Biomimetic Approach in Control and Design of Robotic Architectures Using Smart Materials

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***Abstract*—Biomimetics, Bionics, Biomechatronics is a fusion science which implies medicine, mechanics, electronics, control and computers. The actual paper present the experimental biomimetic platforms from Mechatronics Department, University of Craiova and the resulting experiments in using shape memory alloy for actuation of two-link leg/finger tendon driven. The PI controller (based on experiments) offers a suitable structure for individual leg control architecture. In the second part of article the main control strategies are summarized.**

***Index Terms*— Biomimetics, Control architecture, Control Strategy, Robotics, Shape Memory Alloy**

I. 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 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 biomimetic 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. These parameters do not have a random nature, being included in primary math 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 [1].

Electro-active polymers, due to the flexibility of the activators potions, are a perfect solution for the implementation of animatronics 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.

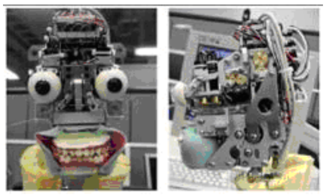

Fig. 1 Android robot Repliee R1 – Osaka University

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

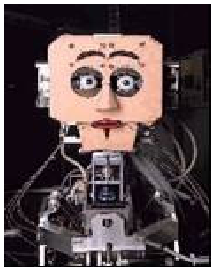

Fig. 3 Humanoid Cranium - Prof. Takanishi Atsuo, Waseda University in Tokyo

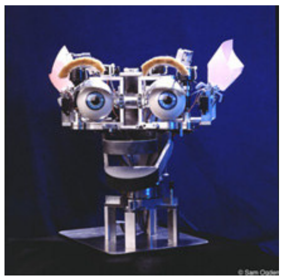

Fig. 4 Robotul Kismet dezvoltat de Cynthia Breazeal, MIT (Cambridge, Mass)

II. BIOMIMETIC EXPERIMENTAL PLATFORMS

At Department of Mechatronics, Faculty of Control, Computers and Electronics, University of Craiova, graduated students and PhD students are implied in projects regarding biomimetic robotic structures.

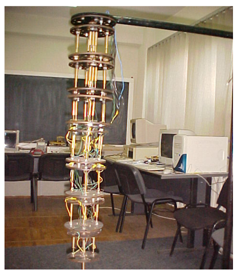

Fig. 5 Experimental trunk

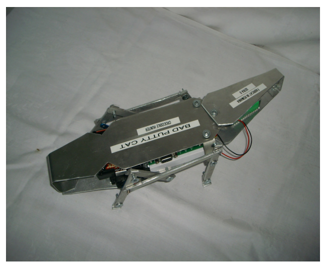

Fig. 6 Experimental crocodile

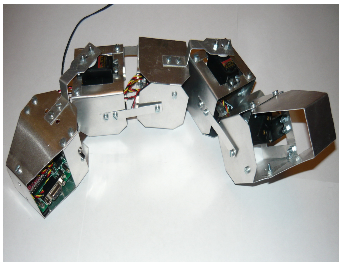

Fig. 7 Experimental Snake

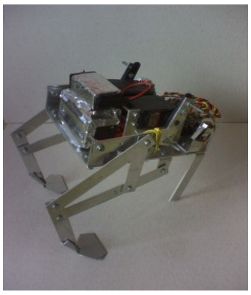

Fig. 8 Experimental Frog

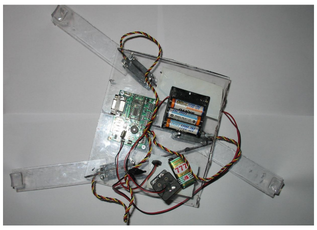

Fig. 9 Experimental Tripod Structure

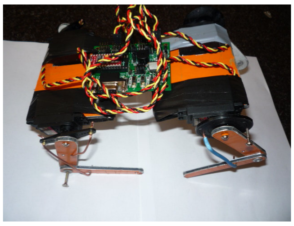

Fig. 10 Experimental Rabit

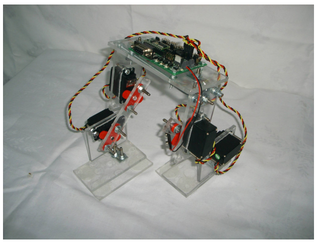

Fig. 11 Experimental Biped

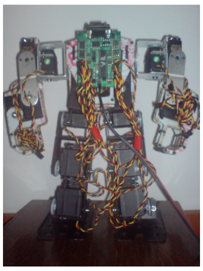

Fig. 12 Experimental Humanoid

The key aspects of projects concern the movement's similarity with movements of biological counterparts, obtained using particular mechanical and kinematical architecture and especially control programs implemented in individual control architecture.

