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Grounding Emotion Appraisal in Autonomous Humanoids

by

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Abstract

The work presented in this dissertation investigates the problem for resource management of autonomous robots. Acting under the constraint of limited resources is a necessity for every robot which should perform tasks independent of human control. Some of the most important variables and performance criteria for adaptive behavior under resource constraints are discussed. Concepts like autonomy, self-sufficiency, energy dynamics, work utility, effort of action, and optimal task selection are defined and analyzed as the emphasis is on the resource balance in interaction with a human. The primary resource for every robot is its energy. In addition to the regulation of its “energy homeostasis”, a robot should perform its designer’s tasks with the required level of efficiency. A service robot residing in a human centered environment should perform some social tasks like cleaning, helping elderly people or delivering goods. Maintaining a proper quality of work and, at the same time, not running out of energy represents a basic two-resource problem which was used as a test-bed scenario in the thesis. Safety is an important aspect of any human-robot interaction. Thus, a new three –resource problem (energy, work quality, safety) is presented and also used for the experimental investigations in the thesis.

The main contribution of the thesis is developing an affective cognitive architecture. The architecture uses top-down ethological models of action selection. The action selection mechanisms are nested into a model of human affect based on appraisal theory of emotion. The arousal component of the architecture is grounded into electrical energy processes in the robotic body and is modulating the effort of movement. The provided arousal mechanism has an important functional role for the adaptability of the robot in the proposed two- and three resource scenarios. These investigations are part of a more general goal of grounding high-level emotion substrates - Pleasure Arousal Dominance emotion space in homeostatic processes in humanoid robots. The development of the architecture took inspiration from several computation architectures of emotion in robotics, which are analyzed in the thesis.

Sustainability of the basic cycles of the essential variables of a robotic system is chosen as a basic performance measure for validating the emotion components of the architecture and the grounding process. Several experiments are performed with two humanoid robots – iCub and NAO showing the role of task selection mechanism and arousal component of the architecture for the robot’s self-sufficiency and adaptability.

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Preface

This thesis consists of six chapters which include an introduction and an overview of relevant research, and the following three articles:

- Paper I: Kiryazov, K., Lowe, R., Becker-Asano, C., & Ziemke, T. (2011). Modelling Embodied Appraisal in Humanoids: Grounding PAD space for Augmented Autonomy. In *Proceedings of the Workshop on Standards in Emotion Modeling*
- Paper II: Kiryazov, K., Lowe, R., Becker-Asano, C., & Randazzo, M. (2013). The Role of Arousal in Two-Resource Problem Tasks for Humanoid Service Robots. In *proceeding of: IEEE 22th Symposium of Human and Robot Interactive Communication*, Gyeongju, Korea
- Paper III: Kiryazov, K. & Lowe, R. (2013) The role of arousal in embodying the cueXdeficit model in multi-resource human-robot interaction. In *proceeding of: 12th European Conference on Artificial Life*, Taormina, Italy

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Chapter 1

Introduction

In recent decades research about emotional robots has grown in popularity in different areas of cognitive robotics (Cañamero, 2005). On the one hand, emotion is an important part of humans and animals, so robots, as modeling tools, should also incorporate emotion mechanisms. On the other hand, emotions have important adaptive roles in biological systems, for example: enabling top-down attention, providing reinforcement to the learning process, boosting relevant memory retrieval, triggering fast behavioral responses in urgent situations etc. (Breazeal & Brooks, 2004; S. C. Gadanho & Custódio, 2002), which could be useful for robots as well. From a functional point of view one of the main roles of animal's emotions is to provide adaptive goal selection mechanisms under different resource constraints (Breazeal & Brooks, 2004; D. Cañamero, 1998). Animals have to survive in complex hazardous environments under the constraints of limited resources like food, water, heat etc. Evolution has provided solutions to these high-dimensional problems with non-trivial complexity. These problems sometimes are similar to the ones - which autonomous robots face while dealing with complex tasks in unpredictable environments. Robots also have to act under the constraints of different resources such as energy and workload. Service robots should work in a human habitable environment and cooperate with humans. One of the main challenges of such robots is to achieve their tasks related to human satisfaction with high enough performance under the constraints arising from various resources. A basic resource constraint is electrical energy supply. The robot market has grown continuously in the last few years and so does the cost of the energy used by the robots. Thus the efficient management of electrical energy becomes a more and more important issue for robotics researchers. Moreover, the charging process takes a big part of the robot's lifetime so it should be done efficiently in the most suitable time related to robots' work and their owners behavior (Deshmukh, Vargas, Aylett, & Brown, 2010). In addition to determining the right time of switching between charging and working behavior, it is also a challenge to adopt the proper tradeoff between mechanical effort and energy efficiency. Safety is an important aspect in human-robot interaction, which needs to be taken more seriously into account as the service robotics market grows (Mandel, Huebner, Vierhuff, & Christian, 2005). Another crucial factor for resource management of robots is the fast and efficient interaction with humans. Emotion-expression is considered as a fast communication channel (Bar-On & Parker, 2000) which should be exploited by robots interacting with people (Breazeal & Brooks, 2004). The emotion state of the robot expressed in a believable way could induce similar states in a human (Hatfield, Cacioppo, & Rapson, 1994). Recognizing human emotions can also allow the robot to adapt its behavior regarding human emotion - useful heuristics for anticipating important events (Rani, Sarkar, Smith, & Kirby, 2004). The papers supporting this thesis present a cognitive architecture at different stages of development for managing limited resources for robots in

human inhabited environments. The presented architecture uses some bio-inspired task selection mechanisms, which are based on abstract ethological models (Sibly, 1975). The architecture treats physical constraints of the environment, social constraints and designer requirements in the same homeostasis regulation framework. In order to increase the efficiency of the animal strategies and make them more applicable to the service robotic world, where a robot should cooperate with humans, other bio-inspired mechanisms are used based on the appraisal theory of emotion. (Scherer, 1984).

The appraisal theory of emotion is widely used in cognitive robotics research (Lowe, Herrera, Morse, & Ziemke, 2007). The work in this thesis pays extra attention to the arousal component of the emotion architecture, its generation through appraisal processes and its role in modulating the behavior of robots. Arousal is an important phenomenon which is a central part of almost every theory of emotions. The state of arousal corresponds to some neural and psychological changes induced in an affective way, which are supposed to have an adaptive role for coping with the emotional event. One of the main roles of arousal is to prepare the body for coping with the emotional event (Gadanhó & Hallam, 2002). Maintaining a proper level of arousal is tightly coupled to the homeostatic balance of the living organisms and is of crucial importance for optimal performance in daily tasks. (Silver & Lesauter, 2008).

The minimalistic nature of the proposed architecture allows one to focus on the role of the coupling of the robot and the environment - its situatedness, embodiment and the emergent characteristic of the behavior of the robot. Moreover, it also makes the architecture computationally efficient, which is an important factor for the energy thrift. The architecture has top-down components which support representing and expressing high-level affective states. These states are grounded in bottom-up processes in the body of the robot in order to comply with recent research studies about emotion as hierarchically nested in different levels, where at the bottom is the metabolic process (Damasio, 2012).

Several experiments with humanoid robots were conducted in order to explicate the role of the affective components of the architecture in resolving the challenge of having to act efficiently under resource constraints whilst interacting with humans. More specifically, experiments with two humanoid robots- NAO and iCub revealed the role of the arousal component of the architecture in the above-mentioned problems.

