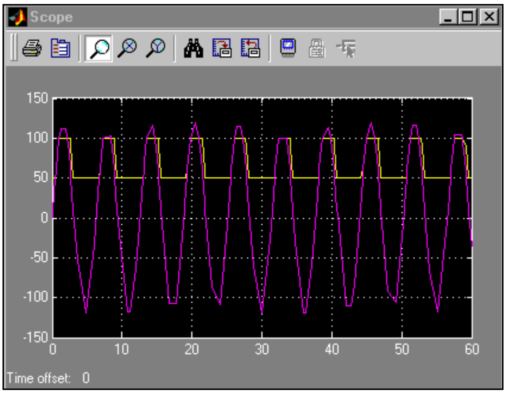

Fig. 11. The response of SMA numerical model for sinusoidal thermal input

The electrical activation of SMA actuator imposes the following relations for the current, temperature and response time:

For heating

$$T_{Max} = 4{,}928\frac{I}{d} + 1{,}632\frac{I^2}{d^2} = K_{T1}\frac{I}{\sqrt{F_L}} + K_{T2}\frac{I^2}{F_L} \quad (7)$$

T_{Max} - maximum temperature, d – wire diameter, I – electrical current, F_L - required force

$$t_{Heating} = J_h \ln\frac{T_{Max} - T_{medium}}{T_{Max} - T} \quad (8)$$

$t_{Heating}$ – heating time, Jh – heating coefficient, Tmedium – medium temperature, TA – ambient temperature, T - aim temperature upon heating

$$J_h = 6{,}72 + 3{,}922d^2 = K_{J_1} + K_{J_2}F_L \quad (9)$$

For cooling

$$t_c = J_c \ln \frac{T_H - T_A}{T_c - T_A} + \frac{28,88}{M_S - T_A} \tag{10}$$

$$J_c = 4,88 + 6,116d^2 = K_{J_{c1}} + K_{J_{c2}} F_L \tag{11}$$

tc – cooling time, T_H - initial temperature upon cooling, T_A - ambient temperature, d –wire diameter, T_C - aim cooling temperature, J_C - time constant for cooling, M - martensitic start temperature.
One can observe the time dependence of required force and required stroke.
The electrical calculations for direct current heating determine:

- The amount of current needed for actuation in the required time
- The resistance of the nickel titanium actuation element
- The voltage required to drive the current through element
- The power dissipated by the actuation element.

The first requirement can be establish using the material description tables (Waram, 1993).
The resistance is determined using the following expression:

$$\text{Resistance}/\text{mm} = \frac{1,019\text{x}10^{-3}}{d^3} \Omega/\text{mm} \tag{12}$$

The voltage and power requirements results from:

$$V = IR\,;\quad \text{Power} = I^2 R \tag{13}$$

I – current in amps, V voltage in volts, R resistance in Ω.
In case of using pulse width modulation heating the following relation can be used:

$$\text{duty cycle}(\%) = \frac{t_1}{t_2} \text{x} 100 \tag{14}$$

t_1 – the width of constant current pulse, t_2 the total cycle time.

$$\text{duty cycle}(\%) = \frac{100}{I_i} \sqrt{\frac{P_{avr}}{R}} \tag{15}$$

$$\text{duty cycle}(\%) = \frac{100}{V_i} \sqrt{P_{avr} R} \tag{16}$$

P_{avg} – average pulsed power (effective DC power), I_i applied pulse current, V_i applied pulsed voltage, R electric resistance.

4. Biomimetics design of mechatronics structure

4.1 Modular adaptive implant

Bionics or Biomechatronics is a fusion science which implies medicine, mechanics, electronics, control and computers. The results of this science are implants and prosthesis for human and animals. The roll of the implants and prosthesis is to interact with muscle, skeleton, and nervous systems to assist or enhance motor control lost by trauma, disease, or defect. Prostheses/implants are typically used to replace parts lost by injury (traumatic) or missing from birth (congenital) or to supplement defective body parts. In addition to the standard artificial limb for every-day use, many amputees have special limbs and devices to aid in the participation of sports and recreational activities.

4.1.1 The parametric 3D model of the bones

To obtain the bone cross sections of the bones, a PHILIPS AURA CT tomograph installed in the Emergency Hospital from Craiova was used –Fig. 12.

Fig. 12. The PHILIPS AURA CT tomography

To obtain the tomography of the two bones (tibia and femur) were used two scanning schemes presented in Fig. 13 ,Fig. 14 . For the ends of the bones the scanning operation was made at the distances of 1 mm and for the medial areas at the distances of 3 mm.

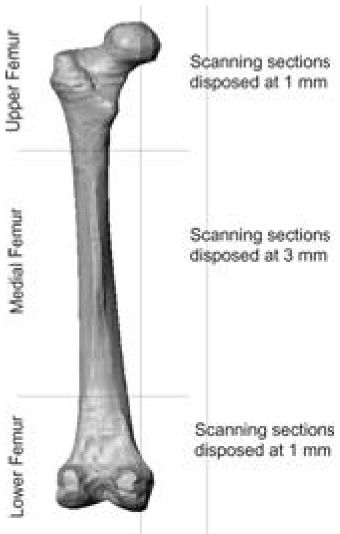

Fig. 13. Scanning schemes applied to the femur

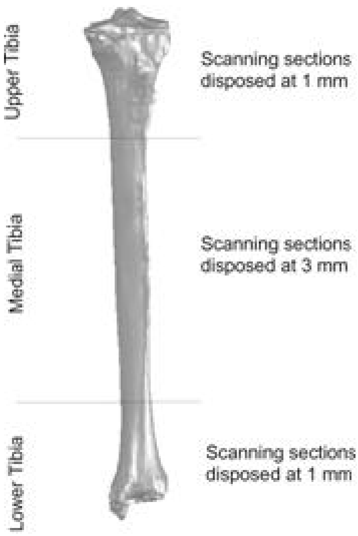

Fig. 14. Scanning schemes applied to the tibia

Were obtained 16 images folders and, after a strict selection, were used only 6, 3 for each bone component including the upper and lower areas (scanned at 1 mm) and the medial areas (scanned at 3 mm).
In Fig. 15 were presented two important images of the upper femur in the area of the femoral head.

