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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 engineering.

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 following 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 assumptions

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.

Thermogravimetric Analysis (TGA), Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (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 $A_s=80^\circ\text{C}$ and $A_f=111^\circ\text{C}$. The enthalpy of the endothermal transition process is $\Delta H_h = 36.8858 \text{ J/g}$. The temperature corresponding to maximum transformation speed is 98.79°C .

The transformation temperatures at cooling (austenite to martensite) result from Fig. 8: $M_s=69^\circ\text{C}$ and $M_f=48.25^\circ\text{C}$. The enthalpy of the exothermal transition process is $\Delta H_c=-28.7792 \text{ J/g}$ 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 $A_s=58.89^\circ\text{C}$ and respectively $A_f=67.93^\circ\text{C}$. The enthalpy of the endothermal transition process is $\Delta H_h=9.2 \text{ J/g}$ and the temperature corresponding to maximum transformation speed is 60.42°C .

The transformation temperatures at cooling (austenite to martensite) are $M_s=45^\circ\text{C}$ and $M_f=33^\circ\text{C}$, the enthalpy of the exothermal transition process is $\Delta H_c = -5.03 \text{ J/g}$ 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 strip. 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 parameter ε , is proportional to the partial derivative of equation with respect to ε :

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

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:

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

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 $\Delta \varepsilon_{\text{tr}\Sigma A}(\xi_V)$

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:

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

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

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

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

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

t_{Heating} - heating time, J_h - heating coefficient, T_{medium} - medium temperature, T_A - ambient temperature, T - aim temperature upon heating

$$J_h = 6,72 + 3,922d^2 = K_{J1} + K_{J2} F_L \quad (9)$$

For cooling

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

$$J_c = 4,88 + 6,116d^2 = K_{Jc1} + K_{Jc2} F_L \quad (11)$$

t_c – 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:

$$\text{Resistance} / \text{mm} = \frac{1,019 \times 10^{-3}}{d^3} \Omega / \text{mm} \quad (12)$$

The voltage and power requirements results from:

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

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:

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

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

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

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

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

Fig. 23. Sections for the tibia bone - upper tibia

Fig. 24. Sections for the tibia bone - lower tibia

Solidworks permits to obtain a solid by "unifying" the sections drawn in parallel planes. The shape which solidifies these sections is the Loft Shape and it defines the solid starting with the sections and a Guide Curve defined automatically by the software. In Fig. 25, Fig. 26 is presented the definition scheme for the femur bone and for the tibia bone.

Fig. 25. The definition scheme of the virtual femur

Fig. 26. The definition scheme of the virtual tibia

For defining the virtual models of the bones, the software SolidWorks are used. The virtual models can be transferred into kinematic simulation programs or into finite element analysis programs.

The structure of the femur bone **Fig. 27** has the following characteristics: the finite element size is 10 mm, the structure factor is 0.0132. A number of 13399 nodes and 7178 finite elements are obtained for femur.

Fig. 27. The mesh structure of the virtual model of the femur bone (first 3) and tibia bone

4.1.2 Studies of normal regime bones mechanical loads

In order to identify the target shape of modular implants, a study for walking regime was developed (Tarnita et al. , 2006). The studies identify the tension maps developed by tibia and femur for different moments. In Fig. 28, Fig. 29, Fig. 30 is exemplified only few simulation results, important for identifying tension distribution:

Fig. 28. Tension map for t=0.12 sec., angle tibia-femur $\alpha=30^\circ$

Fig. 29. Tension map for t=0.2 sec

Fig. 30. Tension map for t=0.8 sec

4.1.3 Modular adaptive implant

The design idea of modular adaptive implants results from the following observations:

- the doctors have a limited degree of freedom in selecting the proper dimensional apparatus for bones fractures;
- the current mechanical devices used in orthopedics lose some of their mechanical characteristics after some time (especially elasticity, which should ensure a constant tension that is mandatory for the correct anatomical healing of the fractured bones) (Bizdoaca et al., 2006);
- the process of fracture healing has a particular dynamic, which imposes the necessity of particular progressive tension or discharge to improve the recovery time, depending on the normal structure and function of the bone (Crossley et al., 2006);
- to improve the healing process, the fractured parts have to be in permanent contact in order to ensure the proper conditions to develop bone calluses (Giladi et al., 1987). The actual or external fixator – Ilizarov apparatus – Fig. 31 and Taylor Spatial Frame Fixator – Fig. 32, has to be manually adjusted with respect to the main axis of the bone Fig. 33. Unfortunately, the degrees of freedom of current devices are limited to 3 or 4 vertical screws;

Fig. 31. Iliazov external apparatus

Fig. 32. Taylor Spatial Frame Fixate

Fig. 33. Manual adjust for external apparatus

- a minimally invasive surgery ensures protection from blood edema and improves bone recovery and vascularization of the region.

The solution to these problems is the **Modular Adaptive Implant - MAI**.

In order to identify the optimal design different implants was developed and experimented using numerical simulation and prototypes:

- Internal implants

Fig. 34. Internal modular implants - design 1

Fig. 35. Internal modular implants - design 1 - accidental tension and forces

Fig. 36. Internal modular implants - design 2

Fig. 37. Internal modular implants - design 2 - accidental tension and forces

Fig. 38. Internal modular implants - design 3

Fig. 39. Internal modular implants - design 3 - accidental tension and forces

Fig. 40. Internal network implants - design 3

Fig. 41. Internal network implants - design 3 - accidental tension and force

Fig. 42. Internal network implants - design 3 – prototype

External implants and network

Fig. 43. External modular implants - design 1 – male

Fig. 44. External modular implants - design 1 – female

Fig. 45. External modular implants - design 1 – prototype

Fig. 46. External modular implants - design 2 – male

Fig. 47. External modular implants - design 2 – female

Fig. 48. External modular network implants - design 2

Fig. 49. External modular network implants - design 2 – prototype

Fig. 50. External modular implants - design 3 - male

Fig. 51. External modular implants - design 3 - female

Fig. 52. External modular network implants - design 3

Fig. 53. External modular network implants - design 3 - prototype

Fig. 54. External modular implants - design 4 - view 1

Fig. 55. External modular implants - design 4 - view 2

Fig. 56. External modular network implants - design 3

Fig. 57. External modular network implants - design 3 - prototype

The proper shape of MAI is related to the bones microscopic structure and to the numerical simulation presented in the previous chapter. As one can observe, comparing the structure of a healthy bone Fig. 58 with that of an osteoporotic bone Fig. 59, the internal architecture of the healthy bone has a regular modular structure (Burstein et al., 1976) .