The next section (2) begins with definitions of some of the basic concepts exploited in the thesis like "resource" and "autonomy". An overview of the main aspects of the problem of resource management for autonomous robots is provided. Special attention is given to resource managing whilst interacting with a human. A short summary of the major engineering approaches to handling the problems of resource management is provided. Section 3 gives an overview of the state of the art of robotic emotion architectures. A critical review of the most influential implementations is presented. Finally, a proposal for a new architecture for resource management is put forward. Section 4 is a short resume of the ideas for the grounding of top-down emotion components in the bodily processes of robots. Section 5 is a summary of the papers included in the thesis – the architecture developed, the experiments conducted and their results. Section 6 is an overview of the main contribution of this thesis. It also contains conclusive remarks and directions of future research towards a full PhD thesis completion.

Chapter 2 Managing limited resources of autonomous robots

2.1 Autonomy, homeostasis and self-sufficiency

In order to define the most important problems in the area of resource management, first of all the basic concepts like “resource” and “autonomy” and related concepts should be specified.

A robot interacting with humans and not controlled remotely should have a high degree of autonomy as it will face a challenge to produce efficient actions (in alliance with its designer requirements) in an unpredictable and dynamic environment. Autonomy is a concept which is hard to be defined succinctly in a general framework. However one possible way to define it is an independence of outside control (McFarland, 2008). Such a definition suggests to predefine the boundaries of the agent for which autonomy is concerned. In the robotic case, that usually is the robot’s controller or body (including controller). However, in some particular cases these boundaries can be moved further away and include the surrounding environment, for example the achievement of a certain task emerges from the coordination of swarms of robots (Ducatelle, Di Caro, Pinciroli, & Gambardella, 2011).

McFarland has defined three different types of autonomy: energy, motivational and mental (McFarland, 2008) corresponding to the following three different levels of independence:

- From an energy source
- From the choice of particular set of actions for performing a goal
- From the choice how a certain goal is achieved

The first level corresponds to “energy autonomy”. According to (Wawerla, 2010) “energy autonomy” should be distinguished from self-sufficiency. In his thesis Wawerla emphasizes the difference between the two concepts by giving the following definition of self-sufficiency

“self-sufficient agent, we mean an agent that satisfies its demand for all essential resources at every moment in time, over an extended period of time, in a given environment” (Wawerla, 2010)

Thus one arrives at the necessity for a definition of “resource”. In the same work it is stated that:

“Every agent can be described by a set of hidden or observable state variables that defines its situation in the world ... Such state variables can be blood oxygen, body fat, money etc.. Within this thesis, we define resources as items provided by the environment or other agents that satisfy a need for at least one of the state variables.” (Wawerla, 2010)

These *important state variables* will be referred to the thesis as “essential variables” in a way similar to (Lowe et al., 2010; McFarland & Spier, 1997). The definition of a resource of Wawerla makes one background assumption which is important to be clarified. It supposes having some knowledge about the interaction between environment and body

which allows to establish the pairing between certain actions related to a physical object in the environment and the change of certain essential variables of the robot. Generally, in order that such a pairing is there, it will require knowledge about the environment-body interaction. Usually authors, as in the current thesis, provide an ad-hoc solution for these problems by having in advance the pairing between certain essential variables and a representation of the corresponding object of the environment already predesigned. But it is important to be aware of that process which in the ideal case should emerge from the interaction between the robot and the environment.

The definition for a resource presented above is quite broad, including “intuitive” resources like an energy source (fuel) and some more “abstract” resources like work activity for example. The “items provided in the environment” do not necessarily need to take different locations in space as in most of the examples in (Wawerla, 2010) and similar research but it could happen that they are at the same space location while their gathering requires a different behavior. For example in (Radice & McInnes, 2003) a space satellite should balance trade-off between the resources temperature and energy, which is maintained by switching on and off a heater which increases the temperature but decreases the battery level. Such a broader framework allows handling resources related to another important essential variable for every physical object like its integrity.

In the same work of Wawerla - two types of resources “viable” and “dispensable” are specified concerning whether the lack of the resource is causing the “death” of the agent or it is just not “desirable” (Wawerla & Vaughan, 2008). The vital resources are easy to be defined however it is not clear what does desirable mean if it is not related to the agent’s survival. For the animal desirable could be “evolutionary fit”. However, the question what is a desirable resource for an artificial agent remains. McFarland in (McFarland & Spier, 1997) provides an interesting analogy between the evolutionary pressure in animals and the designer’s requirement for the robots:

“possible ultimate fitness function for autonomous agents may be based on satisfying the owner as opposed to simply surviving”

Such a framework where balancing the designer requirements is made analogical to the maintaining process of the internal agent’s homeostasis is useful because it provides minimalistic solutions to the complex challenges for the autonomous robots - to remain viable from one side and from another side to fulfill the designer requirements. This framework takes inspiration from the basic mechanisms of homeostasis and bioregulation which exist in all living systems. It aligns with the cybernetics tradition and the notion of ultra-stable system developed in (Ashby, 1960). Ashby defines ultrastability as the ability of an agent to find a stable state for its essential variables when disrupting changes in the environment occur. In the implementation of his ultrastable system inspired by biological notion of homeostasis Ashby used several feedback loops. In one loop, the organism “directly” interacts with the environment via sensorimotor feedback. Through another loop, a random behavior is generated induced by the deviation of the level of the essential variables from some set point. The agent’s behavior is adjusting the essential variables in a trial and error manner until equilibrium between the agent and the environment is achieved. Sensorimotor activity by the agent that leads to deviation from the ideal essential variable range may be considered analogous to pain in animals.

2.2 Energy autonomous robots

A physical robot or an animal will have absolutely no role in the world if it does not perform some actions. An action in the physical world requires some sort of mechanical

movement. Any movement requires energy. Thus energy level is the most important essential variable for every living organism or robot (Wawerla & Vaughan, 2009). Every energy autonomous robot should be able to gather and store energy and use it to perform desired actions. The energy storage/ consumption parameters (like storage limits) and internal dynamics are of crucial importance for the resource managing process. In the following section the existing power management systems and some of the basic properties of the energy system which are important for the energy autonomy are summarized.

In McFarland's study of robotic autonomy - (McFarland, 2008), "energy autonomy" is suggested as a basic requirement for the autonomy of robots. Robots which are connected to a power grid and cannot work unless connected are dependent on that particular energy source and as proposed by McFarland they are not energy autonomous. Jens Wawerla (2010) points out that *self-sufficient* is often replaced by *energy autonomous* probably because the energy is the most-studied resource in the research of resource management.

A robot's energy is not only spent for performing movements. The robot's processor also needs power correlated with the intensity of the performed computation. An experimental study shows that a Pioneer DX robot consumes 33-65% of its energy for powering its CPU (Deshmukh et al., 2010). However in the current thesis the research is focused on the relation between the movement properties and energy dynamics. Humanoid robots should consume much more energy for moving in space than a wheeled robot as Pioneer DX. For example just for a standing still posture a humanoid should empower its actuators as opposed to a wheeled robot which could just power-off and generally consumes less energy when it moves. Thus a proper power balanced movement for a humanoid robot should crucially relate to the overall energy expenditure.

