Modelling Embodied Appraisal in Humanoids: Grounding PAD space for Augmented Autonomy

Kiril Kiryazov[1], Robert Lowe[1], Christian Becker-Asano[2], and Tom Ziemke[1]

[1] Cognition & Interaction Lab, University of Skovde
{kiril.kiryazov, robert.lowe, tom.ziemke}@his.se
[2] Freiburg Institute for Advanced Studies, University of Freiburg
christian@becker-asano.de

Abstract. A computational emotion architecture is presented which grounds an aspect of an appraisal theoretic architecture in energy related processes. The incorporation of an energy constraint on emotional-cognitive behaviour allows greater potential for autonomous agency when implemented on a physical (NAO) robot platform. In this paper we present an algorithm that enables metabolic grounding of the arousal component of the PAD emotion space used in the architecture. We describe an exemplar problem that abstracts variables and performance criteria relevant to service robotics applications. Future work on further integration based on neurobiological grounding is discussed as well as means by which the exemplar scenario may be scaled up to more realistic service robotics based scenarios.

Keywords: appraisal theory, homeostasis, autonomy, emotions, humanoids, robots, WASABI, virtual agents

1 Introduction

Researchers into service robotics applications for man-made environments over the past two decades have acknowledged the need for a high degree of autonomy for such robots [1],[2]. McFarland [3] has suggested that fully autonomous robots should be imbued with three levels of autonomy: energy, motivational, mental levels. It has also been suggested that cognitive-emotional capacities must be grounded in basic homeostatic regulatory processes (forms of metabolic regulation) in order for agents to be not only truly autonomous but also capable of displaying ‘higher’ level capabilities such as reasoning and planning [4-7].

Humanoid environments being complex, somewhat dynamic and unpredictable require agents to operate in a highly flexible manner in order to adaptively (and optimally) balance work-based and refuelling activities. For example, a cleaner or general purpose domestic robot may have to act rapidly to prevent potentially damaging unpredicted events from happening, e.g. items falling from surfaces, fire hazards, boiling water overflowing. Some mechanisms enabling integration of levels imbuing forms of energy constrained action selection in wheeled robots with simulated artificial metabolism have been investigated [8],[25]. Humanoid robots operating in human-built environments may require human-like cognitive mechanisms in order to account for more complex sensor-motor morphologies involved in human-relevant tasks. The aim of the present paper is to report on the motivation for, and simulations-based demonstration of, the first phase of the grounding of the WASABI (WASABI Affect Simulation for Agents with Believable Interactivity) architecture in homeostatic regulatory mechanisms. This phase entails embedding mechanisms that permit energy autonomy in a humanoid (NAO) robot required to trade off 'work' and 'recharging' activities. We provide a simple initial test scenario that is deliberately made as abstract as possible in order for us to assess cycles of work-refuel activity that, as a measure of the autonomy of the agent, are required to be sustainable according to a dynamic problem. This scenario can be viewed as a minimalist analogy to a service robot having to refuel but also carry out a task that involves unpredictable dynamics. Our particular architecture may be considered to be commensurate with a perspective that emotions serve a higher homeostatic/allostatic regulatory function [11], [22].

WASABI is chosen as a base for our architecture for several reasons. It is a psychologically plausible model and it includes the full spectrum of emotions which humans have. From another perspective, it has been successfully implemented and tested in several applications with a virtual human as a museum guide and a card game partner, respectively [16],[19]. WASABI is based on one of the most popular theories of emotions – appraisal theory which has been used in several architectures for emotional robots [24]. WASABI has been successfully applied in the virtual domain but hasn't been applied to robotic scenarios until now. The main problems which are usually tackled with architectures in real-world applications are related to perception and action. For that reason most of the approaches for making embodied robotic architectures consist in grounding components of the architecture into robotic sensory-motor systems. Another important aspect is the fact that robots have physical bodies which have physical limitations. For example, energy level should be kept within appropriate limits, body integrity should be maintained and damage should be avoided. Grounding certain components of the model into physiological processes inside the robot could be useful for solving those problems.