Fig. 58. Normal bone

Fig. 59. Osteoporosis affected bone

Osteoporosis affect the bones net and leads to additional load. These problems increase the risks for bones fracture or they can limit the relative bones mobility (Evans, 1976).

A modular net, identical in structure with the bone and locally configurable in terms of tension and release, is best design solution in terms of biocompatibility. The identification of the mechanical solicitation of the particular bone structure, using finite element method, leads to the concept of the practical implementation of a feasible device able to undertake the functionality of normal bones. This device will partially discharge the tensions in the fractured bones (the fractured parts still need to be tensioned to allow the formation of the callus) improving the recovery time and the healing conditions.

The proposed intelligent device has a network structure, with modules made out of Nitinol, especially designed in order to ensure a rapid connection and/or extraction of one or more MAI modules. The binding of the SMA modules ensures the same function as other immobilization devices, but also respects additional conditions concerning variable tension and its discharge. Moreover, these modules allow little movement in the alignment of the fractured parts, reducing the risks of wrong orientation or additional bones callus.

Fig. 60. MAI conceptual connection network

Fig. 61. SMA modul - design 1

Fig. 62. MAI - SMA network - design 1

We suggest the design shown in Fig. 61 for the unitary SMA module structure, a design which ensures not only the stability of the super-elastic network Fig. 62 and constant force requirements, but also a rapid coupling/decoupling procedure.

Doctors can use SMA modules with different internal reaction tension, but all the modules will have same shape and dimension.

The connection with affected bones and the support for this net are similar to those of a classic external fixator, but allowing for the advantages of minimal invasive techniques.

Using Solid Works package and COSMOS software (Solidworks 98) we proceed to various numerical simulation of SMA module, in order to test the proper mechanical design. First design relives that applying high force -30N and torques to the MAI terminals, the coupling connectors will conduct to spike mechanical deformation Fig. 63, Fig. 64 , potential dangerous for the patients.

Fig. 63. MAI - design 1 – deformation for accidental tension and forces.

Fig. 64. MAI - design 1 – tension distribution for accidental tension and forces.

The shape of the MAI from Fig. 65 is an improved solution based on previous conclusions. This solution Fig. 66 respects the protection of the patients for accidental unusual mechanical tension.

Fig. 65. MAI - SMA module - optimal design

Fig. 66. MAI - SMA network optimal design

In Fig. 67 and Fig. 68, the MAI response to destructive tension and forces, which can appear in accidental cases, is shown.

Fig. 67. Deformations response of MAI - optimal design - for accidental tension and forces

Fig. 68. Tension distribution of MAI - optimal design - for accidental tension and forces

The implant prototype and the experimental MAI network were obtained using a rapid prototyping device - 3D Printer Z Corp -Fig. 71.

Fig. 69. Implant prototypes MAI network - optimal design

Fig. 70. Implant prototypes MAI network - optimal design

Fig. 71. Rapid prototyping device - 3D printer

The new device leads to a simple post-operative training program of the patient. The relative advanced movement independence of patient with MAI network apparatus can lead to possibility of short distance walking. Actual devices (Fig. 72) are quite expensive and implies, for implementing, 3 persons: the patient, the current doctor and a kinetoterapeut.

Fig. 72. KINETEK device for functional

4.2 Two-link tendon-driven finger

4.2.1 Dynamics of two-link finger

There are many methods for generating the dynamic equations of mechanical system. All methods generate equivalent sets of equations, but different forms of the equations may be better suited for computation different forms of the equations may be better suited for computation or analysis. The Lagrange analysis will be used for the present analysis, a method which relies on the energy proprieties of mechanical system to compute the equations of motion. We consider that each link is a homogeneous rectangular bar with mass m_i and moment of inertia tensor.

$$I_i = \begin{bmatrix} I_{xi} & 0 & 0 \\ 0 & I_{yi} & 0 \\ 0 & 0 & I_{zi} \end{bmatrix} \quad (17)$$

Letting $v_i \in \mathbb{R}^3$ be the translational velocity of the center of mass for the i^{th} link and $\omega_i \in \mathbb{R}^3$ be angular velocity, the kinetic energy of the manipulator is:

$$T(\theta, \dot{\theta}) = \frac{1}{2} m_1 \|v_1\|^2 + \frac{1}{2} m_1 \omega_1^T I_1 \omega_1 + \frac{1}{2} m_2 \|v_2\|^2 + \frac{1}{2} m_2 \omega_2^T I_2 \omega_2 \quad (18)$$

Since the motion of the manipulator is restricted to xy plane, $\|v_i\|$ is the magnitude of xy velocity of the centre of mass and ω_i is a vector in the direction of the y axis, with $\|\omega_1\| = \dot{\theta}_1$ and $\|\omega_2\| = \dot{\theta}_1 + \dot{\theta}_2$. We solve for kinetic energy in terms of the generalized coordinates by using the kinematics of the mechanism. Let $p_i = (x_i, y_i, 0)$ denote the position of the i^{th} centre of mass.

