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A Self-Organizing System for Online Maintenance of a Living Organism

Yevgeniya Kovalchuk
School of Computer Science and Electronic Engineering
University of Essex
Colchester, UK
yvkova@essex.ac.uk

Victor Callaghan
School of Computer Science and Electronic Engineering
University of Essex
Colchester, UK
vic@essex.ac.uk

Abstract— **Intelligent environments have the ability to assist people in their everyday life, with the aim of improving their wellbeing. One aspect of a humans' wellbeing is their health. The ability to monitor, understand, and correct bodily processes in real time and in convenient way can help people to improve their state of health, foresee and prevent diseases, will promote wellbeing and a longer life. To achieve these goals, this paper proposes a conceptual model of a self-organizing system which allows for online tracking and tuning of bodily processes. The system includes a Biofeedback Module, a Biological Module, an Adjusting Module, and a Recommender Module. This research exploits an interdisciplinary approach. The Biofeedback Module deploys innovations in bio-sensing technology and uses concepts from biological and mathematical sciences; it is responsible for biological signal processing and is designed to form a Multi-Agent System (MAS). The Adjusting Module is inspired by findings in sport, nutrition, pharmacy, meditation, and other health related areas. Its computational model is implemented using Agent Technology and Game Theory. The Recommender Module provides interaction with a user, presenting computational results in a readable format. All elements can be integrated into a small handy device. The proposed system has a wide range of applications, including biology, health care, sport, entertainment, robotics, and military.**

Self-organising systems; healthcare systems; agent technology; game theory; intelligent environments; self-understanding.

I. Introduction

The problem of stabilizing dynamic systems has been explored for many years. For example, a lot of effort has been put into ways to stabilize political and economic systems; the stability of a nuclear reactor is important to prevent a catastrophe; closer to the heart of this conference, much research has been invested in stabilising multi-agent and pervasive computing systems [39]. People try to keep a balance in their external environment often forgetting, at the same time, about their inner world of body and mind. Mainly, this is due to the fact that we are still a long way from understanding how the physical body works; a lot of secrets are still hidden inside the biological organism. It is not yet possible for humans to track and control their bodily processes in real time. We are usually not aware when the body is dehydrated or lacks a particular vitamin or microelement, when the blood pressure drops down or cholesterol level goes up. We feed and exercise our bodies approximately based on a somewhat vague feelings which can lead to discomfort. For example, you may feel that you cannot stop eating fatty cheese when the body needs calcium, while a pot of plain yogurt could be enough to bring the system into balance. When under stress, we tend to crave for sugars or rely on coffee and cigarettes instead of doing a one minute breathing exercise. We think we are tired, so drop our work, but the actual reason for tiredness is dehydration, thus a glass of water could give us that extra energy to continue the work.

Usually, a set of wired equipment is required to measure different parameters of the body. People need to attend laboratories to have the analysis done, and they tend to do this only when they feel unwell, which is often too late to prevent problems or reveal the real cause. It is not yet possible for a non-expert to get a snap-shot of the body's internal environment at any time and place. A lot of research, especially in the field of biotechnology, is currently concentrated on finding new solutions to ease the procedures of measuring bodily processes. Not only can the general populace benefit from such solutions, but also groups with special needs such as the elderly, disabled or infants could take advantage of the up-to the minute diagnosis.

This paper tries to address the above problems and introduces a conceptual model of a system that we argue could help to keep a biological organism (e.g., the human body) in balance in real time. The conception is based on findings from many disciplines, such as biology, information technology, hardware and electronics, and mathematics.

From a biological prospective, scientists are used to dividing all human behaviour into voluntary and involuntary responses [10]. Voluntary responses include any responses that involve active control of muscles: a swing of the arm, a wink of the eye, and so forth. Involuntary responses include heart beat, blood pressure, and EEG (electroencephalography) wave patterns, as well as more subtle responses such as urine production by the kidneys. It has long been assumed that humans could not control, except in a very limited way, involuntary responses. However, it is becoming increasingly clear now that some responses earlier thought to be involuntary can actually be modified, if not fully controlled [10].

