High Level Humanoid Postural Control Architecture with Human Inspiration

Santiago Martinez, Alberto Jardón, and Carlos Balaguer

Systems Engineering and Automation Department,
Carlos III University of Madrid,
Leganés, Spain
{scasa,ajardon,balaguer}@ing.uc3m.es

Abstract. This paper presents the novel humanoid postural control (PC) architecture for the humanoid robot TEO. It is outlined the high level and human inspired system for improving task performance. The study of the human PC system has inspired all processes involved in the control system. The information coming from sensors is interpreted applying neurophysics concepts and, then, the resulting perceptual parameters are applied for task performance improvement. The new PC system is an anticipative module complementing an existing reactive subsystem. This design tries to replicate the operation of the human case. In this way, the reactions can be more complex and higher perturbations levels can be overcome.

1 Introduction

Lots of human-like mechanical designs have been developed during last fifty years, from first prototype Wabot-1 [1] to cutting-edge humanoid robots ASIMO [2], HUBO [3] and HRP-3 [4]. From a mechanical point of view, the development of these robots has taken the advantage of leading technologies existing in their time but the concepts used were based on traditional mechanical solutions. For instance, joint designs have been mainly created with rotary motors joined to mechanical transmissions to increase velocity and torque at their output. But mechanical limitations and the desire of high human appearance favour the searching for new solutions for the humanoid robot design. In this sense, the field of bionics seeks to design technology by mimicking the salient features of biological structures [5]. Lessons learned from bionics state that success of natural inspired designs relies on effective embodiment: on clever morphology and use of material properties [6]. Taking this in account, it is obvious that it is necessary to develop new human inspired technologies to enable this embodiment. In this way, full body humanoid robot development has been slowing down during last decade and the mechatronics research efforts have been redirected to solve more focused problems: artificial muscles, advanced materials, etc.

It has been demonstrated the feasibility of building full body humanoid robots. However, it has been recently paid attention to the second main issue involved in human being replication: the imitation of human behaviour.

M.A. Armada et al. (eds.), *ROBOT2013: First Iberian Robotics Conference*, Advances in Intelligent Systems and Computing 252,
DOI: 10.1007/978-3-319-03413-3_45, © Springer International Publishing Switzerland 2014

This paper presents a different point of view when talking about the development of control architectures for humanoid robots. Specifically, the postural control (PC) architecture proposed is inspired by the study of the human PC system. The research carried out shows that there are two main sub-systems involved in human PC: a reactive one, and other predictive or anticipatory. The aim of the work is to replicate these control systems for the humanoid robot TEO. In this way, the work has been oriented to establish a predictive system complementing the reactive existing one.

The anticipative control system has been analysed in the human case and it has been extrapolated to the architecture for controlling the humanoid robot TEO. The operation of this control system is based on the composition of sensorial perceptions; then, the evaluation of the resulting stimulus through the use of the psychophysics theory of the surprise and, finally, the creation of events that can be used for activating determined motor reaction strategies (synergies).

The performance of the anticipative system for PC is being tested through simulations and the application of the results in the humanoid robot TEO from the RoboticsLab research group in the Systems Engineering and Automation Department from the Carlos III University of Madrid.

2 Principles of Human Posture Control

The PC correspond to a complex motor response that involves the integration of a variety of sensorial information, elaboration and execution of movement patterns [7]. The human PC system is continuously being developed from birth and it is critically influenced by sensor system maturation and the development of the Central Nervous System (CNS). During the growth process, humans learn to control posture by means of experience acquired in response to sensorial inputs. So, the human posture control system is basically composed by a sensor input system which collects information, an integration system which process this information, and an end-effector system which performs the movements to keep the right posture (Fig. 1).

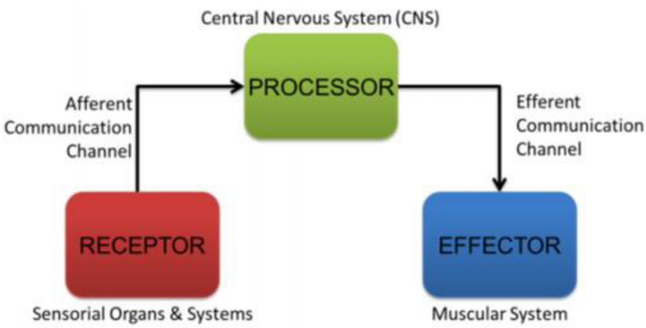

Fig. 1. Basic human PC system components

PC is performed continuously because it is the foundation of any kind of task. That is, one task can be considered as a sequence of controlled and learned postures. During the execution of each posture of the sequence, the sensorial inputs are evaluated to generate appropriate CNS stimuli that are transmitted to the neural processor centres. Depending on the result of the evaluation, different levels of PC could be fired if it would be necessary. These reactions are classified in reflex, automatic or voluntary movements depending on the response velocity required.