The paper breaks down into the following sections: 2) A background to appraisal theory and the role of internal (somatic) states as well as a discussion on cognitive-emotional architectures with robotics applications, 3) A short description of the basic components of WASABI - the base of our homeostatic cognitive-emotional architecture , 4) An overview of the new architecture with an accent on a particular energy constrained arousal mechanism that provides a first step to the grounding of WASABI PAD space, 5) A test scenario and methodological set-up concerning an abstract two-resource problem, 6) A discussion of appropriate performance measures for incarnations of the proposed integrated architecture as well as future steps towards integration and elaborated test scenarios.

2 Appraisal Theory, Somatic States and Autonomous Agency

Classically, appraisal theoretic models have been divided according to appraisal and response with the former causally antecedent to the latter. The appraisal part concerns evaluation of the onset of events of survival relevance to the agent. The response part concerns innate or learned bodily and behavioural dispositions adaptive to the appraised event. The appraisal may be characterized by an unconscious part which entails a fast response to unexpected change in the environment and a conscious part which is slower and enables more deliberative emotional responses to complex, e.g. social, events [9].

The extent to which purely cognitive appraisal and purely emotional response distinctions are apt to human neurobiology and psychology has been contended [10], as bodily and behavioural dispositions can impact on ongoing appraisals. It has been argued that appraisal may induce changes in the internal milieu constitutive of an emotional response that may in turn impact on ongoing appraisals [9]. On the other hand, it has been argued that direct perceptions of events or stimuli can induce bodily changes that comprise simultaneously the emotion response and the (embodied) appraisal [5]. The latter perspective emerged from the tradition of the somatic feeling theory of emotion of James that has more recently been adapted by Damasio [23].

Damasio's somatic theory of emotions also entails higher cognitive (and emotional) capabilities being grounded in increasingly elaborate forms of homeostatic regulation [11]. Much recent research into autonomous robotics continuing the cybernetics tradition of the 1950s has provided a focus on grounding robot behaviour and adaptive mechanisms in homeostatic processes [7], [12]. McFarland and Spier [12], for example, proposed a simple ethology-based motivation model to guide robotic action selection. This was known as the cue x deficit model whereby the deficit consists in an abstract physiological 'error' and the cue pertains to the strength of an external stimulus. A biologically plausible implementation of such inputs is lacking; however, some attempts have been made to render cue x deficit based architectures more biologically grounded, e.g. Avila-Garcia and Canamero ([13]) use a cue x deficit action selection architecture equipped with a hormone-biasing mechanism.

From an appraisal theoretic point of view, early attempts to simulate affect have been prone to follow the symbolic reasoning approach derived from classical artificial intelligence methodologies [14]. After the insufficiencies of solely grounding an implementation of affect on rational appraisal theories (such as the OCC model of emotions [15]) became more and more apparent , a number of architectures have been newly designed [16] or extended [17] as to better account for the dynamics of emotions, for which the above mentioned idea of integrating homeostatic processes has been very influential (for a review see [18]).

The grounded appraisal theoretic architecture we are developing is based on WASABI (Wasabi Affect Simulation for Agents with Believable Interactivity) architecture. WASABI is a top-down cognitive architecture that integrates classical appraisal theories of emotion with a cognition independent emotion dynamics in PAD space [16]. We grounded some of the components of the model in energy processes as the dynamics of battery level due to charging and energy consumption from the robot actuators. Conceptually, this combination allows us to explore the effects of linking energy related processes (as powering system in robots) with the arousal component of WASABI.

3 WASABI

WASABI is a psychologically plausible appraisal theoretic model that has been successfully implemented and tested in the context of the virtual human MAX, who served as a museum guide and a card game player [16],[19]. In WASABI two types of emotions are distinguished, namely primary and secondary emotions. Primary emotions are considered innate affective states and they are mainly elicited by reactive processes. The primary emotions of WASABI include five of Ekman's six basic emotions (excluding “disgust”) and in addition “bored”, “annoyed” and “depressed”. They are represented in the three-dimensional space of pleasure, arousal, and dominance) by points with activation and saturation thresholds. The space itself is commonly referred as PAD space [20]. Secondary emotions, in WASABI, similarly to primary emotions, are represented as regions in PAD space. Their expression, however, depends on higher cognitive mechanisms such as planning, memory, and anticipation. These secondary emotions are part of the prospect based emotions cluster of the OCC theory of emotions, namely hope, fears-confirmed, and relief. In addition, the idea of an emotion dynamics is central to WASABI which ensures mood congruent elicitation of emotions. For example, when the system is in a positive mood state it is more likely to generate positive emotions.