2.3 The basic two-resource problem for autonomous robots

In the study of (McFarland & Spier, 1997), it is suggested that the basic two-resources which an autonomous robot should handle are energy and work activity. In (Lowe & Kiryazov, 2014) it is said:

"Generically, a two-resource problem consists of the need for the robot to cycle its behavior between two drive satisfying actions-relating to two resources. These resources may involve some notion of 'work', on the one hand, and some more or less complex form of 'refuelling', on the other hand."

Energy resources have natural dynamics depending on the specific energy storage system of the robot. In the most trivial case there is a fixed charger and for gathering energy the robot should find its location and move itself to it. Other types of robots like solar panel powered ones or Microbial Fuel Cell robot (Kelly, Holland, Scull, & McFarland, 1999) need more complex systems for localizing the resource in the environment.

The "work" resource is more abstract and it is dependent on the designer's requirements as mentioned in the previous section. For example a cleaning robot should complete cleaning of its designated area at certain times in order to say that it fulfills its designer requirements – so in a more abstract sense – 'stays viable'.

The main questions which are important for solving such kinds of two-resource problems are:

- What is the time to switch from refueling to working and vice versa (Wawerla & Vaughan, 2008)?
- Can we find the appropriate action set for the activities of gathering the resources (work and fuel)? For example can we find the path between the work and energy

station (Parker & Zbeda, 2007) or perform charging and docking (Deshmukh et al., 2010)?

- What is the most efficient way (corresponding to the two-resources expenditure) to perform each movement – in terms of speed, joint stiffness etc.?

This thesis mainly elaborates on the problems in the last topic in the list, which have not been exploited enough in the state of the art of resource management. A basic property of a certain movement which a robot performs is its speed. Higher speed leads to faster completion of the performing behavior thus a faster achievement of the designer requirements and gathering more of the work resource. On the other side, speed of the movement correlates with the homeostasis of energy. Moreover, higher speed usually provides more of a safety hazard. Safety in movement is an important designer requirement when the robot is required to interact with a human.

2.3.1 Energy consumption dynamics

Animals need to process energy in order to survive. Energy resource gathering and storage concern all the important life processes like movement, reproduction, growth, work. Mammals have a complex metabolic system in order to gather, store and use energy for their actions. Usually they are heterotrophs – use organic materials as a source of energy which are obtained by ingestion of other organisms (Klappenbach, 2013).

Robots have much simpler “metabolism” based on electric energy storage of some kind. In the table below the main energy maintaining systems available in research of autonomous robots are summarized.

Table 1 Types of "robotic metabolism"

Type of energy system	Example robotics system	Resource in the environment
Regular electric batteries	iCub (Sandini, Metta, & Vernon, 2007)	Electric charger
Solar energy system	Mars rover Opportunity (Edmondson et al., 2007)	Sun-light
Microbial fuel cell	Ecobot (Melhuish, Ieropoulos, Greenman, & Horsfield, 2006)	Organic matter, water
Bio-gas fuel convertor	EATR (Wikipedia, 2013)	Biomass or gas
Ocean thermal energy	SOLO-TREC (Buis, 2010)	Differences in water temperature
Ocean wave-energy	Liquid robotics (Smith, Das, Hine, Anderson, & Sukhatme, 2011)	Mechanical energy from ocean waves

From the above table, it could be concluded that it is easier to provide an energy system for the robot inhabiting the ocean. Maybe that is one of the reasons that life has originated in water – it is easier to have a metabolic system there.

A solar powered robot needs to find an appropriate place where there is enough sun to charge the robot's batteries. Even when the sun light is not occluded all the time, it still makes sense to track the sun moving across the sky to optimize energy gathering (Wettergreen et al., 2005).

Organic matter and water usually are easily accessible in places where humans reside. For that reason a MFC robot (although its current implementations are quite limited in abilities) could be considered as having the potential for the "highest" energy autonomy

from the list above in a human habitable environment. Of crucial importance for its energy systems dynamics is the charge/ recharge rate of its capacitor in relation to the availability of the fuel matter and water. An MFC powered robot will require both fuel and water to be self-sufficient through maintaining a viable charge /recharge rate of its capacitor. In this case a resource problem for maintaining its electrical energy could turn into a non-trivial two-resource problem as there are environments where both resources are depletable and have different locations (Lowe et al., 2010).

The main properties of an energy system corresponding to resource management problem are (Michaud & Audet, 2001):

- Storage capacity (upper and lower limit)
- Rate of energy gain when charging
- Rate of energy loss when performing different actions

If all the resources vital for the robot are located at different places, the robot should move between them in order to manage their balance. In the case of no obstacles the main decision which the robot should take while it is approaching a resource is the movement speed. The functional relation between the movement speed and the electrical energy consumption per certain distance can basically have two profiles the adoption of which depends on the position of the optimal speed for the lowest energy consumption in the space of all possible speeds (Figure 1).

Figure 1. The basic speed/energy consumption profiles: (A) energy optimal is the fastest movement (left). (B) Energy optimal is not the fastest movement (right) Min is the lowest possible speed of movement. Max is the highest possible speed. Opt is the optimal speed for lowest energy consumption.

Analogical distinction can be found in a study regarding horses' oxygen consumption in (Hoyt & Taylor, 1981). Different patterns of horses' gaits obtain an inverted u-shape relation between the running speed and oxygen consumption ("B" profile). Only the data from the fastest gait- gallop has the "A"-energy case. Although this data could be not be complete because of ethical concerns - the horses are not forced to run at a too high speed.

Industrial robot arms (Kolibal & Smetanová, 2010) have the "B" energy consumption profile too. It is obvious that even if a robot has the "B" profile it could still be reasonable that only certain speed limits are exploited for safety reasons so practically it could be put in the "A" category (if the Max speed is switched to a value lower than the Opt speed). Generally, such kind of categorization should include a third profile, in which the lowest possible speed is the optimal one. Such a profile however is unrealistic for humanoid robots which all the time should compensate for gravity and making very slow movements is energy inefficient.

In the first case (A) in order to gain benefits from the resources of both kinds (work, energy), the choice of an optimal speed is trivial, the robot should simply move at the highest possible speed. In the other case the choice of speed is a challenging optimization problem. So in the basic two-resource problem, a crucial factor is to have an adaptive strategy depending of the current available type of energy consumption dynamics, which chooses the proper speed of movement. Even in the A-case however the resource problem is not trivial when safety is concerned as it could be seen below.

2.3.2 Work utility

Evaluating work performance is generally a high level task that requires the robot's designer's decisions. In (McFarland & Spier, 1997) three different classes of work utility functions were specified depending on how one evaluates different stages of the robot's behavior when it is not working i.e. it may be either neutral (0) or negative (-).

Table 2 Basic work utility types (adapted from (McFarland & Spier, 1997), page 2)

	Work	Find fuel	Refuel
Utility type I	+	-	-
Utility type II	+	0	-
Utility type III	+	-	0

Maybe one could consider the above table as incomplete as it does not assign any utility to the obvious fourth behavior "going to work". Of course not all types of environments will allow the robot to start working immediately after refueling as working, similar to finding the charging place could require moving to a certain place first where work needs to be performed. For example in studies of two-resource problems (Wawerla & Vaughan, 2008) and (Avila-García & Cañamero, 2004) this aforementioned behavior is separately studied. In the robot ecosystem (McFarland & Spier, 1997) robots should knock lamps in order to work but "go-to" work will obviously require energy and time to move to the lamps. However, the reasonable utility value in this "going to work" behavior could be the same as in the "going to fuel" behavior (neutral or negative).