This work uses the principals of biofeedback to control and modify physiological processes (involuntary responses) of a biological organism. Biofeedback refers to the use of electronic instruments to show the activity of one or more of bodily processes [10]. Such techniques as exercising, nutrition, meditation, hypnosis, and the use of drugs can be applied to adjust those processes which act abnormally (i.e., provide the biofeedback that falls out of the predefined recommended measures). The design of mathematical instruments such as Multi-Agent Systems (MAS) and Game Theory (coalitional games, in particular) are used to construct the computational mechanism that performs adjustments in order to bring a living organism into balance.

The paper is organized as follows. First, the aspects of medical diagnostics, bio-sensing technology, MAS, and Game Theory are defined, and related work is outlined. Next, the conceptual model of the proposed system is presented followed by formalization of the computational problem. Finally, conclusions and tasks for future work are provided.

II. STATE OF THE ART

A. Measuring Bodily Processes

While functionality of some biological processes can be easily estimated by using simple techniques, estimation of others requires special arrangements that involve complicated medical equipment. For example, heart rate can be measured at any time manually. It can be taken at any spot on the body where an artery is close to the surface and a pulse can be felt, such as at the wrist (radial artery), the neck (carotid artery), the elbow (brachial artery), or the groin (femoral artery). Sometimes, more sophisticated methods have to be applied to measure the heart rate. This is particularly important during exercising when the motion of exercise often makes it hard to get a clear measurement using the manual method. In such cases, a heart rate monitor or ECG/EKG can be used to get a more accurate heart rate measurement. Electrocardiography (ECG or EKG) is a non-invasive method for recording of the electrical activity of the heart over time via skin electrodes.

Electroencephalography (EEG) is another example of capturing biological signals from the body. It is the recording of electrical activity produced from the firing of neurons within the brain by means of multiple electrodes placed on the scalp.

Other methods for looking at brain activity and other bodily processes include Positron Emission Tomography (PET) and Functional Magnetic Resonance Imaging (fMRI). PET is a nuclear medicine imaging technique which produces a three-dimensional image or picture of functional processes in the body. The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule. Images of tracer concentration in three-dimensional space within the body are then reconstructed by computer analysis. In modern scanners, this reconstruction is often accomplished with the aid of a CT X-ray scan performed on the patient during the same session, in the same machine.

fMRI is relatively new method that measures the hemodynamic response related to neural activity in the brain or spinal cord of living organisms. Other novel techniques based on imaging include also Photometric Stereo technology that has been recently developed by Machine Vision Lab at the University of West of England [3], [29].

Blood tests are used to determine physiological and biochemical states such as disease, mineral content, drug effectiveness, and organ function. Since blood flows throughout the body, acting as a medium for providing oxygen and nutrients, and drawing waste products back to the excretory systems for disposal, the state of the bloodstream affects, or is affected by, many medical conditions. Blood is usually drawn from a vein in the arm. A vein at the inside of the elbow or on the back of the hand is usually selected. Other specialized blood tests, such as the arterial blood gas, require blood extracted from an artery.

Biosensors, nanosensors and biochips have become extremely popular as a tool for medical diagnostics and therapy due to their non-invasive or minimally invasive nature [31]. A biosensor is a device that detects, records, and transmits information regarding a physiological change or the presence of various chemical or biological materials in the environment. More technically, a biosensor is a probe that integrates a biological component, such as a whole bacterium or a biological product (e.g., an enzyme or antibody) with an electronic component to yield a measurable signal. It can detect and measure concentrations of specific bacteria or hazardous chemicals; it can also measure acidity levels (pH).