Fig. 73. Two link finger architecture

Letting r_1 and r_2 be the distance from the joints to the centre of mass for each link, results

$$\begin{aligned} x_1 &= r_1 \cos(\theta_1) & \dot{x}_1 &= -r_1 \dot{\theta}_1 \sin(\theta_1) \\ y_1 &= r_1 \sin(\theta_1) & \dot{y}_1 &= r_1 \dot{\theta}_1 \cos(\theta_1) \\ x_2 &= l_1 \cos(\theta_1) + r_2 \cos(\theta_1 + \theta_2) & \dot{x}_2 &= -(l_1 \sin(\theta_1) + r_2 \sin(\theta_1 + \theta_2)) \dot{\theta}_1 - r_2 \dot{\theta}_2 \sin(\theta_1 + \theta_2) \\ y_2 &= l_1 \sin(\theta_1) + r_2 \sin(\theta_1 + \theta_2) & \dot{y}_2 &= (l_1 \cos(\theta_1) + r_2 \cos(\theta_1 + \theta_2)) \dot{\theta}_1 - r_2 \dot{\theta}_2 \cos(\theta_1 + \theta_2) \end{aligned} \quad (19)$$

Using the kinetic energy and Lagrange methods results:

$$\begin{bmatrix} \alpha + \beta c_2 & \delta + \frac{1}{2} \beta c_2 \\ \delta + \frac{1}{2} \beta c_2 & \delta \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} -\frac{1}{2} \beta s_2 \dot{\theta}_2 & -\frac{1}{2} \beta s_2 (\dot{\theta}_2 + \dot{\theta}_1) \\ \frac{1}{2} \beta s_2 \dot{\theta}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (20)$$

where

$$\alpha = \frac{m_1}{12} (l_1^2 + w_1^2) + \frac{m_2}{12} (l_2^2 + w_2^2) + m_1 r_1^2 + m_2 (l_1^2 + r_2^2)$$

$$\beta = m_2 l_1 l_2$$

$$\delta = \frac{m_2}{12} (l_2^2 + w_2^2) + m_2 r_2^2;$$

with w_1, w_2, l_1, l_2 the width and respectively the length of link 1 and link 2.

4.2.2 Tendon actuated fingers.

Consider a finger which is actuated by a set of tendons such as the one shown in Fig. 73. Each tendon consists of a cable connected to a force generator. For simplicity we assume that each tendon pair is connected between the base of the hand and a link of the finger. Interconnections between tendons are not allowed. The routing of each tendon is modelled by an extension function $h_i : Q \rightarrow R$. The extension function measures the displacement of the end of the tendon as a function of the joint angles of the finger. The tendon extension is a linear function of the joint angles $h_i(\theta) = l_i \pm r_{i_1} \theta_1 \pm \dots \pm r_{i_n} \theta_n$ with l_i - nominal extension at $\theta = 0$ and r_{i_j} is the radius of the pulley at the j^{th} joint. The sign depends on whether the tendon path gets longer or shorter when the angle is changed in a positive sense. The tendon connection, proposed is a classical one, as is exemplified in Fig. 74.

Fig. 74. Geometrical description of tendon driven finger

The extension function of the form is:

$$h_1(\theta) = l_1 + 2\sqrt{a^2 + b^2} \cos\left(\tan^{-1}\left(\frac{a}{b}\right) + \frac{\theta}{2}\right) - 2b \quad (21)$$

$\theta > 0$,

while the bottom tendon satisfies: $h_2(\theta) = l_2 + R \theta$ $\theta > 0$, when $\theta < 0$ these relations are reversed.

Once the tendon extension functions have been computed, we can determine the relationships between the tendon forces and the joint torques by applying conservation of energy. Let $e = h(\theta) \in R^p$ represent the vector of tendon extensions for a system with p

tendons and define the matrix $P(\theta) \in R^{n \times p}$ as $P(\theta) = \frac{\partial h^T}{\partial \theta}(\theta)$. Then $\dot{e} = \frac{\partial h}{\partial \theta}(\theta) \dot{\theta} = P^T(\theta) \dot{\theta}$.

Since the work done by the tendons must equal that done by the fingers, we can use conservation of energy to conclude $\tau = P(\theta)f$ where $f \in \mathbb{R}^P$ is the vector of forces applied to the ends of the tendons. The matrix $P(\theta)$ is called the coupling matrix.

The extension functions for the tendon network are calculated by adding the contribution from each joint. The two tendons attached to the first joint are routed across a pulley of radius R_1 , and hence

$$h_2 = l_2 - R_1\theta_1$$

$$h_3 = l_3 + R_1\theta_1$$

The tendons for the outer link have more complicated kinematics due to the routing through the tendon sheaths. Their extension functions are

$$h_1 = l_1 + 2\sqrt{a^2 + b^2} \cos\left(\tan^{-1}\left(\frac{a}{b}\right) + \frac{\theta_1}{2}\right) - 2b - R_2\theta_2 \quad (22)$$

$$h_4 = l_4 + R_1\theta_1 + R_2\theta_2 \quad (23)$$

The coupling matrix for the finger is computed directly from extension functions:

$$P(\theta) = \frac{\partial h^T}{\partial \theta} = \begin{bmatrix} -2\sqrt{a^2 + b^2} \sin\left(\tan^{-1}\left(\frac{a}{b}\right) + \frac{\theta_1}{2}\right) & -R_1 & R_1 & R_1 \\ 0 & 0 & -R_2 & R_2 \end{bmatrix} \quad (24)$$

The pulling on the tendons routed to the outer joints (tendons 1 and 4) generates torques on the first joint as well as the second joint.

Fig. 75. Experimental model for a single link robotic structure

4.2.3 Numerical simulations

Based on the theoretical background presented, numerical simulations are required in order to evaluate the efficiency of real mechanism. For flexible studies all the elements are developed as configurable Simulink blocks:

- Shape memory alloy block wire – Fig. 9
- Dynamics of two link fingers block – based on equation 20 :

Fig. 76. Two link kinematics fingers block

Coupling block – based on equation 24

Fig. 77. Two link fingers coupling block

Connecting all this blocks , for numerical simulations the following parameters are used:

- for the elements of the finger:
 - with = 2 cm
 - length = 10 cm
 - mass = 5 g
 - radius pulley = 2cm
 - height = 2 cm

- shape memory alloy parameters:
 start temperature of martensitic state = 60°C
 final temperature of martensitic state = 10°C
 start temperature of austenite state = 50°C
 final temperature of austenite state = 100°C
 lower force $M_1 = .5 \text{ N}$
 higher force developed by the SMA $M_2 = 5 \text{ N}$

Fig. 78. Complete structure of two link fingers block

The results of numerical simulations are:

- For the element 1 of the finger:

Fig. 79. Finger first phalange response for sinusoidal input

- For the second element of the finger:

Fig. 80. Finger second phalange response for sinusoidal input

In the upper part of the figure is modelled the evolution of the SMA wire and in the lower part of the figure is the evolution of the angle θ_i of the joint. In the mathematical model the architectural limitation are implemented by imposing the angle evolution as $\theta_i \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

4.3 Hopping robot

In this section is presented a model for hopping robot, based on the physical laws of mechanics. The variables in the model are positions and velocities, and the dynamic equations come from Newton's laws of motion. When humans walk, feet never lose contact with the ground and alternate between having both feet on the ground and a swing phase in which one foot is on the ground and the second leg swings like a pendulum. When run, we alternate between a flight phase in which both feet are off the ground and a stance phase in which one foot is on the ground. Kangaroos hop with a flight phase alternating with a stance phase in which both feet are on the ground simultaneously. A pogo stick with a single leg provides a simple model for running and hopping Fig. 81.