Assigning negative utility to certain behaviors would prevent an unconstrained increasing of the work resource which is an implicit necessity if we need the resource to have a depleting dynamics suitable for the homeostatic framework described above. As we have seen before, maintaining homeostasis presupposes that all the resources could be depleted at a certain moment. On the other side, this would allow to obtain analogy to an animal and work can be also mapped to some of the animal's vital resources like food or mating. Of course, such a constraint is not obviously required from the designer's perspective of a general performance measure of the work of the robots. In the architecture developed in this thesis, an attempt is made to have a work utility function which succeeds in naturally representing a reasonable requirement for robot performance and from another side has such "depleting" continuous dynamics (see Paper II). This work utility has dynamics of the type I (from Table 2) which however is not provided ad-hoc (explicitly set an abstract value to the different robot behaviors.) but emerges from a natural evaluation of the performance of the robot and its interaction with the environment.

Work utility classification in Table 2 doesn't explicitly consider the time when the work is performed. In (Wawerla & Vaughan, 2008) arguments are provided that timing of work is of crucial importance. As he states "*work that the robot performs now is always more valuable than the same amount of work performed later*". In that research for a two-

resource problem he assigns a discount factor of work utility which is increasing with time. In the architecture provided in this thesis, there is no explicitly set discount factor. However, one could consider that discounting of the work emerges from the dynamics of the work utility and the robot- environment interaction.

2.4 Basic cycles and behavioral stability

An energy autonomous robot doesn't have an unlimited power supply, which means that its energy level will have cyclical dynamics over time modulated by the charging/discharging activities, naturally constrained with an upper and lower limit determined from the energy storage system properties. Generally speaking, because of the physical constraints for any material objects, the dynamics of any physical resource will have upper and lower limits. In the study by Wawerla (2010), it is pointed out that removing the upper limits in a robot inhabiting a virtual world could significantly simplify the problem of task selection. As mentioned in the previous section, work utility could also have similar properties if defined properly. A robot maintaining homeostasis by managing its resources will have a behavior with cyclical properties. As claimed in the study (Hallam & Hayes, 1992) - *"Cyclic behavior occurs automatically in robots with rechargeable batteries."*

If all the resources which a robot should handle have limited and continuous properties, trajectory (of the essential variable) of such a robot will be cyclical in the space of the essential variables corresponding to the resources. This trajectory provides an intuitive way of selecting a goal for the robot's controller - the robot should not go into irrecoverable deficit in any of the state variables (McFarland & Bösner, 1993). In the case the trajectory goes too close to the lethal boundaries (planes defined from the extreme levels of essential variables, which leads to the death of the robot or to an unacceptable behavior from the designer's point of view) that is an indicator for unstable behavior and vice versa. McFarland proposed a basic measure of behavioral stability - the robot should produce sustainable behavioral cycles for a sufficient amount of time. Reasonable is the question of how long "sustainable" should be. McFarland doesn't give an answer, it is obvious that this relates to the complexity of the environment where the two- resource problem should be solved. If the complexity of the environment is hard to assess in advance, it also makes it more complicated to evaluate the required number of cycles for estimating if a certain behavior is stable or not. As seen in the previous section McFarland identified the following three main parts of the basic cycle - "work", "search for fuel" and "refuel". If we plot the dynamics of the state space of the two resources one basic cycle will have the following profile (Figure 2 - left).

Figure 2. (left) Stages of basic cycles of energy autonomous robots. Adapted from (McFarland & Spier, 1997); (right) Extended version of the basic cycles for energy autonomous robots

If we include the forth obvious behavior – “going to work” mentioned in the previous section the basic cycles takes the form in Figure 2 (right).

In his “Work-Refuel” model (Wawerla, 2010) identify the same four stages (two stages “work”, “refuel” and two for the transitions between them). Analogical four different stages with the similar dynamical relations are observed in the work by Avila-García and Cañamero (2004) regarding the two-resource problem where however the resources are heat and food. In the same paper two different types of behaviors are defined corresponding to the four stages – two consumatory and two appetitive. Consumatory behaviors are related to gathering the resources, appetitive - approaching them.

In a lot of scenarios like the ones used in this thesis, it could happen that two types of behavior are naturally combined and it is reasonable only appetitive behaviors should be included in the task selection mechanism. For example a cleaning robot - the robot recharging could start almost immediately after it has arrived at the target location if the charging station and robot have the correct properties.

Monitoring the state space dynamics could be useful to find important properties of the behavior of the robot like for example opportunism and over-opportunism (which are beneficial or harmful for the robot viability and efficiency) (Avila-García & Cañamero, 2004) and are important criteria for the robot’s motivational autonomy (McFarland, 2008).

2.5 Multi-agent two-resource problem

When an animal should maintain behavior stability under resource constraints there are usually competitors – other animals which desire to consume the same resource. That significantly increases the complexity of the problem as the animal should additionally choose if it should avoid a certain resource because it is already “occupied” by another animal or decide to fight and push the competitor off the resource. In the study (Avila-García & Cañamero, 2004) two-resource competitive robot experiments are showing the extra challenges which occurs when there is a competition compared to a non-competitive scenario.

However, in most of the practical robotic scenarios, such type of “aggressive” competition is usually not so likely to happen. Few exceptions are related to different robotic games which are made for a performance benchmark (Michel & Rohrer, 2008) for different intelligent architectures. Most of the practical examples would consider cooperation between the robots instead of competition. However even when cooperative,

having another agent in the environment, the complexity of the problem of resource management increases because the robot should additionally (Novitzky et al., 2012):

- recognize the other agent- find its location in the environment and its current action
- recognize the status and intention of the robot (what is its current resource deficit and the chosen action)
- express its intention in a meaningful way to the other agent
- perform an action in a way considering its effect on the other agent

It could be argued that the first three points could be easily solved in the case when all the agents are robots as we could have a centralized controller - one architecture to control all the robots. That is however not entirely true because wireless communication could be a main source of energy consumption and make the robot more expensive and complex (Hoff, 2011). It could be more efficient if every robot had the same local resource management strategies. On the other side, any centralized approach has its drawbacks as for example fault intolerance. Moreover, all these three problems are not trivial in the case when the other agent is a human.

Having multiple robots which should efficiently manage co-operation recharging activities provides an interesting social solution to the resource management problem. For example (Zebrowsk & Vaughan, 2005) a robotic simulation was performed where one specialized robot – tanker moves in the environments and searches for robots which need to be recharged. Some authors develop robot teams where the robots could exchange power between each other by physically exchanging batteries or just transfer a certain amount of their battery power (Ngo & Schioler, 2006).

2.6 Resource management and human-robot interaction

When an autonomous robot is situated in a human habitable environment and the task is supposed to be performed in cooperation with humans, the challenges described for the multi-agent resource management have some specific properties. The robot should detect the human's body position at any time (in order to avoid collisions for example). It should meaningfully interpret the social signals (verbal and nonverbal) and act accordingly (Bicho, Louro, & Erlhagen, 2010). For that reason the robot should first be able to recognize the human internal state (e.g. the human is tired and the robot should slow down and/or spend more energy on anticipating possible failures if the human is anxious – an eventual signal for anticipated danger (Rani et al., 2004). On the other side, the robot should express its internal state (for example express anxiety if it is not able to respond to high work deficit – so the human is aware that the robot probably needs help). Humans are able to process and exchange information via different social signals. One very time efficient way to exchange information is by expressing/ interpreting emotion state (Bar-On & Parker, 2000; Breazeal & Brooks, 2004)

One crucial aspect in any human-robot interaction is safety (Kuli , 2006). To maintain safety as it was mentioned above the robot should sometimes “sacrifice” fast task accomplishment and correspondingly decrease the level of the work resource. Acting in a safe manner could be considered as another “abstract” resource (with a separate essential variable corresponding to the amount of the safety hazard). Thus the basic challenge for a robot interacting with a human could be a three – resource (energy, work, safety) problem.