Nanosensors provide new and powerful tools for monitoring in vivo processes within living cells, leading to new information on the inner workings of the entire cell [32]. Fiberoptic sensors are used for remote in situ monitoring. They could be fabricated to have extremely small sizes, which make them suitable for sensing intracellular/intercellular physiological and biological parameters in microenvironments [30]. Biochips are designed by combining integrated circuit elements, an electro-optics excitation/detection system, and bio-receptor probes into a self-contained and integrated micro-device [31].

These achievements in bio- and nanotechnology will hopefully make it possible soon to sense all bodily processes easily and at once. For example scientists from the Oak Ridge National Laboratory in USA have built an array of chips to collectively monitor bodily functions including body temperature, blood pressure, oxygen level, and pulse rate. The researchers have also developed biosensors to monitor the status of diabetes without using blood samples, applied optical techniques to detect skin, cervical, and colon cancers, and combined their different findings in miniaturized devices [36]. Researchers in the UK have shown it possible to use implanted versions of this type of technology to predict disabling seizures or the onset of tremors helping to give their users a better quality of life [40]. A lab-on-a-chip (LOC) is another promising technology [15]. LOC is a very small device that integrates one or several laboratory functions on a single chip. It is suitable for chemical analysis, environmental monitoring, and medical diagnostics [37]. Simulating bodily responses can assist in testing such devices. One method is “Electronic sensing”: it allows reproducing human senses using sensor arrays and pattern recognition systems. Research has been conducted since 1982 [16] to develop technologies, commonly referred to as electronic noses, that mimic human olfaction and could detect and recognize odours and flavours. The more commonly sensors used in this technology include metal oxide semiconductors (MOS), conducting polymers (CP), quartz crystal microbalance, surface acoustic wave (SAW), and field effect transistors (MOSFET).

To conclude, it is not that long till bodily processes could be monitored easily by unskilled personal users and in real time.

B. SPOT™

Apart from a set of sensors, the monitoring system should also include a signal processing unit, as well as a computation unit capable of calculating a recipe for correcting issues found in an organism. The target is to develop a small and compact device that can provide all these at once. Sun Small Programmable Object Technology (SPOT™) [38] is one possible platform for this. A SPOT™ is a small, wireless, battery-powered ARM device developed by Sun Microsystems Ltd. The device supports a specially designed small-footprint multi-threaded Java virtual machine, called Squawk, which requires no underlying operating system and facilitates simple interfacing of external sensors. The device can be duty cycled to run for months on a single charge of the battery.

C. Multi-Agent Systems

Agents and Multi-Agent Systems (MAS) belong to one of the most rapidly advancing areas of computing technology with a number of potential applications [6, p.8]. A good introduction to MAS can be found in [33].

According to [6], agents are computational systems that are capable of autonomous, reactive and proactive behaviour, and are also able to interact with each other. Jennings [9], has pointed out the flexible, high-level interactions of agents that make the engineering of complex systems easier. In large complex systems it is very difficult to know every possible interaction, making such environments highly unpredictable. MAS decentralization addresses this problem by letting each agent continuously adapt its interaction with other agents, instead of making this agent apply a set behaviour prescribed at design-time. Thus, MAS can manifest self-organization and complex behaviours even when the individual strategies of all their agents are simple.

Examples of problems which are appropriate to MAS research include e-Commerce [6], supply chain management [4], disaster response [24], modelling social structures [28] and intelligent environments [41]. Because of its ability to deal with complexity, MAS has found applications in medicine, computational biology, and bioinformatics ([19], [20], [17], [26]). However, no approach similar to the one presented in this paper has been proposed in the literature so far.

D. Game Theory

Game theory provides a formal analytical framework with a set of mathematical tools to study the complex interactions among rational players [21]. The proposed approach is based on the principals of coalitional games. In essence, coalitional games involve a set of players, denoted by N = {1, . . . ,N} who seek to form cooperative groups, i.e., coalitions, in order to strengthen their positions in the game. Any coalition $S \subseteq N$ represents an agreement between the players in S to act as a single entity. In addition to the player set N, the second fundamental concept of a coalitional game is the coalition value. Mainly, the coalition value, denoted by *v*, quantifies the worth of a coalition in a game. A coalitional game is uniquely defined by the pair *(N, v)*. A number of algorithms have been proposed for defining the coalition value including Shapley value [25], core [14], anonymity-proof core [34], and nucleolus [23].