Fig. 81. A simple model for running and hopping

The robot is regarded as a “point mass” with a springy leg attached to the mass. As a first approximation, one can think of the spring as the tendons in the leg. By contracting muscles, the animal changes the force of the leg spring, enabling it to bounce off the ground. When in flight, we assume that the animal is able to swing the leg so that it will point in a new direction when the animal lands on the ground. At landing, the leg shortens, compressing the spring. The compressed spring exerts a vertical upward force that together with additional force exerted by the muscles propels the animal into its next flight phase. Simplifying, the hopping movement can be divided in hopping in place and hopping forward or backward.

Hopping in place and hopping forward/backward can both be divided into two different phases: an aerial phase (where the mass is airborne) and a ground phase (where the mass and spring are on the ground).

4.3.1 Hopping In Place

When the leg hops in place, the model is one of a spring, where the entire force of the spring is directed in the +y direction. The motion results from gravity trying to pull the mass toward the earth and the spring trying to push the mass away from the earth. In this case there is only one variable (y) because motion is only in one direction. As mentioned earlier, hopping in place has an aerial phase and a ground phase, with a different differential equation describing each.

Fig. 82. Hopping in place positions

For hopping in place, the equations are:

$$m \frac{d^2 y}{dt^2} = -mg \quad (25)$$

$$m \frac{d^2 y}{dt^2} + ky = mg \quad (26)$$

For equation 25, while the mass is in the air, the acceleration of the object is equal to the acceleration due to gravity (9.8 m/s^2) in the $-y$ direction, and therefore as the mass goes up, it starts to decelerate to zero m/s and then begins to accelerate as it falls down.

The evolution of this simplified hopping robot have no influence regarding the stiffness of the spring, or actuator nature.

Equation 26 shows that force of the spring subtracted from the force of gravity equals the mass multiplied by its acceleration. This equation describe the touch down moment. For this simple model, last equations, if we choose to experiment the influence of temperature, in case of using a SMA spring, we obtain the results exemplified in Fig. 83.

From this simulation the advantage of using SMA spring is clear: a smart spring improve by reducing the touch-down time, and the energy losses.

Fig. 83. Hopping in place for a SMA based robot

As one can easily observe, from the numerical simulations, the deformation of the contact terrain is up to 4 times reduced in case of a 100° C energized SMA spring.

4.3.2 Hopping Forward

Modeling a leg hopping forward is more complicated than hopping in place and can be thought of as running. It can be assumed that the mass spring takes off at an angle (θ) against the ground, which means that it is very important to keep the vectors straight. Instead of one direction in which to move, there are two directions: vertical (x) and horizontal (y). This means that there must be two equations for both the ground and aerial phases. The equations for the aerial phase are:

$$m \frac{d^2 y}{dt^2} = -mg \quad (27)$$

$$m \frac{d^2 x}{dt^2} = 0 \quad (28)$$

The equation 28, means that there is no acceleration in the x direction, and equations 27 means the same thing it did in the example of hopping in place.

The ground phase is such that the leg lands at an angle ($-\theta$) to the ground, pivots on the ground while being compressed, and then decompresses as it pivots to angle θ . At angle θ , the mass takes off into the aerial phase. The process repeats at the end of the aerial phase. The whole calculation assumes constant forward velocity (u) which is related to θ . The equations for the ground phases are given by the following equations:

$$\frac{d^2 y}{dt^2} = \frac{ky}{m} \left(\frac{1}{\sqrt{x^2 + y^2}} - 1 \right) - g \quad (29)$$

$$\frac{d^2x}{dt^2} = \frac{kx}{m} \left(\frac{1}{\sqrt{x^2 + y^2}} - 1 \right) \quad (30)$$

$$l = \sqrt{x_0^2 + y_0^2} \quad (31)$$

$$w = \sqrt{\frac{k}{m}} \quad (32)$$

$$l \sin(\theta) = u \frac{t_c}{2} \Rightarrow \theta = \arcsin \left(\frac{u \cdot t_c}{2 \cdot l} \right) \quad (33)$$

$$\ddot{x} = 0 \quad (34)$$

$$\ddot{z} = -g$$

$$\ddot{\theta} = \frac{k_{\text{hip}} (\theta_{\text{hip}} - \theta + \varphi)}{J_{\text{leg}}}$$

$$\ddot{\varphi} = \frac{-k_{\text{hip}} (\theta_{\text{hip}} - \theta + \varphi)}{J_{\text{body}}}$$

and the degree of freedom for stance stage are:

$$\begin{aligned} \ddot{r} &= -g \cos \theta + r \dot{\theta}^2 + \frac{k_{\text{leg}} (r_0 - r + p_{\text{leg}})}{m} \\ \ddot{\theta} &= \frac{k_{\text{hip}} (p_{\text{hip}} - \theta + \varphi) - 2mr \dot{\theta} + rm g \sin \theta}{J_{\text{leg}} + mr^2} \\ \ddot{\varphi} &= -k_{\text{hip}} \frac{p_{\text{hip}} - \theta - \varphi}{J_{\text{body}}} \end{aligned} \quad (35)$$

For equations 31, l is the initial, unperturbed length of the spring: x_0 and y_0 are the coordinates of the mass at that length.

The coordinates (x_0, y_0) are most likely given by:

$$y_0 = l \sin(\theta); \quad x_0 = l \cos(\theta) \quad (36)$$

Equations 29, 30, 31 and 32 separate the ground phase into horizontal (x) and vertical (y) directions, which relates the accelerations in the x and y directions to positions x and y , gravity, θ and the equilibrium position of the mass. In equations 33, t_c is the time the system is in contact with the ground.