2.7 More than two-resource problem

McFarland has suggested that the two-resource problem is a basic problem in resource management and the one-resource problem is trivial. In (Wawerla, 2010) however non-trivial variants of one resource problems are presented. It is pointed out that even if there is only one essential resource in the environment for the robot, there could be several different behaviors to gather it (for example there are two chargers and the robot should choose which one is more suitable in a particular moment) so it makes the resources problem again non-trivial. Actually even the two-resource problem scenarios developed in (McFarland & Spier, 1997) could be considered as one-resource where the only resource is energy - and “working” (knocking on lamps) could be seen again as high order charging behavior because this is the only way that the robot can “buy” energy with its work points later .

It is interesting to show how the resource management challenges scale up when the essential resources are more than two. In (Spier & McFarland, 1997) it is claimed that adding a third resource doesn’t increase considerably the complexity of the problem as task selection mechanisms could consider at any time the choice between one of the resources and a bundle of the rest. However as seen in previous sections, not only is the resource selection important, but the specific properties of the robot’s behavior used for the resource gathering could influence the energy consumption dynamics and therefore substantially influence the resource management, which could make three- resource problems interesting to study as well.

In addition to energy, another obvious resource which an autonomous robot should handle is internal heat (too much power could lead to better performance but at the same time could lead to overheating which could be damaging for the robot (Ma, 1999). In (Radice & McInnes, 2003) in addition to the basic two-resources (energy and work) the robot should balance its internal heat. Safety is a basic work performance requirement when the robot is interacting with a human and could be considered as a third resource as mentioned above.

2.8 Safety and the three resource problem

Safety is one of the major aspects of human-robot interaction (Kuli , 2006). The robot interacting with a human should always maintain some safety demands in addition to its basic performance requirements - its primary working task. In the proposed two –resource framework, safety could be considered as a part of the work utility (general designer requirements) and still one has to solve a two-resource problem. However, as it was considered before safety could be a separate third resource because it usually requires an opposite modulation of the movement effort compared to working. Higher speed and joint stiffness usually lead to faster and more accurate task achievement but increase the safety hazard. We can say that in a some abstract space safety and work are separate resources having different locations.

Speed of the robot is a major factor for calculating the eventual collision strength with humans (Kuli , 2006). Other factors of the more general concept of effort of movement like joint stiffness are also important for safety. Therefore effort and safety are tightly connected.

In order to exploit the role of the effort (and more specifically movement speed) to the so proposed three resource problem, one of the most important factors is the type of “energy metabolism” which the robot has. In Figure 3 with “+” resources which benefit

from the same change of speed (acceleration / deceleration) are connected, and with “-“ the links between the resources, which require the opposite “speed behavior” are marked.

Figure 3. The role of movement speed for defining optimization tradeoffs for the three resource problem (in both cases of energy metabolism – “A” and “B”)

The change of the speed (effort) for “gathering” safety could be done in different ways. Usually when a safety hazard is detected an industrial robot completely stops. This solution is also used for gathering safety in Paper III. Another more flexible solution which could be suitable for “soft” robots is just to slow down or decrease joint stiffness when safety should “be gathered”.

2.9 Resource management solutions

As it was shown, one of the basic problems for resource management is the appropriate action selection. The good old fashioned AI strategies of action selection are based mostly on some sort of planning algorithms. Planning usually supposes having a model of the environment (complete knowledge of how the actions of the robot reflect the change in the state of the world). If such a model is available, one can use planning strategies like A*, D* (Johansson & Balkenius, 2006; Wettergreen et al., 2005). The benefits from using such algorithms are obvious – there is usually a guaranteed optimal solution. Among the drawbacks, it also holds that the complete knowledge of the environment is very hard to obtain and even if it is available, it usually contains errors. So such approaches are not robust to noise and unpredicted events.

At the other extreme of planning algorithms there are reactive algorithms, which rely only on the current sensor data to take a specific action. The classical example is Braitenberg vehicles (Braitenberg, 1986). Reactive algorithms are computationally very simple and don’t require models of the environments. But of course their behavior could be very limited as the robot doesn’t keep track of past experience and doesn’t have a representations of its goals - future desirable states. It is interesting whether a purely reactive architecture can solve a resource management problem as a resource deficit usually reflects some internal state of the robot. However, as mentioned before having internal states is not always necessary in order to provide some solution for the resource balance problem. For example in (McFarland & Spier, 1997) it has been observed that a very simple purely reactive algorithm (using only external cues from the environment) for action selection gives very close performance to the “winner” - the cue-deficit strategy of action selection in most of the environments.

If the sensing of the resources like for example battery level is considered as external to the robot there are a few examples of such reactive architectures for two-resources problems (Jung, Nies, & Sukhatme, 2002). The subsumption architecture of Brooks

(Brooks, 1985) is a classical application of a reactive architecture tested in a real world problem in complex unpredictable environments (Toal, Flanagan, Jones, & Strunz, 1996). There are a lot of attempts to combine the strengths of both previously shown extremes – reactive and planning - trying to avoid their drawbacks and building hybrid systems (Arkin & Mackenzie, 1994).

Another way to solve non-trivial tasks like resource balance is to use black box strategies as artificial evolution (Parker & Zbeda, 2007). The advantages of evolutionary algorithms are obviously in the cases when they succeed to find suboptimal solutions in the absence of designer intervention. Among the drawbacks, there is the long time to finish, which generally requires experiments in a simulator rather than in the real world and of course there is no guarantee for finding a solution. Wawerla, (2010) considers artificial evolution as not the best solution for resource management for several reasons as for example once evolved and transferred to the real robot, the algorithm is not changing any more so that it makes it rigid to unpredicted changes of the environment.

In addition to “engineering” solutions like the one mentioned here, a big part of the state of the art exploits architectures taking inspiration from affective mechanisms in biological systems.

Chapter 3 Emotion architectures in robots

Usually the reason to develop an emotion robotic architecture is two-fold: to provide an experimental demonstration of the principles of an emotion theory, or to exploit the functional role of emotion in animals and humans in order to develop emotion-inspired mechanism for improving the robot's behavior. In order to say that a robotic architecture is an emotion architecture it should be based on one or more emotion theories. Some of the most famous theories of emotion are:

- Behavioral theories (Watson & Morgan, 1917)
- Somatic feeling theory (Cannon, 1927)
- Processing mode theory (Oatley & Johnson-laird, 1987)
- Somatic theory (Damasio, 2003),
- Cognitive appraisal theory (Lazarus, 1994)
- Embodied appraisal theory (Prinz, 2006)

In order to differentiate the functional roles of the emotions inspired mechanism in achieving the robot's tasks one could use the following (Cañamero, 2005; Thill & Lowe, 2012) :

- Homeostatic behavior under different resource constraints
- Plan evaluation and plan switching
- Saliency in perception
- Reinforcement (value – system)
- Interrupting ongoing behavior in case of unexpected change in the situation
- Managing social behavior and communications

Yet another way classifying the emotion robotic architectures is to differentiate the specific implementation methodologies which are used:

- Rule-based systems
- Reinforcement learning
- Neural networks
- Evolutionary algorithms
- Agent based solutions (society of mind)

Of course the categorization criteria mentioned above are not exclusive - there could be an architecture inspired by several emotion theories, implementing various functional roles of emotion and using multiple modeling methodologies. This is why in this thesis there is no focus on specific theories, functional roles or modelling techniques in order to describe the state of the art. Instead, a critical review of some existing emotion architectures which have an implication to the developed emotion architecture in the thesis is provided.