Throughout the past decades, game theory, and coalitional games in particular, have made revolutionary impact on a large number of disciplines ranging from engineering, economics, political science, philosophy, or even psychology [13]. An overview of applications of coalitional game theory for communication and wireless networks can be found in [21]. The model in [11] tackles the problem of how to fairly allocate the transmission rates between a number of users accessing a wireless Gaussian MAC channel. In this model, the users are bargaining for obtaining a fair allocation of the total transmission rate available. In [12], canonical games are used for studying the cooperation possibilities between single antenna receivers and transmitters in an interference channel, while in [7], games are used to solve an inherent problem in packet forwarding ad hoc networks. Coalitional games in open anonymous environment, such as Internet, are discussed in [34]. Many application of game theory can also be found in biology. Commonly, the proposed solutions try to model and explain the behaviour of living organisms and interactions between them ([27], [8], [35]), rather than to control biological processes within an organism.

III. CONCEPTUAL MODEL

The following artifacts constitute the proposed model.

- Organism: any living thing, including humans, animals, plants, fungus, and micro-organisms. The proposed model is primarily focused on the human body.
- Physiological process: any function or activity of an organism that supports life in it, for example, cardiovascular, respiratory, reproductive or virus physiological process.
- Biological quantity: a quantitative representation of functioning of a physiological process, for example, heart rate, blood pressure, cholesterol or sugar level.
- Sensor: a device that measures a biological quantity and converts it into a signal.
- Adjuster: a technique that influence one or more physiological processes in an organism, for example, a physical exercise, a breathing exercise, food or a drug.

The system includes a Biological Module, a Biofeedback Module, an Adjusting Module, and a Recommender Module (Fig.1). The modules are described below.

1) *The Biofeedback Module:* Includes a set of sensors applied to an organism to capture various biological signals from it. Sensors can be attached or removed from the system to meet the given requirements.

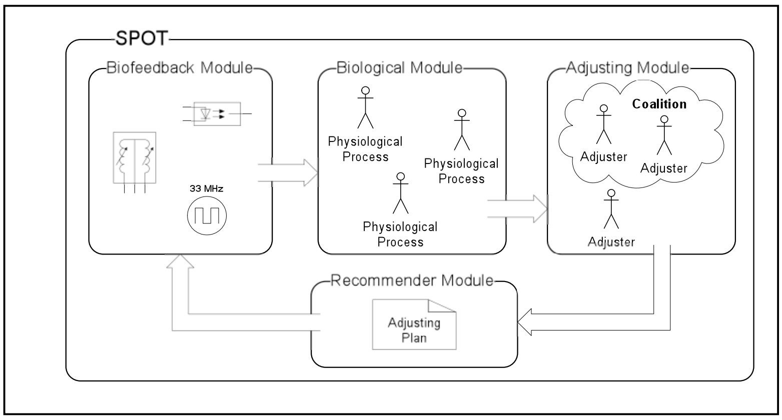

Figure 1. *Conceptual model of the system for online maintenance of a living organism*

2) *The Biological Module*: Is responsible for signal processing as well as determining biological quantities that fall out of recommended boundaries. It includes a database of physiological processes involved in functioning of the organism. Processes can be added to or removed from the database, depending on purposes of the system. The module is designed as a MAS: an agent is assigned to every physiological process. Each such agent is responsible for maintaining its process: the agent receives signals from a sensor, processes the signals, and detects quantities to be tuned. The agent recognizes its sensor, method for signal processing, as well as recommended boundaries for correspondent biological quantities. Agents report the issues they found to the Adjusting Module.