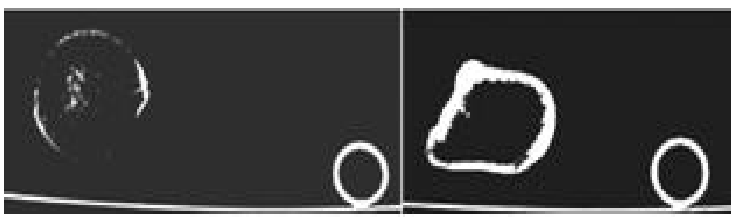

Fig. 15. Images obtained in the upper area of the femur

In Fig. 16 and Fig. 17 are presented main images of the medial and lower femur, which shown the changes of the shape of the bone.

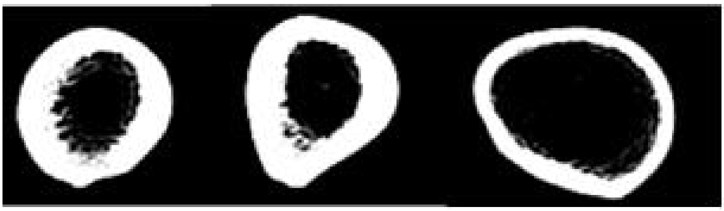

Fig. 16. Images obtained in the medial area of the femur

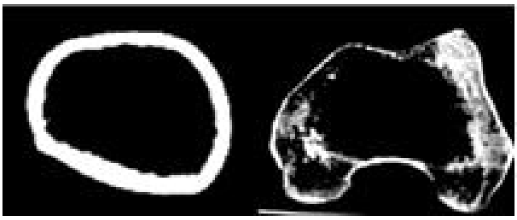

Fig. 17. Two images obtained in the lower area of the femur

In Fig. 18 , Fig. 19 and Fig. 20 important images of the upper tibia, the medial tibia and the lower tibia, which show the shape changes of the bone, are presented.

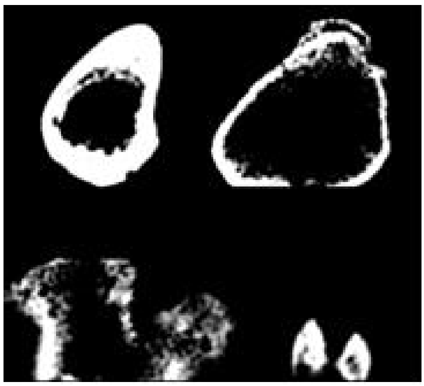

Fig. 18. Four main images of the upper tibia

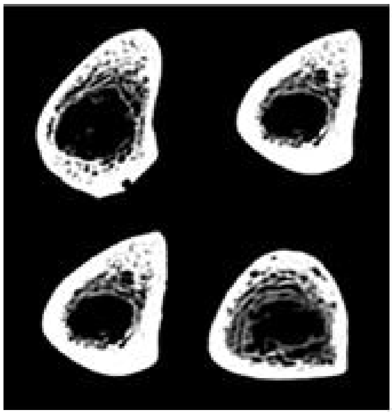

Fig. 19. Four main images made in the medial tibia area

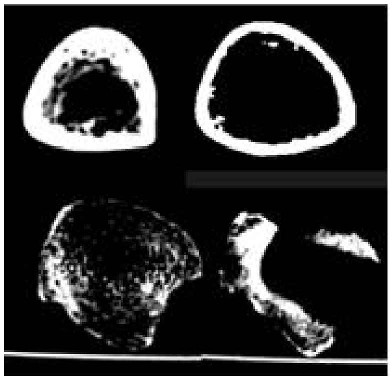

Fig. 20. Four main images scanned in the lower tibia area

The obtained images were re-drawn in AutoCad over the real tomographies and the drawings were imported in SolidWorks (a parametrical CAD software), section by section, in parallel planes. The sketches made in the upper and lower areas for the femur bone and for the tibia bone are presented Fig. 21, Fig. 22 and Fig. 23, Fig. 24.

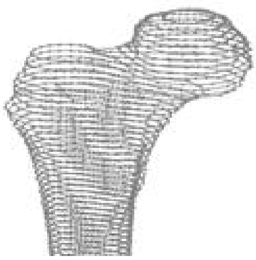

Fig. 21. Sections for the femur bone – upper femur

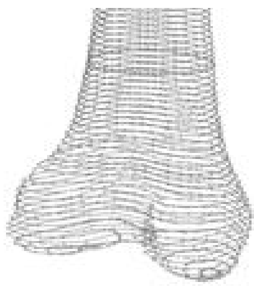

Fig. 22. Sections for the femur bone – lower femur