3.1 Grounding motivation in energy autonomy

In (Lowe et al., 2010) a bottom-up architecture for providing a Microbial Fuel Cell (MFC) powered wheeled robot with energy and motivational autonomy was presented. The

architecture was tested in a two-resource problem scenario where the resources were food and water corresponding to the MFC mechanism's essential variables. The architecture doesn't explicitly encode any knowledge about the resources in the environment - the pairing between the related objects and the corresponding metabolic processes is in the robot's body (which was discussed in section 2). The bio-inspired architecture contains an active vision component connected to the MFC module via an adaptation of a gas-net network. This network is an artificial neural network, where some of the nodes (in this particular case connected to the essential variables) emit gas which continuously modulate the activity of the neighboring nodes. The architecture uses an evolutionary algorithm to tune its parameters in a way to allow the robots to solve the two resource problem. The evolutionary algorithm evolved not only the weights of the network but also its topology (number of nodes). The robot in this case can be considered to have energy and motivation autonomy (see section 2.1). The gas-net network represents some sort of bottom-up cue-deficit algorithm as it provides motivation for choosing the "correct" resource based on internal deficit and environmental cues. The gas-net component could be seen as means of grounding high-level cognitive states (active vision) into metabolism processes provided by the Microbial Fuel Cell dynamics. The results of the experiment reveal some interesting findings about the usefulness of grounding the motivational states in the robotic metabolism in order to increase the robot's adaptivity in the two-resource scenario. For example, that a higher metabolic constraint on the evolved solution could lead to better robot performance.

3.2 Emotion driven learning

In (Gadanhó & Custódio, 2002; Gadanhó, 2003) a robot architecture is presented which finds proper coordination of several hand-coded behaviors in order to increase the viability of a robot in real world scenarios. A reinforcement learning subsystem is connected to a "goal" system which provides reinforcements to the learning process by managing a set of homeostatic variables (the essential variables for the robot). The "emotion add-on" (goal subsystem) is inspired by the Damasio hypothesis about emotion as a general homeostasis balance system. Similar to the work in the current thesis, the homeostasis variables have continuous dynamics based on the deficits of the different important resources, which correspond to a set of regulating behaviors. A combination of perceptual values and internal signals are used to compute the single emotion state which is similar to the appraisal process and emotion representation in the architecture provided in the thesis. The robot should not run out of energy while searching for chargers and should avoid obstacles. We could say that the architecture solves again a two-resource problem where one of the resources is the energy and the other is the robot's welfare. The second one corresponds to the body integrity mentioned in the previous section, which level is decreasing in the case of events which harm the robot like crashes into the obstacles. Using reinforcement learning, a robot's controller can adapt through its life time to the environment while searching for a solution to a problem. Reinforcement learning could be seen as a tradeoff between supervised learning algorithms where a designer should provide an error signal for every action of the robot and unsupervised learning when there isn't any error signal at all. In reinforcement learning, this signal is provided at specific states of the world. One of the biggest drawbacks of the reinforcement learning algorithms is that the definition of appropriate reward is not a trivial problem itself (similar to defining the fitness function in an evolutionary algorithm). However, multi-resource scenarios could provide a good framework for the reinforcement learning approach as the reward could be naturally defined and assigned to the states where the robot is consuming a resource and a

punishment when it goes close to a lethal limit of some of its essential variables. Another challenge for reinforcement learning is when to trigger state transitions. In the presented architecture, the emotion component is used to trigger such transitions when the emotion intensity is surpassing a certain threshold. In these studies of Gadanho, it is empirically shown that the emotion “add-ons” to the reinforcement learning subsystem increases the adaptivity of the robot (according to several indicators like time to accomplish the learning process).

3.3 Hormonal modulation of action selection

In (Cañamero, 1997) a hormonal-like mechanism is used to modulate an ethologically inspired action selection architecture in order to improve the robot’s viability when environmental challenges increase - having another robot competing for the same resources. The action selection mechanism is a variant of a cue-deficit model. The cue-deficit model is a top-down ethological model which takes inspiration from optimal foraging theory assuming that animals are tuned evolutionarily to solve optimally foraging problems maximizing energy intake per time. The model is computationally simple but at the same time it provides a solution to complex resource management tasks. The motivation for selecting a behavior for gathering a certain resource is based on two basic variables: cue and deficit, corresponding to the strength of the external stimuli from the perception of the resource and internal deficit of it (deviation of the values of the essential variables from its ideal range corresponding to the resource). In its original form the agent with a cue-deficit model of action selecting should not search for a resource if its cue is zero – it is not visible from the agent, regardless how high is its deficit. That is considered a significant drawback by the authors in this study who modify the cue-deficit rule adding more weight to the deficit so the agent still searches for it even it is not visible. Another modification of the cue-deficit strategy is that cue value is varied from the hormonal module providing some sort of saliency mechanism.

Cue – deficit strategies could be considered a particular implementation of a more general *drk* strategy of action selection (Spier & McFarland, 1996). Instead of the simple cue representing the external signal from the environment of the resources detected by the agent—extra parameters providing information of the ease of gathering of the resource can be used – availability and accessibility, which basically represents the concentration of the resource in the environment and the speed of gathering when it is accessed. The *drk* model has been applied in energy autonomous robots who search and eat slugs in order to maintain their energy (Kelly et al., 1999).

In the work of Cañamero several useful for the resource management emergent properties of the robot’s behavior were found like opportunism and persistence. It is empirically demonstrated that the hormonal modulation crucially improves the action selection mechanism in order to tackle the new challenges in the environment. In the presented architecture in the thesis is also used a cue-deficit strategy. An arousal mechanism similar to the hormonal one presented here modulates the action selection for handling extra environmental challenges such as urgent situations in interaction with humans.

3.4 Socially constrained power management

If a robot has the ability of representing and expressing human-like emotions this could be very useful for service robots interacting with humans as it was shown in Section 2. Enabling robots to have the ability to express human-like emotions could lead to anthropomorphism. However it should be pointed out that a robot which is able to recognize or express emotions doesn't necessarily have emotions, i.e. the underlying mechanisms analogical to those found in humans. (Thill & Lowe, 2012).

In (Deshmukh et al., 2010) a top down model of emotion based on appraisal theory is used for balancing a robot's energy needs and its social tasks. The top-down components of the model allows the robot to easily express explicitly its current state and plans to a human in an understandable way (i.e. verbally). The social demands are viewed as a constraint of the homeostatic behavior of the robot which is similar to the idea presented in this thesis- to treat the social and energy demands as equivalent. The architecture is implemented in a wheeled robot with a display of human facial expression in a social helper scenario. However there are no comparative results to show the role of the emotion components in resources balancing or experiments providing evidence that the robot could have long- term behavioral stability.