Application of agents, in this case, helps to deal with the complexity and versatility of a biological system. By assigning a separate agent to each bodily process, the processes can be studied separately, as well as in interaction with each other. Agents make it easier to model and understand dependencies between the processes. In addition, this approach contributes to effective modification of the system: any process (agent) and the infrastructure assigned to it can be removed without ruining the whole system.

3) *The Adjusting Module*: Holds a computational mechanism that finds a set of adjusters to be applied to an organism in order to bring its state into balance. Given the requests from agents in the Biological Module with regards to which biological quantities have fallen out of their recommended boundaries, the task of the Adjusting Module is to insure that all physiological processes within the organism function properly again. The model keeps a database of adjusters, which can be modified by adding, removing or editing records representing adjusters. Similar to the Biological Module, this module is designed as a MAS: an agent is assigned to every adjuster. Each agent can affect one or more physiological processes. They do this in different way. While positively influencing one physiological process, an adjuster can have negative (side) effect on another process. On the other hand, the problem can be fixed by applying another adjuster at the same time. Thus, there is the need for a mechanism to find the optimal combination of adjusters. Such mechanism is implemented based on principals found in game theory. It is outlined in the next section. The Adjusting Module is also responsible for handling exceptional situations, when no optimal solution can be found or external assistance should be sought (e.g., consulting a doctor or urgent hospitalization).

4) *The Recommender Module*: Generates a list of recommendations in a user-friendly format based on results calculated by the Adjuster Module (for example, a routine of exercises or a certain food, or a drug, or combination of these). The module outputs the list to the specified device, such as an email account, mobile phone, iPod or printer.

All the modules reside on a SPOT^{TM}. Sensors, that constitute the Biofeedback Module, are either physically attached to the SPOT or send signals to it wirelessly. The remaining three modules are implemented as databases and programs run on the device. The SPOT sends a recommendation list to the defined display system wirelessly.

The combination of the Agent Technology, Game Theory, SPOT, along with achievements in biosensor technology would make it feasible to simulate physiological processes and study bodily responses in a controlled manner before applying the system to living organisms.

IV. COMPUTATIONAL MODEL

Knowledge of biological quantities along with the affect each actuator makes on bodily processes is not enough to bring an organism into balance. Both physiological processes and actuators are interconnected and interdependent. While treating one issue, an adjuster can cause a new problem. Possible combinations of processes and adjusters should be constantly reviewed in order to find the best possible plan for stabilizing the system. Initial sets of bio sense-actuate combinations can be built up offline and stored in a database which the Adjusting Module would consult to find an adjusting plan. However, this database should be updated in real time so as to meet particularities of the given subject (biological organism).

The principals of game theory are used to solve the problem. More specifically, the concept of coalitional games is particularly well-suited for the environments where entities should work together in order to increase the overall outcome, and contribution of each participant to the result has to be estimated. Game theory also assumes existence of random processes, which can be due to noise from sensors or accidental external factors in this case.

Formally, coalitional games involve a set of players, denoted by $N = \{1, . . . ,N\}$ who seek to form cooperative groups, i.e., coalitions, in order to achieve a higher payoff. Any coalition $S \subseteq N$ represents an agreement between the players in *S* to act as a single entity. The contribution of each player to achieving a high payoff is defined by value function *v*.

For the given scenario, actuators represent players in a game. The game is played in order to find the combination *S* of actuators (an adjuster) that influences an organism in the most positive way, i.e. brings the organism to the state when all biological quantities are close to their ideal values. The task is to estimate the contribution of each actuator in generating an adjuster. The payoff is represented by a real-valued function *v(S)* that measures the performance of the generated adjuster using the set of actuators *S*.