WASABI has two appraisal modes: conscious and unconscious appraisal. Unconscious appraisals classify the environmental state as neutral, positive or negative and send a positive/negative impulse to the emotion dynamics module. This classification is based on predefined rules which map the environmental state to the bipolar valence. For example, the detection of human skin colour generates small positive impulses because human presence is evaluated as something positive. Furthermore, high level appraisal is based on an expectation mechanism in the reasoning module where expectations are generated and the possible future states are evaluated. The conscious reappraisal uses already generated emotional states from the emotion dynamics and appraises them and the reasoning induced by them according to the current environmental context. The conscious appraisal generates the secondary emotions in the model. Conscious appraisal generates prospect based emotions like hope and fear based on expectations of the future state of the world and the concept of goal conduciveness. In addition, it appraises already generated emotions based on the verification of past (memorized) expectations and generates more prospect based emotions like relief.

Emotional behaviour in WASABI can be both involuntary and deliberative. Involuntary behaviours are simple reactive behaviours as for facial expression generation. Deliberative behaviour is controlled from the reasoning module based on the emotions which the agent is aware of. Finally, WASABI’s reasoning module is based on the Belief-Desire-Intention (BDI) architecture for cognitive modelling [21]. Beliefs represent the perceived current state of the world. Desires are the goal states which the agent would like to achieve. Intentions are plans associated with the current goals which consist of sequences of actions.

There are several approaches for modelling cognitive emotional virtual agents which are more or less similar to WASABI. For example, in the FeelMe framework for modelling cognitive emotion agents [26], a BDI reasoning component is available as well and the appraisal process results in modulating emotional state represented in a multi-dimensional continuous space, which is similar to WASABI's PAD space. By using FeelMe, in [26] an approach for run-time scaling of the appraisal modules based on the available computation time of the computer is presented. That approach allows the flexible management of trade-offs between "emotional quality" and computational load. This issue relates to another important aspect for autonomous robotics– the limited computational power of a robot's computer. In our current work, however, we focus on the electrical energy management alone.

4 The New Architecture

Figure Fig**. 1** depicts a high level schematic of the extension we applied to the WASABI architecture with physiology processes. The physiology module contains a simple energy system model which simulates the dynamics of energy production which is affected by charging and energy utilization of the robot actuators (i.e. regarding its movement). The physiology module monitors the energy level of the robot and uses that information to derive positive/negative impulses that are sent to the emotion module driving the emotion dynamics. The physiology module is also responsible for robot's movement and perception. The perception process constructs a description of the external and internal states which are evaluated and arousal impulses are generated (analogically to the emotion impulses in WASABI)

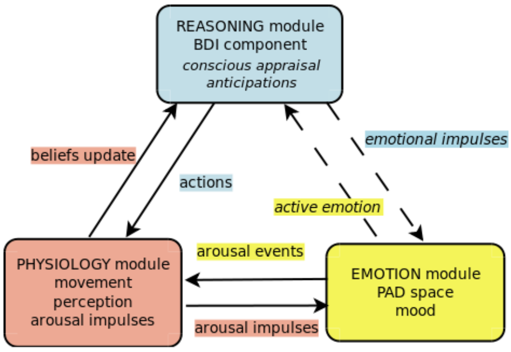

Fig. 1. Schema of the basic components of the new architecture

The reasoning module arbitrates which goal should be fulfilled at a given moment – working, refuelling or changing activity (finding fuel for example). That process (based on the BDI component of WASABI) is according to the current beliefs and the highest priority goal. Beliefs are generated from the physiology module which monitors environment and internal state. The links between the reasoning and the emotion module as well as the anticipation and conscious appraisal are inherited from WASABI but not used in the current implementation. In the next chapter some ideas how these components also could be grounded in homeostatic processes are explained.
The arousal impulses sent from the physiology module (Fig. 1) to the emotion module are based on an appraisal function which evaluates the robot state in respect to its energy balance and work importance. The arousal impulses are similar to WASABI's emotional impulses which are part of its unconscious appraisal (explained in the previous chapter). We use the label "arousal|" because we only use the arousal dimension of the PAD space in the current stage of development of the architecture. The process of generating arousal impulses represents the grounding of the arousal component of PAD space (in the emotion module) as a function of energy level and 'motivation' with respect to McFarland and Spier's cue x deficit model [12]. The function is as follows:

$$Arousal\ impulse = Energy * (Cue_{work} * Deficit_{work} + Cue_{fuel} * Deficit_{fuel}) \quad (1)$$

Thus, the robot arousal level increases only if one of the fuel and work resources is sensed (the cues) and if there is a certain deficit in some of them (e.g. the robot should urgently attend work) and the robot has a degree of usable energy. The arousal level when beyond a certain threshold triggers a disposition to an energy constrained behaviour change. There are two modes of behavioural actuation: slow movement, fast movement. The latter may be considered energy inefficient but provides a type of emergency measure, i.e. when 'work' is required to be carried out over a short period of time. Switching between the two behaviours is achieved by transmitting a message to the physiology module in the case when a certain threshold in the arousal level is passed (arousal events Fig. **1**). We can say that the robot is required to be both motivated and energized in order for the arousal level to have a strong dispositional effect. In this sense the higher level cognitive-emotional capabilities of the robot are grounded in motivational and energy autonomous capacities.

5 Tests and results

The particular scenario on which we are testing the integrated architecture used by a humanoid robot, e.g. a NAO robot, is a two-resource problem [12]. It is made as minimalist as possible so as to promote the apprehension of basic dynamic principles concerning the grounding of WASABI and the *behavioural stability* [27] of the robot. The robot resides in a room with two objects: a charger – place for recovering battery power – and a ‘work’ location. The robot should be able to maintain its energy level at such limits that it can continue to power its actuators (so as to be mobile). From another side it should show a certain work performance. For a pre-set time period the two resources provide a fixed value; after the pre-set time period, the work resource switches to “urgent” mode. This requires the robot to engage an emergency mechanism (arousal) so as to mobilize energy resources in order to deal with the demands of the task.

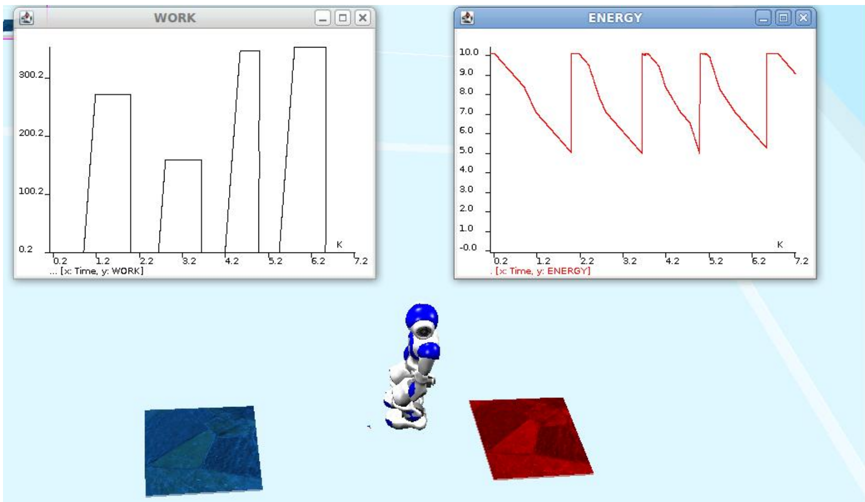

Fig. 2. A NAO robot in the two-resource test-bed scenario. The red square represents ‘charger’ and the blue square represents ‘work’ to which the robot is required to attend. Top left. Work performance dynamics are charted over time. Top right. The energy level history is charted. Both charts are updated at each simulation step all of which are printed on the abscissa in thousands (K).