Fig. 84. Hopping forward schematically trajectory

If the scope of the experiment is to obtain the same forward velocity (u) the relation for ground time contact is:

$$t_c = \frac{2mg}{ku} \quad (37)$$

4.3.3 Shape memory alloy spring influences

Studying the influence of SMA spring in robotic structure we can observe, first, the evolution of time contact, considering constant forward velocity - u .

For the Nitinol, for spring temperature of 20°C, 60°C and 120°C the reduction of time contact is:

$$t_{cSMA20^{\circ}C} = \frac{C_1}{2750} \quad t_{cSMA60^{\circ}C} = \frac{C_1}{13000} \quad t_{cSMA120^{\circ}C} = \frac{C_1}{20700} \quad \text{with } C_1 = \frac{2mg}{u} \quad (38)$$

Fig. 85. Evolution of time contact, as energizing SMA spring temperature, considering constant forward velocity

Considering the contact time constant, as 8 msec, using equation 29- 35, the temperature influences for SMA spring can arise. A Matlab Simulink temperature comparative models was developed, based on the equations 29-38.

Fig. 86. Matlab Simulink temperature comparative models

The evolution of hopping robot, for case of 20°C, 60°C and 120°C SMA spring energising temperature for x and y trajectory is shown in the Fig. 87, Fig. 88, Fig. 89.

Fig. 87. Y Axis Trajectories for different energising SMA spring temperature

Fig. 88. X Axis Trajectories for different energising SMA spring temperature

Fig. 89. Trajectories for different energising SMA spring temperature

The numerical simulations uncover the strong influence of energising temperature in case of SMA spring based hopping robot. The results of 20° C energising temperature of SMA spring correspond to usual steel spring. As the energising SMA spring temperature is increased to 60°C and 120°C, the total displacement is up to 5 times increased compare with the usual spring.

4.4 Tentacle SMA Robot

The tentacle robot structure contains units with SMA actuators. The first unit (starting from gripper) has the load equal with the weight of gripper and the work load. The unit contains 4 SMA actuators and a spherical articulation.

The actuator used is a SMA spring based actuator, structural presented in the Figure 1.

The superior units are obligatory to a highest load, because of the weight of the inferior unit. This is the reason that the superior unit use 2, 3 and 4 spring in parallel connection. The particular robotic structure demand special constructive requirements:

The load applied to a particular unit, is increased with the weight of inferior units, reason for every units has a individual parameters as shape memory alloy spring diameters wire, in and out spring diameter, number of turns, length, applied load, reset load. The relations used for unraveling these parameters are:

$$d = \sqrt{\frac{8W_C}{\pi T_C}} \sqrt{F_L} = K_1 \sqrt{F_L} \quad (39)$$

d – wire diameter, W_C – Wahl correction factor, T_C – maximum shear stress, c – spring index, F_L force exerted by spring (required force)

$$n = \frac{1}{\pi c^3 \Delta \gamma} \frac{S}{K_1 \sqrt{F_L}} = K_2 \frac{S}{\sqrt{F_L}} \quad (40)$$

n – the number of coils, $\Delta \gamma$ difference between the low and high temperature shear strains, S – required stroke for the spring

$$F_{\text{reset}} = G_l \left(\frac{F_L}{G_h} + \frac{s^2}{F_L} \frac{T_{cc}}{\Delta\gamma W_c} \right) \quad (41)$$

F_{reset} – recovery force, G_h shear modulus at high temperature, G_l shear modulus at low temperature.

Numerical computation is simple and can be easily integrated in a SMA calculus tools.

The requirements applied to robotic structure conduct to a robotic tentacle structure with different elements. An important result expresses the angle dependence from the variation of SMA spring:

Fig. 90. Schematically representation of SMA robotic unit

$$\alpha = \arcsin \left[\cos(\arctg(l_h)) \frac{2l_b^2 + l_c^2}{2l_b} \right] + \arctg(l_h) \quad (42)$$

l_h – the length after the heating process, l_c – the spring length after cooling, l_b – the base length

Fig. 91. The SMA robotic unit

The dependence is highly nonlinear but the graphical form of this dependence for real variation (between 100 and 108) results:

Fig. 92. The dependence of angle α as function of l_h

5. Control for biomimetic SMA robotic tentacle structure

5.1 Control architecture for SMA robotic tentacle unit

In order to investigate the SMA unit comportment a Quanser modified platform was used for experiments. The basic control structure uses a configurable PID controller and a Quanser Power Module Unit for energizing the SMA actuators.

Fig. 93. Simulink blocks for tentacle unit control

PID controller was changed, in order to adapt to the particularities of the SMA actuator. A negative command for SMA actuator corresponds to a cooling source. The actual structure use for cooling only the ambient temperature. The best results arise when a PI controller is used. The PI experimented controller parameters are: the proportional parameter $K_R = 10$ and the integration parameter is $K_I = 0,05$. The input step is equivalently with 30° angle base variation and the evolution of this reference is represented with the response of real system in Fig. 94. The control signal variation is presented in Fig. 95.

Fig. 94. System response, for step input

Fig. 95. PI controller response, for step input

For negative step, the evolution of the system and the control variable evolution are presented in Fig. 96 and Fig. 97.

Fig. 96. System response, negative step input

Fig. 97. PI controller response, negative step input

The PD experimented controller parameters are: the proportional parameter $K_R = 10$ and the derivative parameter is $K_D = 2$.

Fig. 98. System response, step input

Fig. 99. PD controller response, step input

One can observe the high dynamics of the control variable – Fig. 99. The time response is longer then the case of PI controller, but the stationary error is less then the anterior case – Fig. 98.

The PID experimented controller parameters are: the proportional parameter $K_R=10$ and the integration component is $K_I=0,005$ and the derivative component is $K_D=2$.

The experimental results are illustrated in the figure, and the control signal variation is presented in Fig. 100 and Fig. 101.

Unfortunately, even with the complication of the controller, the time response is inferior to the case of the PI controller and the stationary error is near zero.