3.5 Affective interaction between humans and robots

Breazeal (Breazeal & Brooks, 2004; Breazeal, 2004) presents an affective cognitive architecture implemented in a robotic head in a human-robot interaction scenario. The architecture takes inspiration from ethology that the basic motivational forces should be the "drives" which satisfy certain essential needs of the organism. Instead of having animal's drives related to hunger, thirst etc, the robotic architecture has analogous drives for social contacts, playing, boredom and fatigue. The drives subsystem is connected to another emotion component based on appraisal theory which modulates the emotion state in Pleasure Arousal Dominance space (PAD). An emotion state is a single point in 3 dimensions, which moves continuously driven from the appraisal process. Similarly, in the architecture developed in this thesis, the emotion dynamic component is used to modulate a single emotion's state in the PAD space from an appraisal module. The use of dimensional models, such as PAD, is reasonable for human-robot interaction scenarios as they reduce high dimensional space into discrete emotion categories which can be easily mapped to some believable emotion expressive behaviors. These expressive behaviors are signals to a human who can adapt its actions according to the robot's needs thus regulating the robot's homeostatic balance. In addition to reflecting expressive behavior (facial expression or body posture) this emotion's state biases the cognitive system in various ways by focusing attention, prioritizing goals, etc. The architecture is agent based, having specialized agents for drives, emotions, behaviors etc. Regardless of their specialization, the units are connected in a network seeding valenced activation and symbolic messages.

It is interesting to see how a single emotion architecture could combine ideas from a number of emotion theories but this approach can also turn out to be too eclectic and complex. The robot's behavior looks natural and believable and several experiments are performed to evaluate how engaging the robot is in the interaction with humans. However there are not experiments validating the role of the robot's emotion components in its long term sustainability.

3.6 Summary

As we can see from the examples given above, most of the architectures which address sub-emotion levels and bottom-up mechanisms provide flexible biologically plausible solutions of the resource problem but it's hard to see how these architectures scale up to present human-like affective mechanisms. It is not clear how the bottom-up architectures are scalable to be implemented in more complex robots such as humanoids which have to interact with humans. Moreover, the top-down architectures don't provide appropriate criteria or experimental evidence for long term self sufficiency in the resource management tasks. In this thesis, an attempt is made to bring both approaches together by grounding top-down emotion models in the body processes of humanoid robots.

Chapter 4 Grounding of top-down models of emotions in homeostatic processes

In order to provide a robot with a model of animal's affective mechanisms a proper analogy between an animal's and a robot's world should be made. For example, such an analogy could concern the resource management. Animals should deal with resources like food, water and mating, where the robot has to balance its electrical energy, work efficiency, and safety when a human is nearby. In (Wawerla & Vaughan, 2008) is stated that animal and robot worlds are quite different because:

“The rational robot and its owner are interested in gaining maximum reward by working at the robot's task, and are indifferent to the lifespan of the robot. This is a key difference between the purpose of robots and animals.”

However, as it was shown in the previous two sections, both worlds could be connected using an appropriate mapping. This mapping - based on structural correspondence - will be to a certain extent “disembodied”, as it will connect systems with different body/environment properties. As a result of the mapping it is possible to transfer some affective mechanisms. In order to enrich these transferred mechanisms and in order to be able to exploit better the specific body/environmental properties, these affective mechanisms should be tightly coupled with the particular sensory/motor components of the robotic body. One way to provide such coupling is to ground the top-down models into specific properties of the robot's body (e.g. energy level dynamics).

Using top-down cognitive models in robots was found to be beneficial because it allows high-level cognitive mechanisms to be incorporated in the models. Such mechanisms could be useful for making a meaningful and efficient human-robot interaction. Such high-level mechanisms are quite hard to be generated via bottom-up algorithms like evolutionary algorithms.

“...emergence of higher level psychological/cognitive competences are not easily amenable to minimalist evolutionary robotics approach. After all, it took biological evolution several billion years to go from single eukaryotic cells, with all their surprising complexity, to multi-cellular organisms with nervous systems and neo-cortical processes.” (Lowe & Kiryazov, 2014).

From another side, it was shown that using ethological top-down models in resource management tasks provides simple, computationally cheap algorithms for behavioral switching.

Grounding of top-down models in bottom-up mechanisms provides a two-way dynamics which will decrease the designer's control and potentially give the robot more autonomy, which could lead to increasing efficiency in uncertain and non-deterministic environments (Lowe & Kiryazov, 2014).

According to Damasio (2003) emotions are grounded according to a homeostasis nesting principle. At the bottom level are metabolic processes, pain –pleasure behaviors etc. At the top-most level are high-level emotions and feelings (Damasio, 2003). One way of following

Damasio's perspective is to ground affective states of top-down emotion models (top-level) in sensory-motor capabilities (bottom-up level).

Appraisal theory is dominant among emotion theories. Generally, an appraisal process consists of an heuristic evaluation, which processes the state of the world according to some internal needs or goals of the organism. According to cognitive appraisal theories, the detected changes in the inner or outer conditions are judged according to cognitive states as intentions, beliefs and generate some internal “emotional” state. As a response, the emotion system changes the behavior disposition or internal state and in this way adapts to the appraised situation. Different authors consider the importance of the body in the appraisal (Prinz, 2006; Klaus Scherer, 2009).

“Moreover, the body does not play a merely passive role in affective computing - it is not simply an output device triggered by a ‘feed-forward’ cognitive appraisal. Rather, the body itself influences how real, or imagined, environmental stimuli are perceived and evaluated. The body orients, physiologically ‘prepares’ and acts dynamically in relation to its external environment.” (Lowe & Kiryazov, 2014).

In Prinz’s theory of embodied appraisal (Prinz, 2006) emotion is a perception of bodily changes which represent certain relations between the individual and the world. *“Emotion represents changes in organism-environment relations by tracking changes in the body”*. Different emotions correspond to different body state prototypes, which are patterns of specific bodily features like skin conductance value. In this way, a change in a bodily state could be caused by a cognitive judgment (as mentioned above) or could be directly linked to perception.

All this provides one of the reasons for developing the emotion architecture presented in the thesis, which is to ground affective states in the sensory-motor states of the humanoid robot’s body. More specifically, the goal is to ground higher level emotion components - the PAD dimensional model. Grounding of the three components of emotions postulated in the PAD model (pleasure, arousal, and dominance) is a challenging task that has not been explored so far. The main focus in the current work is on grounding of the Arousal function and it is achieved by constraining it to the energy consumption of the robot. Planned future work about grounding of the other dimensions – Pleasure and Dominance - can be found in the last section of the thesis.