Table 1. Properties of the three motor systems in balance movement control

	Motor System		
	Reflex	Automatic	Voluntary
Activation	External stimulus	External stimulus	External stimulus Self-generator
Role in PC	Muscle force regulation	Resist disturbances	Purposeful movements
Latency	Fixed 20-60ms	Fixed, 130-170ms	Variable >150ms

Another factor influencing response velocity is the operation type of the human PC system. There exist two basic modes of operation of the system when a disturbance is detected: reactive and predictive. Specifically, this paper is centered on the study of the predictive PC mechanism, in which the sensorial inputs are used to predict the possible consequences from perturbations. According to the human system operation, the main function of this predictive system is preparing the effector system to apply a reaction. It is essential when higher level disturbances are detected or faster reactions are required than the feedback control loop can manage or trigger.

2.1 Basic Operational Mechanisms of the Human Postural Control System

Different theories were developed in the past to explain how the human body controls its posture. But nowadays, PC has been oriented to a systemic point of view. Today researchers recognize that PC is complex and context-dependent and that all levels of the nervous system must be examined to account for this complexity [8]. Although some controversy exists regarding the range of subsystems involved, there is general agreement that the neurological system, the musculoskeletal system, the sensory system, the environmental context, and the task demands are important contributors to PC [9].

Besides relying on their feedback systems, humans also maintain balance using anticipatory motor actions. During human movement, two control actions are performed continuously and in parallel: movement and PC. Meanwhile movement control system commands body limbs position, the PC performs actions to maintain balance taking in account the proprioceptive information. Fig. 2 shows this basic idea, but this control system is defective in the sense that it only provides information about the feedforward anticipative and feedback reactive postural adjustments produced by voluntary movements.

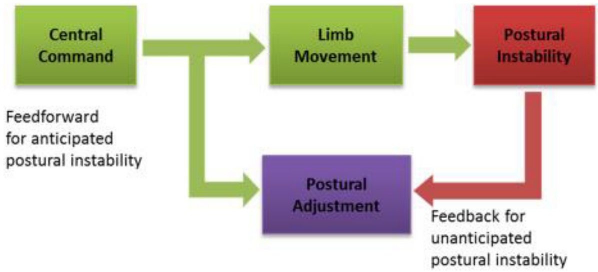

Fig. 2. Postural adjustment scheme from [10]

It is important to state that posture and movement are close related but they are essentially different. From a biomechanical point of view, the movement can be described as the combination of motor gestures. Purposeful or voluntary motor acts are performed moving one or several body segments towards a goal [11]; meanwhile other segments must be positioned in order to regain posture and equilibrium. It is ease to point out that voluntary movements are one source of postural perturbations.

Therefore, posture poses a static and dynamic dual nature. The former, static or postural fixation, is a local mechanism to maintain the body segments in stationary positions against internal (e.g. weight) or external forces (e.g. load ported) [12]. The latter, dynamic posture component is the continuous looking for keeping the desired target according to the task performed.

2.2 Sensorimotor Integration in Postural Control

To maintain PC during both static and dynamic situations, individuals rely on their sensory systems (visual, vestibular and somatosensory) to provide information such as their limbs locations and movement with respect to the surrounding environment. The CNS then interprets the sensory information and commands the musculoskeletal systems to adjust the body parts position trying to keep a desired or stable posture. However, since human beings are constantly interacting with their surroundings, one must not ignore the environment when studying PC. The influence of environmental factors such as light conditions, concurrent distracting factors, special surface characteristics, etc. are affecting the requirements to the PC. Similarly, it is easily understood that the PC demands during the task of walking and other locomotive activities are different from the demands when humans perform manipulation tasks (Fig. 3).

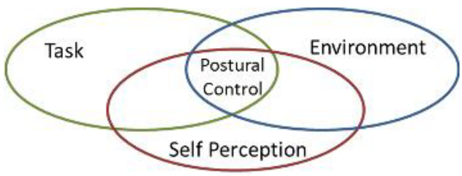

Fig. 3. PC is influenced by factors related to the individual, the task, and the environment adapted from [13]

Since PC has been defined as the control of the body's position in space, it must be performed adjusting parameters such as centre of mass, base of support, joint momentum, etc. The adjustments are counterbalancing actions of the limbs, the head and the trunk influenced by the muscular strength, previous experience, etc.

2.3 Interpretation of Sensorial Incomes for Postural Control

One key point of the human PC system is the way in which the disturbances are sensed and how this perception commands body reactions. Using psychophysical principles, it is possible to model these disturbances as unexpected events or surprise events produced depending on the task context [14].

Since surprise depends on the 'unexpectedness' of the stimulus [15], at least the three following layers and each corresponding test must be distinguished in order to provide an exhaustive model of surprisingness generated by expectation failure [16].