Fig. 100. System response, step input

Fig. 101. PID controller response, step input

As a conclusion: the best results arise when a PI controller is used. The PI experimented controller parameters are: the proportional parameter $K_R = 10$ and the integration parameter is $K_I = 0, 05$.

Using PID, PD controller the experiments conduct to less convenient results from the point of view of time response or controller dynamics.

Using heat in order to activate SMA wire, a human operator will increase or decrease the amount of heat in order to assure a desired position to robotic link.

Because of medium temperature influence, can not be establish, apriority, a clear control law, available for all the points of the robotic structure workspace.

5.2 A SMA Tentacle Manipulator model

A tentacle manipulator is a manipulator with a great flexibility, with a distributed mass and torque that can take any arbitrary shape. Technologically, such systems can be obtained by using a cellular structure for each element of the arm. The mathematical model developed (Ivănescu 1986) and (Ivănescu 1984) conduct to the following dynamics of bi-dimensional tentacle structure:

$$\begin{aligned} & \rho A \int_0^s \left(\sin(q - q(r)) \dot{q}^2(r) + \cos(q - q(r)) \ddot{q}(r) \right) dr + \\ & + M \int_0^L \left(\sin(q_L - q(r)) \dot{q}^2(r) + \cos(q_L - q(r)) \ddot{q}(r) \right) dr + \\ & + \rho A \int_0^L \cos(s) ds + Mg \cos(q) = U \end{aligned} \quad (43)$$

with initial conditions:

$$\begin{aligned} q(s, 0) &= q^0(s), \\ \dot{q}(s, 0) &= \dot{q}_1^0(s), \\ q_L &= q(L, t), \end{aligned} \quad (44)$$

with U is a generalised input, q generalised coordinates, ρ density of , M - generalised mass. Using a spatial discretisation $s_1, s_2, s_3, \dots, s_n$ with $s_i - s_{i-1} = \Delta$

$$\begin{aligned} |q(s) - q(s(r))| &< \varepsilon_1 \\ |q_L(s) - q(s(r))| &< \varepsilon_2 \\ s, s(r) &\in [0, L], \text{ and } \varepsilon_1, \varepsilon_2 \rightarrow 0 \end{aligned} \quad (45)$$

An integro-differential form of discretisation Δ and integration to the curve L conduct to the following expression:

$$\int_0^L \left(\int_0^s \left(\frac{\partial^2 q}{\partial t^2} \cos(q(r,t) - q(s,t)) - \left(\frac{\partial q}{\partial t} \right)^2 \sin(q(r,t) - q(s,t)) - \right. \right. \quad (46)$$

$$\left. \left. - \frac{\partial q(s,t)}{\partial t} \frac{\partial q(r,t)}{\partial t} \cos(q(r,t) - q(s,t)) \right) dr - \right. \\ \left. - g(\sin q(s,t) + \cos q(s,t)) \right) ds = \frac{1}{\rho_0} \int_0^L u(s,t) ds$$

Using a discretised form of the equations results:

$$\sum_{i=0}^m \frac{\partial^2 q_i}{\partial t^2} \cos(q_m - q_i) - \left(\frac{\partial q_i}{\partial t} \right)^2 \sin(q_m - q_i) - \quad (47)$$

$$- \frac{\partial q_m}{\partial t} \frac{\partial q_i}{\partial t} \cos(q_m - q_i) - g(\sin(q_m) + \cos(q_m)) = \frac{1}{\rho \Delta} u_m$$

$m = 0, 1 \dots (N-1)$. If $\varepsilon \rightarrow 0$ and with a suitable choosing of N and Δ for $|q_i(t) - q_{i-1}(t)| < \varepsilon$,

$i = 0, 1 \dots (N-1)$, $t \in [0, t_F]$, results: $\frac{\partial^2 q_i}{\partial t^2} - \left(\frac{\partial q_i}{\partial t} \right)^2 = \frac{1}{\rho \Delta} (u_i - u_{i-1})$

for $i = 1 \dots (N-1)$, u_i și u_{i-1} are two control sequence for unit i and unit $i-1$.

Fig. 102. SMA experimental tentacle robot

5.3 Tentacle's dynamics

It is considered the dynamics of the object defined by the equation (47). For a prescribed trajectory r_d , we define the object (load) motion error as:

$$e_1 = r_d - r \quad (48)$$

$$e_2 = \dot{r}_d - v$$

and the object error dynamic can be rewritten as:

$$\dot{e}_L = A_L e_L + b_L (r_d, \dot{r}_d) + c_L \tau \quad (49)$$

$$\text{where } e_L = \text{col}(e_1, e_2)$$

A is a constant matrix, b, c are vectors and τ is the resultant force which assures the object motion on the trajectory.

The dynamic of the manipulator can be approximated from (46),(47) by using a spatial discretization $s_1, s_2, \dots, s_N$. If this approximation verifies the condition

$$|q(s_i) - q(s_k)| < \varepsilon, \quad i, k = 1, 2, \dots, n^J \quad (50)$$

where ε is a constant sufficiently small, from (Ivanescu, 1984) we obtain

$$M\ddot{q} + C\dot{q} + D + \tau = T \quad (51)$$

where M, C are $(n \times n)$ constant matrices, D is a nonlinear vector and

$$q = \text{col}(q_1, q_2 \dots q_{n^J}) \quad (52)$$

$$T = \text{col}(T_1, T_2 \dots T_{n^J})$$

$$\tau = \text{col}(\tau_1, \tau_2 \dots \tau_{n^J})$$

$$q_i = q(s_i); \quad T_i = T(s_i); \quad \tau_i = \tau(s_i)$$

We define the system error as

$$e = q_d - q \quad (53)$$

where q_d represents the desired trajectory of the tentacle manipulator.

We assume the case in which is difficult to know exactly the influence of the load and we estimate as τ^* the value of the force which assures the desired motion on the trajectory.

Theorem (Ivanescu, Stoian, 1995)

The closed-loop system is stable if the control is defined by

$$T = +Ks + \tau^* - u_F - H(e, q_d) \quad (54)$$

$$K - M\sigma + C \text{ positive definite matrix,} \quad (55)$$

$$u_{F_i} = -k_{F_i} \operatorname{sgn} s_i \quad (56)$$

$$k_{F_i} \geq |\tau^* - \tau| \quad (57)$$

where $H(e, q_d)$ represents the nonlinear part of the dynamic model and τ^* is the estimated values of the forces required at the terminal points of the manipulators.