III. TWO-LINK FINGER/LEG

Easily can be observed that basic actuation element is two link structure. A smooth movement can be obtained using tendon actuation. 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 [2].

The Lagrange analysis was used for the 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 mi and moment of inertia tensor.

$$I_i = \begin{bmatrix} I_{xi} & 0 & 0 \\ 0 & I_{yi} & 0 \\ 0 & 0 & I_{zi} \end{bmatrix} \qquad (1)$$

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

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

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 ith centre of mass.

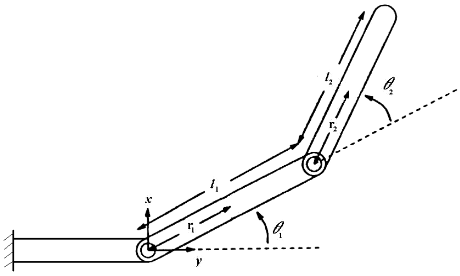

Fig. 13 Two link finger architecture

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

$$x_1 = r_1 \cos(\theta_1); \qquad \dot{x}_1 = -r_1 \dot{\theta}_1 \sin(\theta_1)$$
$$y_1 = r_1 \sin(\theta_1); \qquad \dot{y}_1 = r_1 \dot{\theta}_1 \cos(\theta_1)$$
$$x_2 = l_1 \cos(\theta_1) + r_2 \cos(\theta_1 + \theta_2);$$
$$\dot{x}_2 = -(l_1 \sin(\theta_1) + r_2 \sin(\theta_1 + \theta_2))\dot{\theta}_1 - r_2 \dot{\theta}_2 \sin(\theta_1 + \theta_2);$$
$$y_2 = l_1 \sin(\theta_1) + r_2 \sin(\theta_1 + \theta_2);$$
$$\dot{y}_2 = -(l_1 \cos(\theta_1) + r_2 \cos(\theta_1 + \theta_2))\dot{\theta}_1 - r_2 \dot{\theta}_2 \cos(\theta_1 + \theta_2) \qquad (3)$$

Using the kinetic energy and Lagrange methods results:

$$\begin{bmatrix} \alpha + \beta c_2 & \delta + \frac{1}{2}\beta c_2 \\ \delta + \frac{1}{2}\beta c_2 & \delta \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} -\frac{1}{2}\beta\ s_2 \dot{\theta}_2 & -\frac{1}{2}\beta\ s_2(\dot{\theta}_2 + \dot{\theta}_1) \\ \frac{1}{2}\beta\ s_2 \dot{\theta}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \qquad (4)$$

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.

IV. TWO-LINK FINGER/LEG TENDON-DRIVEN

It is considered a finger/leg which is actuated by a set of tendons such as the one shown in Fig. 13. 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 modeled 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 $h_i(\theta) = l_i \pm r_{i_1}\theta_i \pm \cdots \pm r_{i_n}\theta_n$ with l_i - nominal extension at $\theta = 0$ and r_{i_j} is the radius of the pulley at the jth 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. 14.

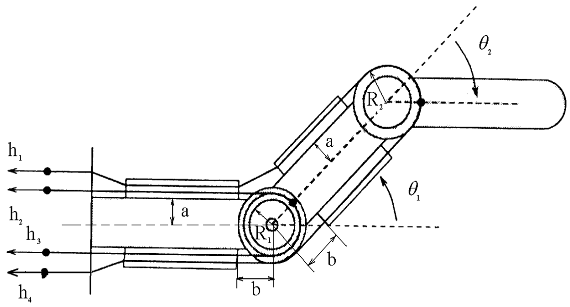

Fig. 14 Geometrical description of tendon driven finger/leg

The extension function of the form is:

$$h_1(\theta) = l_1 + 2\sqrt{a^2+b^2}\cos\left(\tan^{-1}\left(\frac{a}{b}\right)+\frac{\theta}{2}\right) - 2b,\ \theta > 0, \quad (5)$$

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 $P(\theta) \in R^{nxp}$ 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 $f \in R^p$ 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 R1, 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

$$h_1 = l_1 + 2\sqrt{a^2+b^2}\cos\left(\tan^{-1}\left(\frac{a}{b}\right)+\frac{\theta_1}{2}\right) - 2b - R_2\theta_2 \quad (6)$$

$$h_4 = l_4 + R_1\theta_1 + R_2\theta_2. \quad (7)$$

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

$$P(\theta) = \frac{\partial h^T}{\partial \theta} = \begin{bmatrix} -2\sqrt{a^2+b^2}\sin\left(\tan^{-1}\left(\frac{a}{b}\right)+\frac{\theta_1}{2}\right) & -R_1 & R_1 & R_1 \\ 0 & 0 & -R_2 & R_2 \end{bmatrix} \quad (8)$$

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.