The energy level dynamics is shown in figure Fig**. 2**. The moments of recharge and bursting activity can be observed. The work utility per time is shown in the figure too. A simple utility function is used to measure the work progress. The robot gains one work point for every unit of time when it stays at the work place. The work utility is reset to zero at the end of each cycle. This utility function gives a clear measure for a behavioral stability – the robot work level before the end of a cycle (recharging) should be in some predefined limits and in all cases be a positive value. In order to make the scenario non-trivial and closer to the service robotics' one we add a time limitation of going to work – work urgency level. Because of the abstract nature of the scenario the signal of the change of the work state is directly sent to the psychological module (without involving perception processes). The work urgency increases when the time for arriving at the work location decreases. In the current implementation the robot is not penalized in the case of not arriving at the work location on time. Dealing with such "failures" could be combined with some reinforcement learning mechanism which updates certain parameters of the model (like the threshold for switching from slow to fast movement) and this is planned to be achieved in future work.

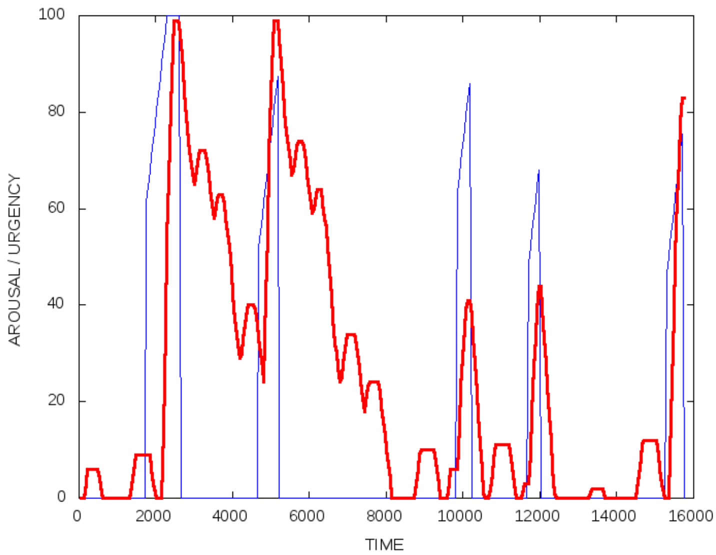

Fig. 3 Work urgency proportional to the time the robot should arrive at the work location (shown with thin line). Arousal level (shown with thick like)

In figure 3 the work urgency level and the robot arousal level are shown. The work urgency ($Deficit_{work}$) leads to a stronger arousal impulse (equation 1). This contributes to an increasing arousal. Notably, the robot arousal does not rise only when the work is urgent. This is because of other contributing factors, for example, a bigger distance to the goal location. In table 1 all contributing factors to arousal (the variables of the equation 1) for that particular scenario are summarized. In order to clearly observe the behaviour of the robot in the two conditions (with and without time limit of work), we made a set of tests in which the work is not urgent in half of the time of the run of the simulation, and urgent in the other half. Figure Fig**. 4** shows the level of the arousal during the run in that case. The values above the threshold are those when the robot switches from slow to fast movement. The robot loses energy for moving and working. The robot loses approximately 3 times more energy when it is moving fast compared to its slow movement. Random draining of energy between 1 and 2 times of the slow movement energy cost is set every time when the robot stays at the work resource.