- Mismatch-based Surprise: based on sensory-motor expectations, it is generated by the mismatch between active knowledge and disturbance perception, exceeding some threshold value [17], [18] (function of Unexpectedness). It is based on some form of 'statistical' learning [19] and its intensity is function of the degree of certainty and the value of the goal.
- Passive Prediction-based Surprise: surprise results from a conflict or inconsistency between the updated set of knowledge and the perceived sensation [15]. Passive expectations are formed after the surprising event has occurred [20].
- Implausibility-based Surprise: This refers to those (quite numerous) situations in which the input proposition expresses information related to non-existent knowledge (function of Incredulity).

Summarizing, capture surprise events or feeling surprise seems to play several functions:

- Redirecting attention on the mismatching facts, concentrating cognitive processing resources on them.
- Activating resources for possible practical activity; physical arousal, bodily preparation for fast reaction.
- There are also long term effects (and functions) of the perceived surprise for a bad prediction (e.g. increasing controls before and during the actions).

2.4 Motor Strategies Used in Postural Control

The motor reactions during PC have been extensively studied in order to try to understand the mechanisms that humans use to overcome any kind of 'postural perturbation'. One of the main conclusions is the existence of learned patterns that are automatically triggered in response to determined stimuli. These patterns are called motor strategies or 'synergies' (e.g. [21], [22]). According to Sherrington, the control of the movement related to the synergies is composed by a reflex motor unit above the voluntary motor unit. Such reflex movements are organised more naturally into collective functional units defined over groups of muscles and joints [23]. By the other side, Bernstein suggests that a restricted number of programs may underlie most of our behaviour.

For any given perturbation, one or more muscle synergies may be activated so that their combined influences define the resulting muscle activation pattern [24]. Extending the concept, complex synergies can be in general considered as programs for controlling some distinctive motor performance extended in space and time, built upon basic synergies of coordinated reflexes as substrate [25]. In summary, the establishment of a synergy is based on a common assumption that regularity in the behaviour of a set of elements is a sufficient sign to claim an existence of a synergy [26].

3 The Humanoid Anticipative Postural Control Architecture

The human PC system, outlined in previous sections, is the result of millions of years of evolution. Its complex operation and physiology are still being researched and they are far from being completely understood. Although technology evolution is much faster than biology evolution, the same problems must be addressed and they are continuously under development. The main studies regarding physiology and human behaviour date back the turn of 20th Century. The advances achieved in the knowledge of the human organism during the last decades have made possible a better understanding of the underlying mechanisms that produce the different human behaviours. There is a variety of human behaviours and their classification is complex. Attending to their nature, behaviours can be classified as innate or learned.

Innate or instinctive behaviours will be those, conscious or unconscious, that have a biological and genetic basis, are performed naturally, and are reinforced by practice. The human being has acquired this kind of innate behaviours thanks to thousands years of evolution, and they are “hard-wired” in the CNS. In general, instinctive behaviours are considered as “pre-programmed" responses triggered by external stimuli. They usually fit into one of the following categories [27]:

- Reflex: it is the most basic innate behaviour. Correspond to the basic reflex arc involving only a few neurons.
- Orientation behaviours: they are coordinated movements like walking, etc.
- Kinesis: it is a change on the speed of movement or a change rate of turn which are directly proportional to the stimuli intensity.
- Taxis: it is a movement directly toward (positive) or away from (negative) a stimulus.

Learned behaviours are skills acquired or modified by the experience resulting from a learning procedure. Taking this into account, it is obvious to conclude that innate and learned behaviours are close related by means of experience. The human being acquires new skills and knowledge through trial and error, observation of other individuals or memory of past events. In general, learned behaviours will always be [27]:

- Non-heritable: behaviour acquired only through observation or experience.
- Extrinsic: it is caused by social interaction.
- Permutable: pattern or sequence may change over time.
- Adaptable: it is capable of modification to suit changing conditions.
- Progressive: subject to improvement or refinement through practice.

The better understanding of the human PC system operation has enabled the development of a large number of control schemes in cybernetic/robotic and biomechanical fields. In the former, theoretical and experimental situations as standing posture and free fall [28], walking [29], run-to-walk and vice versa [30], [31], have been studied considering static or dynamic 2D/3D problems. In the latter field, studies are focused on experimental postural analysis [32], organization of the PC [33] or biomechanical modelling to study PC [34], gait initiation [35], musculoskeletal control [36] or jumping [37].

These works are contributions for a better human motor behaviour understanding. These studies deal more generally with the selection of strategies to balance the external perturbation (force and moment) acting on the human structure. In these cases, the matter under control is the desirable posture during and after the performance of a voluntary movement. From the initial posture, the movement is the succession of instantaneous postures subjected to external perturbations. Then, the reactions against these perturbations are computed and deployed according to the response velocity required and the origin of the disturbance.