The Theorem 1 determines the conditions which assure the motion control in the neighborhood of the switching line. In order to accelerate the motion on the switching line we can use the DSMC (Direct Sliding Mode Control) method. This motion differs by the conventional Sliding Mode by the evolution on the switching line. When the trajectory of the system penetrates the switching line, the damping coefficient is increased and the motion is forced on the switching line toward the origin without the high frequency oscillations. In Fig. 103 is presented the conventional Sliding Mode Control and in Fig. 104, the Direct Sliding Mode Control.

This motion is assured by the following Proposition:

Proposition

The DSMC control is assured if the coefficients k_i verify the condition

$$(c_i + k_i)^2 \geq 4m_i (\sigma_i (-m_i \sigma_i + c_i + k_i) + h_i) \quad (58)$$

Fig. 103. Conventional Sliding Mode Control

Fig. 104. Control trajectory

5.4 Control system

The control problem asks for determining the manipulatable torques T such that the trajectory of the overall system (object and manipulator) will correspond as closely as possible to the desired behavior.

The control system contains two parts: the first component is a conventional controller which implements a classic strategy of the motion control based on the Lyapunov stability and the second is a Fuzzy Controller Fig. 105.

Fig. 105. Control system blocks

The controller receives the error and the change of the error components, $e^i, \dot{e}^i$ for each units of the tentacle manipulator and depending on the values of forces τ_{F_i} , generates the fuzzy

control torques T_F^i . The control rules are determined by the motion in the neighborhood of the switching line as a variable structure controller. We adopted here a special class of SMC named DSMC (Direct Sliding Mode Control) (Tao, 1998). The physical meaning of the rules is as follows: the output is zero near the switching line, the output is negative above the switching line, the output is positive below the diagonal line, the magnitude of the output tends to increase in accordance with magnitude of the distance between the switching line and the state. The DSMC method introduces new rules. This method operates in two steps. First step assures the motion towards the switching line s , by the general stability conditions. The second step starts when the trajectory penetrates the switching line. In this case, the damping coefficients of the motion are changed and system is moving toward the origin, directly on the switching line. The procedure for the design of the Fuzzy Controller is the following:

We consider that all input/output fuzzy sets are assured to be designed on the normalized space. The basic membership of the input variables are proposed as in Fig. 106. The universes of the input variable $e_i, \dot{e}_i$ are initially partition on three fuzzy sets: negative (N), zero (Z) and positive (P) with trapezoid membership function.

Fig. 106. Input fuzzy sets - 3 members

Fig. 107. Input fuzzy sets - 7 members

Fig. 108. Input fuzzy sets - 13 members

The state space of $e_i, \dot{e}_i$ will be partitioned into nine fuzzy regions. The fuzzy if-then rules for these fuzzy regions are presented in:

$\dot{e}^J \setminus e^J$	N	Z	P
P	Z	N	N
Z	P	Z	N
N	P	P	Z

Table 1. The initial fuzzy if-then rules

where the output membership are defined as singletons Fig. 109.

Fig. 109. Output singleton - 3 members

Fig. 110. Output singleton - 9 members

Fig. 111. Output singleton – 13 members

The output u_F of the fuzzy controller is derived to be (Soo, 1997)

$$u_F = \frac{\sum_{i=1}^9 \rho_i f_{e_i}(e_i) f_{\dot{e}_i}(\dot{e}_i)}{\sum_{i=1}^9 f_{e_i}(e_i) f_{\dot{e}_i}(\dot{e}_i)} \quad (59)$$

where ρ_i is one of the centers of the output singletons and $f_{e_i}(e_i), f_{\dot{e}_i}(\dot{e}_i)$ are the membership of the input variable $e_i, \dot{e}_i$ respectively.

The control 59 assure the motion of the system on the first part of the trajectory Fig. 115 with k_i SMALL ($k_i < K_i^S$), when the trajectory penetrates the switching line the DSMC control is applied by the control of the coefficient k_i (Proposition 1) k_i is BIG ($k_i \in K_i^B$).

Fig. 112. Control trajectory strategy

Fig. 113. DSMC Control trajectory

Fig. 114. DSMC Control trajectory increased control variable

The size of k_i is defined as singleton function Fig. 115.

Fig. 115. Two member singleton k_i coefficients

Fig. 116. Three member singleton k_i coefficients

Fig. 117. Four member singleton k_i coefficients

If the evolution described in Fig. 113 is not satisfactory, a new control strategy is adopted. The finer fuzzy domains are introduced (Figure 6b) and new fuzzy partitions are used: big negative (BN), small negative (SN), negative zero (NZ), zero (Z), positive zero (PZ), small positive (SP), big positive (BP). The fuzzy if-then rules for these fuzzy regions are presented in the Table 2, where the outputs are the singletons defined in Fig. 110.

$\begin{matrix} \dot{e}_i^J, \dot{e}_L \\ e_i^J, e_L \end{matrix}$	BN	SN	NZ	Z	PZ	SP	BP
BP	Z	NZ	SN	SN	BN	BN	BN
SP	PZ	Z	SN	SN	SN	BN	BN
PZ	SP	SP	Z	NZ	SN	SN	BN
Z	SP	SP	PZ	Z	SN	SN	SN
NZ	BP	SP	SP	PZ	Z	NZ	SN
SN	BP	BP	SP	SP	PZ	Z	NZ
BN	BP	BP	BP	SP	SP	PZ	Z

Table 2. The fuzzy if-then rules

Fig. 118. The rules surface

The new membership of the inputs μ^* verify the inequality:

$$\mu^*(x_i) \leq \mu(x_i) \tag{60}$$

for every input x_i . Then, new control u_F from 60 will satisfy the condition 58, Theorem 1. Also the new finer distribution of the control allows a new trajectory Fig. 113 determined by the new values of the k_i , small (S), medium (M), big (B). The result of this strategy is evaluated with the performance indexes The procedure of the modification of the fuzzy rule base will be repeated several times Fig. 111 , Fig. 111 , Fig. 114 until the performance requirements are satisfied.