Among other methods, the Shapley value [25] is used to calculate a contribution value of a player (adjuster). According to [5], the marginal importance of a player $i \notin S$ to a coalition *S*, is defined as

$$\Delta_i(S) = v(S \cup \{i\}) - v(S)$$

From here, the Shapley value is determined by the payoff

$$\Phi_i(v) = \frac{1}{n!}\sum_{\pi \in \Pi} \Delta_i(S_i(\pi))$$

where Π is the set of permutations over *N* and $S_i(\pi)$ is the set of players appearing before the *i*th player in permutation π. The Shapley value of a player is a weighted mean of its marginal value, averaged over all possible subsets of players.

Value functions are built for every possible scenario (i.e., combination of biological quantities) in advance. The model is trained offline based on historical records. At the same time, it is constantly updated in real time to meet functional particularities of the given organism.

The concept of dynamic coalition formation games is used to perform online evolution of the computational model. In such games, the main objectives are to analyze the formation of a coalitional structure, through players' interaction, as well as to study the properties of this structure and its adaptability to environmental variations or externalities. The evolution of this structure is important, notably when changes to the game's nature can occur due to external (actuators, in this case) or internal (biological quantities) factors. The coalition formation process takes place in a distributed manner, whereby the players have autonomy on the decision as to whether or not they join a coalition. When studying dynamic coalition formations, [1] define a number of rules for comparing collections of coalitions. One of these rules, known as the utilitarian order, states that, a group of players prefers to organize themselves into a collection $R = \{R_1, . . . ,R_k\}$ instead of $S = \{S_1, . . . , S_l\}$, if the total welfare achieved in *R* is strictly greater than in *S*, i.e., $\sum_{i=1}^{k} v(R_i) > \sum_{i=1}^{l} v(S_i)$. Another important rule is the Pareto order, which bases the preference on the individual payoffs of the players rather than the coalition value. Given two allocations *x* and *y* that are allotted by *R* and *S*, respectively, to the same players, *R* is preferred over *S* by Pareto order if at least one player improves in *R* without hurting the other players, i.e., $x \geq y$ with at least one element x_i of *x* such that $x_i > y_i$. For the given scenario, it means that the combination of actuators *R* is preferred to the their combination *S*, if *R* brings at least one biological quantity closer to its ideal value comparing to its value provided by *S*, without harming other biological quantities (i.e. none of other quantities should deviate from its recommended value more than it is in the context of coalition *S*).

V. CONCLUSIONS

This paper introduced a conceptual model of a self-organizing system for tracking and adjusting bodily processes of a living organism in real time. The proposed model uses findings from many disciplines, including biology, information technology, electronics, and mathematics. In this work we extend the notion of intelligent environments from the external space we inhabit, to include the inner space of our mind and body.

Four modules constitute the proposed system. The Biofeedback Module includes a set of (bio)sensors for measuring bodily processes. The Biological Module models interaction of physiological processes within a living organism using agent technology. This technology allows modelling complex systems and studying separate elements that constitute the system both in isolation and in relation to other elements found in the system. Agents are also used to build the Adjusting Module, the main purpose of which is to fix the problems currently observed in the body. Coalitional game theory is applied to find the better plan for stabilizing the biological system. The Recommender Module outputs the plan in a user-friendly format. All the modules reside on a SPOT™ developed by Sun Microsystems Ltd. The device is small in size and works on a rechargeable battery; it can host multiple computational applications concurrently and requires no underlying operating system.

To the best of the author knowledge, no similar approach exists. By using a multi-agent approach we get a generic conceptual model that can readily adapt to any particular medical problem. In addition, the model can be applied to develop other systems which function similar to living organisms, i.e. where there are a set of internal and external processes that influence the existence/operation of a system. This includes robots, machines, networks etc.

The conceptual model presented in the paper has not been implemented yet. The next step is to build the system according to the specification and to test it. More research has to be also done on developing (bio)sensors to provide inexpensive and convenient way for perceiving bodily processes. The device should perform well in different customized applications and be easy to use for unskilled, disabled, or elderly people.

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