V. SMART MATERIALS - SHAPE MEMORY ALLOY - USED IN TENDON ACTUATION FOR BIOMIMETICS ARCHITECTURES

The unique behavior of shape memory alloy (SMA) 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 [2]. 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).

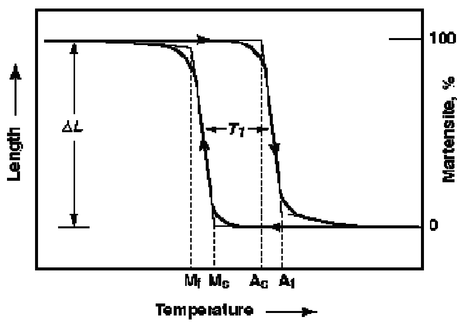

Fig. 15 Shape memory alloy phase transformation

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 (Ms) and respectively martensite finish temperature (Mf)[3].

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.

We consider that each link is a homogeneous rectangular 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 [4,5,6].

- 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. 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 [7]. 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.

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 Af 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.

VI. CONTROL ARCHITECTURE FOR SMA TENDON DRIVEN STRUICTURE

In order to investigate the SMA 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.

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 uses 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 30^0 angle base variation and the evolution of this reference is represented with the response of real system in Fig. 17. The control signal variation is presented in Fig. 18.

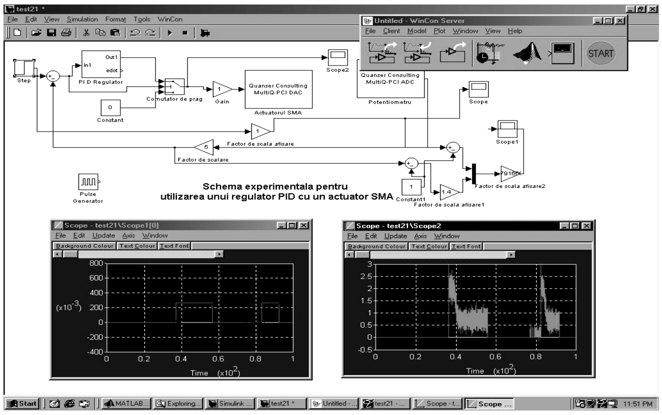

Fig. 16 Simulink blocks for tentacle unit control

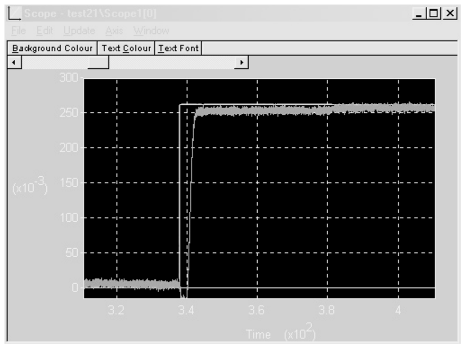

Fig. 17 System response, for step input

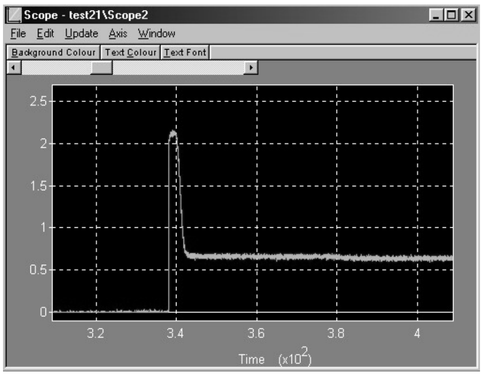

Fig. 18 PI controller response, for step input

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.

As a conclusion: the best results arise when a PI controller is used.

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.

VII. BIOMIMETIC CONTROL STRATEGIES

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 [8,9,10,11,12].

Behavioral 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 lead to a cumulative action [13]. 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 [14]. 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 [15]. 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 [16]. 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 [17]: 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 [18] 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.

VIII. CONCLUSION

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 o huge research domain. The present paper represents only a modest step to the wonderful world of biomimetics.

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