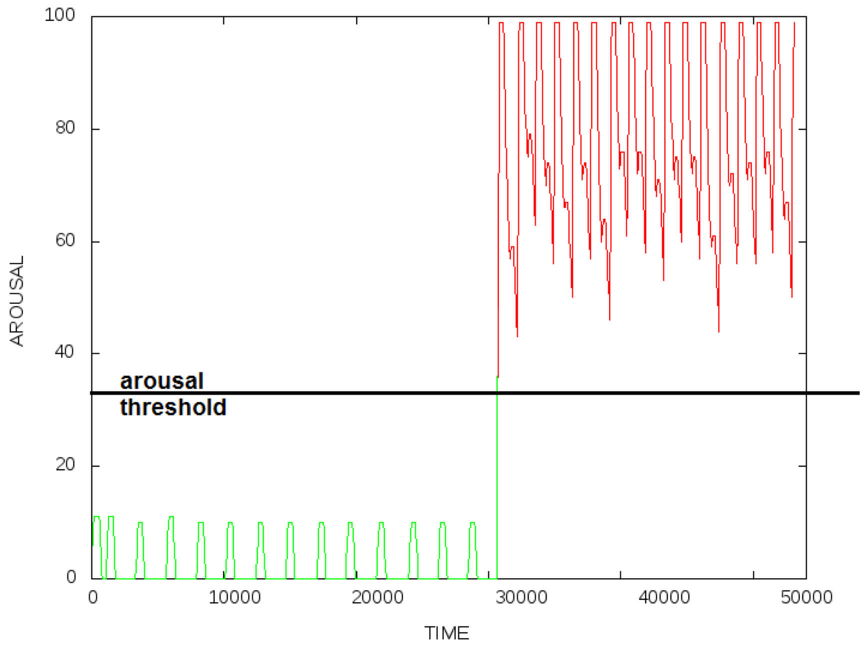

Fig. 4. Arousal level of the robot during the tests. Arousal threshold is the predefined value which triggers urgent movement. The time is measured in simulation steps. The work is “not urgent” until time step 3000, after that it is” urgent” all the time.

In Table 1 all contributing factors to arousal (the variables of the Equation 1) for that particular scenario are summarized.

Table 1. Basic components of the arousal impulse in respect to the current scenario

Cue_{work}	The distance between the robot and work (when the robot is facing towards it, otherwise =0)
$Deficit_{work}$	The work urgency level (between 0 and 1)
Cue_{fuel}	The distance between the robot and energy station (when the robot is facing towards it, otherwise =0)
$Deficit_{fuel}$	10 - battery energy level (10 is the maximum energy possible in the battery)
Energy	The battery remaining energy level

During the test run of the simulation NAO made 30 cycles between work and fuel. In the first half of them work urgency didn’t change and the robot’s arousal level was generally low. In the second half of the cycles work urgency was set to maximum. Figure Fig. **5** visualizes the robot's performance based on the main criteria-high work utility and energy efficiency. Energy dynamics during the run of the system is mapped to the work utility dynamics. It can be observed that in the periods where work is urgent the robot tends to spend less time at the work resource and consume more energy. That is because under time pressure the robot tends to move generally faster which decreases its energy consumption efficiency. According to[12] if we can show that dynamics of (energy, work) can produce sustainable cycles over time that is an indicator for behaviour stability. We will use that performance measure also in the future work when we will improve and extend the architecture and will try to show behaviour stability in longer runs and in more complex environments.

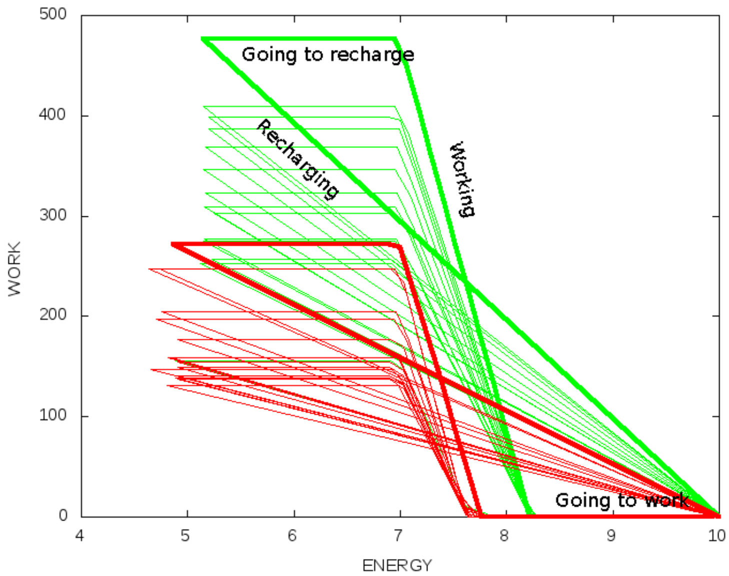

Fig. 5. Basic cycles of activity for the NAO robot according to the energy production dynamic on the x axis, and the work performance dynamic for a cycle on the y axis. The different stages of the robot behaviour are labelled on one of the cycles. The best cycles (based on work utility) in the two conditions are shown with ticker lines. The "relaxed" cycles are shown in green and the "urgency" ones are shown in red.