5.5 Numerical results

The purpose of this section is to demonstrate the effectiveness of the method. This is illustrated by solving a fuzzy control problem for a tentacle manipulator system, which operates in XOZ plane (Figure 10). An approximate model (50) with $\Delta=0.36$ m and $n=7$ is used. Also, the length and the mass of the object are 0.2 m and 1 kg, respectively. The initial positions of the arms expressed in the inertial coordinate frame are presented in Table 3.

TM	$q_1(0)$	$q_2(0)$	$q_3(0)$	$q_4(0)$	$q_5(0)$	$q_6(0)$	$q_7(0)$
TM	$\pi/6$	$\pi/3$	$7\pi/12$	$2\pi/3$	$\pi/15$	$15\pi/8$	0

Table 3. Initial positions of the arms

Fig. 119. Numerical simulation for tentacle biomimetic robotic structure

The desired trajectory of the terminal points is defined by:

$$x = x_0 + a \sin \omega t \quad z = z_0 + b \cos \omega t$$

with $x_0=0.2$ m, $z_0=0.1$ m, $a=0.3$ m, $b=0.1$ m, $\omega=0.8$ rad/s.

The trajectory lies the work envelope and does not go through any workspace singularities. The maximum force constraints are defined by:

$$F_X \leq F_{MAX} = 50N \quad F_Z \leq F_{MAX} = 50N$$

and the optimal index $\min \left(\sum_j F_X^2 \right), \min \left(\sum_j F_Z^2 \right)$ are used. The uncertainty domain of the

mass is defined as $0.8\text{kg} \leq m \leq 1.4\text{kg}$. The solution of the desired trajectory for the elements of the arms is given by solving the nonlinear differential equation:

$$\dot{q}_d(t) = \left[J^T(q) \quad J(q) \right]^{-1} J^T(q) \dot{w}(t)$$

where $w=(x,z)^T$ and $J(q)$ is the Jacobian matrix of the arms.

A conventional controller with $k_i=0.5$ ($i=1,..7$) is determined. A FLC is used with the scale factors selected as $G_{e_i} = G_{\dot{e}_i} = 10$, $i=1,..7$.

The conventional and DSMC procedures are used and new switching line is computed. The condition 59 is verified and the new switching line is defined for $p_i=1.03$: $i=1,..7$.

Fig. 120. The evolution of k_{51} for a DSMC procedure

Fig. 121. The evolution of error e_{51} and error

In Fig. 120 is presented the evolution of k_5^1 for a DSMC procedure and the evolution of the position error e_5^1 and the position error rate $\dot{e}_5^1$ are presented in Fig. 121.

Fig. 122 represents the trajectory in the plane $(e_4^1, \dot{e}_4^1)$ for conventional procedure and Fig. 123 the same trajectory for a DSMC procedure for a new switching line. Fig. 124 presents the final trajectory. We can remark the error during the 1th cycle and the convergence to the desired trajectory during the 2nd cycle.

Fig. 122. Trajectory in the plane $(e_4, \dot{e}_4)$ for fuzzy SMC procedure

Fig. 123. Trajectory in the plane for fuzzy DSMC procedure

Fig. 124. Final trajectory for fuzzy DSMC procedure

6. Conclusion

The nickel titanium alloys, used in the present research, generally referred to as Nitinol, have compositions of approximately 50 atomic % Ni/ 50 atomic % Ti, with small additions of copper, iron, cobalt or chromium. The alloys are four times the cost of Cu-Zn-Al alloys, but it possesses several advantages as greater ductility, more recoverable motion, excellent corrosion resistance, stable transformation temperatures, high biocompatibility and the ability to be electrically heated for shape recovery.

Shape memory actuators are considered to be low power actuators and such as compete with solenoids, bimetal and to some degree wax motors. It is estimated that shape memory springs can provide over 100 times the work output of thermal bimetal.

The use of shape memory alloy can sometimes simplify a mechanism or device, reducing the overall number of parts, increasing reliability and therefore reducing associated quality costs. Because of its high resistivity of 80 – 89 micro ohm-cm, nickel titanium can be self heated by passing an electrical current through it. The basic rule for electrical actuation is that the temperature of complete transformation to martensite M_f , of the actuator, must be well above the maximum ambient temperature expected.

Scientists and engineers are increasingly turning to nature for inspiration. The solutions arrived at by natural selection are not only a good starting point in the search for answers to scientific and technical problems, but an optimal solution too. Equally, designing and building bio inspired devices or systems can tell us more about the original animal or plant model.

The connection between smart material and structures and biomimetics related with mechatronics offer a huge research domain. The present chapter explores using mathematical simulations and experiments only a modest part of the wonderful world of biomimetics.

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This book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of contemporary robotics and autonomous systems. The volume is organized in four thematic parts according to the main subjects, regarding the recent advances in the contemporary robotics. The first thematic topics of the book are devoted to the theoretical issues. This includes development of algorithms for automatic trajectory generation using redundancy resolution scheme, intelligent algorithms for robotic grasping, modelling approach for reactive mode handling of flexible manufacturing and design of an advanced controller for robot manipulators. The second part of the book deals with different aspects of robot calibration and sensing. This includes a geometric and threshold calibration of a multiple robotic line-vision system, robot-based inline 2D/3D quality monitoring using picture-taking and laser triangulation, and a study on prospective polymer composite materials for flexible tactile sensors. The third part addresses issues of mobile robots and multi-agent systems, including SLAM of mobile robots based on fusion of odometry and visual data, configuration of a localization system by a team of mobile robots, development of generic real-time motion controller for differential mobile robots, control of fuel cells of mobile robots, modelling of omni-directional wheeled-based robots, building of hunter- hybrid tracking environment, as well as design of a cooperative control in distributed population-based multi-agent approach. The fourth part presents recent approaches and results in humanoid and bioinspirative robotics. It deals with design of adaptive control of anthropomorphic biped gait, building of dynamic-based simulation for humanoid robot walking, building controller for perceptual motor control dynamics of humans and biomimetic approach to control mechatronic structure using smart materials.

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