Chapter 5 Summary of the articles

In Paper I, an analysis of the most important variables and performance criteria relevant to resource management in service robotics applications is performed. Specific attention is paid to the importance of finding proper effort of movement in the two-resource problem and energy autonomous robots. An overview of the appraisal theory of emotion is provided, with an emphasis on the role of the body in the appraisal process and grounding of emotion abilities in homeostatic processes. In Paper I is presented an affective cognitive model – WASABI (Becker-Asano, 2008), based on appraisal theory of emotion with proven psychologically plausible emotion expressions in several implementations in virtual agents and robots. Paper I presents the first version of the affective cognitive architecture based on WASABI for solving two-resource problems in a framework for service robots. The arousal component of the WASABI emotion engine was grounded in energy processes of the robot body. For the initial investigation a simple “threshold-based” action selection strategy is used as a substitute for the complex deliberative reasoning modules of WASABI and the main accent of the research is on the grounding of the arousal component of PAD space in energy processes and effort of movement. Several tests are performed in an abstract scenario where the two resources - work and fuel are square areas on the ground and a simulation of a NAO humanoid “gathers” them by walking and stepping on the squares. The demonstrative runs of the system in different environments show the role of the arousal mechanism to handle urgent work events. The energy consumption dynamics have pattern –“B” described in section 2-3-1. That makes the choice of the right effort of a movement not trivial in the proposed two –resource problem.

Paper II builds on and further develops the affective architecture introduced in Paper I. In this paper the cue-deficit action selection strategy is used instead of the simple threshold based one. Empirically it is shown that this simple action selection strategy produces sustainable basic cycles in the proposed scenario for a two-resource problem and performs better than the two obvious simple strategies. The experiments are performed in scenarios that are more realistic and closer to the real-world tasks, which humanoid service robots are supposed to solve. The iCub robot should follow a ball held in random positions from a human, while not running out of energy. This scenario represents a dynamic more complex two-resource problem compared to the static one in Paper I- requiring tracking of the moving resource and 3D manipulation. Experimental data is collected from a simulated iCub robot. Data from the real robot is provided for comparison. The cognitive architecture uses a work utility function which from one side presents a natural performance measure of the robot task. From another side it provides cyclical continuous dynamics which allows the implementation of the bio-inspired homeostasis regulating architecture. In this paper the tests with the NAO robot from the Paper I are repeated in the new scenarios with the iCub robot. The results shows that the effect of the arousal on the performance of the robot is the same in both scenarios. An initial investigation for the architecture’s extension with the expression of the robot’s emotional state is performed and some ideas about how this

ability will improve the human-robot interaction are provided. At the end of the paper, the concept of safety and its relevance to resource management and HRI is discussed.

In Paper III the work in the previous papers is extended and integrated with a more detailed examination of the role of safety in human-robot interaction. Safety is introduced as a natural third homeostatic variable for a service robot interacting with a human. Experimental validation of the relationship between arousal and effort introduced in the previous two papers is improved and extended. Experiments in the new three-resource problem is performed. The experimental results show that the architecture can handle a three-resource problem when provided with a reasonable measure of safety deficit. The arousal mechanism serves as means of embodying the cue-deficit action selection strategy into the robot's body processes. More detailed analysis of the basic cycles of the architecture are performed exploring the role of emergent behavioral properties as "opportunism" and "persistence" for the robot's adaptivity in the multi-resource scenarios.

Chapter 6 Conclusion

The main contributions of the thesis are:

1. A detailed explanation of the resource management problem for autonomous robots is presented. Special attention is paid to the analysis of particular aspects of resource management in interaction with humans (for example effort of movement and safety relationship). An overview of the existing solutions for resource management with an emphasis on emotion cognitive architectures is provided. The major pros and cons for the different solutions are pointed out and the aspects of the solution which are related to the motivation for developing of the architecture in the thesis is shown.
2. A bio-inspired cognitive architecture for resource management for autonomous robots interacting with humans is developed. The architecture exploits the idea of grounding of ethological models of task selection through another bio-inspired affective mechanism of appraisal and arousal. The architecture contains top-down components based on descriptive ethological and psychological models of emotion and affect and is grounded in bottom-up processes: energy level and speed of movement. The architecture has some important abilities for HRI like monitoring human actions and safety control.
3. Experimental data validating the proposed architecture in scenarios of two and three resource problems is provided. The analysis of the performance of the architecture shows the role of the cue-deficit model and the grounded arousal mechanism for the efficient behavior in the presented robotic scenarios. The experiments are performed with two humanoid robot scenarios, which tries to include some of the basic necessities for service robotics. A discussion is provided of generalization of the proposed results in respect to other applications of the service robotics industry.
4. Initial investigations of the role of emotion expression / recognition in the proposed problems is presented. The architecture generates facial emotion expression based on the level of arousal. Discussion about the role of the expression recognition system has in the resource management in HRI is provided.

There are several directions, in which the thesis can be developed towards a completion of a PhD thesis:

1. The presented architecture in the thesis doesn't include any learning mechanisms for now. The lack of learning mechanisms helps pay more attention to the particular adaptive properties of the interaction of the robot and the environment and analyzing emergent behavioral patterns of the body-environment coupling. However future work can adopt learning algorithms which will adapt the basic parameters related to resource management during robot's lifetime. For example in the current implementation detecting of a cue of resource is done via a vision module which already "knows" about this resource. Ideally future versions of architecture should "embody" the cue letting the agent "discover" itself during its life time what is the mapping between robot actions and dynamics of its essential

variables, i.e. what are the “resources” which the robot should manage and how to “sense” them in the environment. From another side in the 3D manipulator scenario (tracking a target with a the hand of the iCub) where the experiments of paper II and paper III are performed, the energy which the robot should spend is dependent on the current position of the robot, and could be different for positions at the same distance to the target (the same cue). One and the same targets (end effector state) can have different kinematic and dynamic solutions which could have different energy consumption profiles and time to be performed (e.g. going upwards costs more energy or time). Therefore, rather than using a simple cue in the task selection algorithm, more complex estimation of the resource accessibility could be used related to the robot and target position. One way of implementing this is with a reinforcement learning algorithm, which takes rewards from the current level of arousal- an estimation of the state of the robot according to its resource balance. An initial hypothesis is that a “learning system” will outperform the current one.

2. Experimental data with human subjects could be useful for validating the architecture’s abilities of emotion expression and recognition. A possible experimental design with the cognitive architecture implemented in a virtual robot could have four conditions with or without emotional expression /recognition in a cooperative game with a human. The hypothesis is that both emotional expression (face expressions) and recognition will outperform “non- emotional” variants. In order to validate the transfer to the real robotic world the architecture data in both cases without human player will be compared.

3. The importance of the role of CPU power in energy management is mentioned in the thesis but experimental results were not yet provided. A future development of the cognitive architecture could enable the arousal mechanisms to modulate the rate of computation of the most computational expensive module of the architecture, for example the vision module. The vision module could work on a higher rate or resolution which will require higher CPU power and energy consumption or it could be in an “low-energy” mode when the robot should spare the energy. This will be more prone to mistakes as it will provide the information with a delay affecting negatively the work performance of the robot. This is congruent with the ‘tick rate hypothesis’- arousal level is coupled with the rate of the environmental sampling (Revelle & Loftus, 1992). Initial experimental hypothesis that the cognitive architecture will improve its behavior compared to the case when the rate of vision module stays at a fixed value.

4. The architecture exploits only the arousal dimension of the PAD emotion state dynamics. An extended future version of the architecture could also elaborate the Pleasure and Dominance dimensions. Pleasure dimension could be interfaced with a reinforcement algorithm using reward function based on the resources’ deficit. The Pleasure – Arousal dynamics computed now with the WASABI emotion engine can be better elaborated by providing a new component, which exploits more naturally the biological counterparts of these emotion dimensions. Dominance is related to social position of the robot. It could be connected to reflexive behavior for approach/ avoidance of certain stimuli.

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