6 Further Incorporation of Plausible Metabolic-Energy Constraints

The architecture will be further developed in several directions. One such direction concerns the incorporation of mechanisms relevant to energy autonomy. A more biologically plausible and energy autonomous system is considered and some initial tests have been done. A microbial fuel cell (MFC) substitutes the normal electrical battery of the robot. MFC technology allows robots to convert fuel (biodegradable mass) into usable energy. The powering capabilities of MFCs are very limited given the present state of the art with the only existing robotics application being for a wheeled robot – 'Ecobot' [7]. Nevertheless, the technology is continually developing and the most recent version of Ecobot utilizes a serial connection of several MFCs powering multiple regulatory actuators. Moreover the evolution of MFC technology is tending towards miniaturization and future robots are projected to be able to include large numbers of them enabling high energy generation. We also consider a more efficient approach with specialized MFCs for the different parts of the body and mechanisms which will allow the resource/energy to be efficiently distributed among MFCs and motors according to optimization criteria for the current task. The MFC technology although isnot trying to replicate the exact metabolic processes in animals is closer to them than the regular electric battery powered system and as such could be used for comparing the architecture with experimental data and generate predictions.

Now the architecture uses a limited part of the emotional mechanisms of WASABI, mainly related to primary emotions and unconscious appraisal. In order to exploit conscious appraisal we will further extend our architecture with mechanisms to generate predictions for the energy changes. The appraisal part of the reasoning module will use that information to generate some positive/negative impulses to the emotion module and to trigger some prospect based emotions (hope or fear). That emotion will be processed and appropriate coping behaviour will be generated. The reasoning module will appraise the current state of the world to previously generated expectation in order to generate more prospect based emotions like (relief, fears-confirmed). Regarding further development of energy constraint mechanisms, in order to estimate in advance the energy costs for each movement a sufficiently accurate model of the body is necessary. This is a computationally expensive task and the existence of an internal model of actuator-energy costs may be considered biologically implausible. A more parsimonious approach is to measure the energy expense after each robot action. Then a simple approximation mechanism (like a feed forward neural network) can be used in order to store the experience and to approximate new situations. Energy cost expectation should be generated in the physiology module and sent to the reasoning module before executing each action. The Belief database will be updated with new beliefs like: expect (low_energy), expect (fuel_depletion), expect (fuel_recharge).

The significance of the architecture to autonomous robots applications is hard to be validated from the current test results. Another set of tests/experiments are being considered together with the architecture development. Experiments are planned which would show the efficiency of the proposed solution, comparing to more trivial solution for the same two resource problems. We hypothesize that the current emotion based architecture will overcome a simple rule based system in most of the situations. But similar to natural systems there could be some situations where the architecture will perform worse and a certain period of training will be needed to improve its performance

In the presented work emotional mechanisms as internal regulation only are explored. But in human robot-interaction (for example in service robotics) the robot could use its emotions to influence the human partner in a way that is intuitively understandable and readable to her or him. The expression of emotion can serve as an indicator of the robot's internal state (being busy and unavailable or available and attentive, for example) and thus improve the efficiency of the human-robot communication. A set of experiments are considered that may show the relevance of emotions to the human-robot interaction in different tasks. An example experiment would test two conditions – a robot expressing its internal emotion state (corresponding to the level of arousal) and a robot expressing its current intention in some other way (like starting to 'beep' when it is about to recharge) and measuring the efficiency of the communication in both cases. That measurement could be the score in a cooperative game involving a human and a robot.

7 Conclusion

In this paper, a way of grounding appraisal emotion model in metabolism-like processes is presented. This is performed by grounding the arousal component of the WASABI model into the energy processes of a simulated NAO robot. Several tests were performed in a minimalistic scenario for a two resource problem. The abstract test scenario was designed in order to help establish the key performance measures of the system's behavioural stability and to provide the foundation for its further development. The application of the approach for increasing robotic autonomy in service robotics tasks was discussed. The future extension of the model with a learning mechanism was considered as well as the grounding of other components of the WASABI model.

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