The development of humanlike machines has motivated a deeper research in human PC systems. Early developments of humanoid prototypes were built to research the first postural problem humans must face up in the first year of their life: the equilibrium maintenance. The increase in computer processing power has enabled the fast development of these prototypes and the construction of full size humanoid platforms, which are able of performing complex postural tasks.

The step up in mechatronics and computing has favoured the development of high complexity control schemes and their transformation into 'human inspired' control systems. The final goal of these control schemes is to imitate the human behaviour as much as possible.

This human inspiration has caused a change in how the researcher considers the humanoid platform. The humanoid robot was only a mechatronic platform to test tasks and control schemes. Now, new robotic platforms have been developed to study the cognitive aspect of the human nature. In these platforms, the understanding of cognition and the analysis of how humans perceive the environment, how they interact within it and how the information is processed and applied, are the key point of control. This is one of the reasons why techniques, derived from the study of human behaviour, are taking more importance in PC. Genetic algorithms, neuro-fuzzy controllers, etc. used in Artificial Intelligence are being applied in control, due to their similarity with real human processing.

During the last decade, the RoboticsLab research group has been introduced in the development of humanoid robots. The prototype RH-1 [38], [39], [40] was the first anthropomorphic mechatronics design carried out. It was useful to understand the challenging of the humanoid robot mechatronics and control design. With the new humanoid robot prototype TEO (Task Environment Operator), Roboticslab has applied lessons learned with RH-1. New improvements in mechatronics enable the change on the control philosophy from classical control techniques towards human behaviour inspired control.

This paper deals with this change and the development of human inspired control architecture for TEO humanoid robot. The first version of the control scheme deployed for TEO humanoid robot was a classic feedback control system to regain stability. It matches with the reactive loop in the human control scheme exposed in Fig. 2. The high level architecture proposed in this work adds the open anticipative loop to complete the human inspired PC scheme.

3.1 Performing Humanoid Tasks

It has been exposed that human actions are a mixture of different kind of behaviours composed by simpler tasks. By means of the learning process, tasks become more complex and they enhance the human capabilities during growth. Thus, a task should not be considered simply as a succession of fixed motor patterns. It might be considered as a flexible, adaptable and configurable motor sequences that, as well, includes mechanisms for dealing with unexpected events.

In this way, TEO humanoid robot tasks are not mere sequences of joint angles, velocities and accelerations. There are complete sets of configurable modules established to enable the human inspired postural architecture. Fig. 4 represents the structure of TEO tasks. One task frame is composed by a main movement, which can be configured to perform different movements with the same shape. As well, the mechanisms to react against perturbations have been added by means of the integration of motor patterns or synergies. Finally, it has been included a module which combines motion sequences, depending on the control requirements.

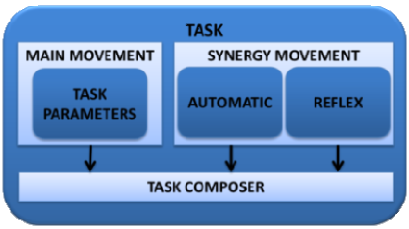

Fig. 4. Humanoid task modules

Then, complex behaviours are those groups of tasks sharing one main characteristic that defines them. Thus, the study of PC has been divided into manipulation and locomotion behaviours or groups of tasks.

3.2 Human Inspired Postural Control Architecture

The main objective of the present paper is to propose a novel human inspired and task oriented control architecture for humanoid robots. This development has been deployed for robot TEO which is the third generation of humanoid robots from RoboticsLab research group. The research in the field of humanoid robots started with the development of the platform RH-1. This mechatronic system integrated a PC to maintain equilibrium during locomotion tasks. The high level control scheme is shown in Fig. 5.

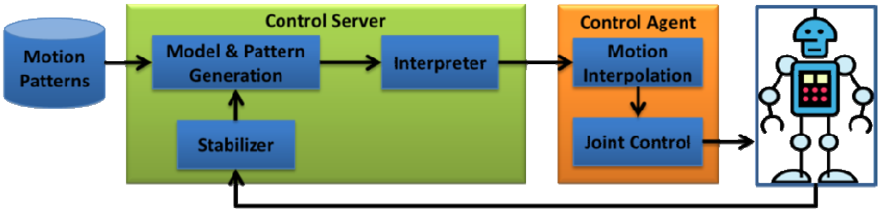

Fig. 5. RH-1 Control architecture

In this scheme, a central pattern generator computes a statically stable locomotion task. It is composed by a sequence of joint positions or postures whose stability was ensured offline. These positions are transmitted to the joint controllers and executed. An internal joint control loop minimizes the posture position error. But this loop is not enough to regain balance if higher disturbances act over the robot. In this case, a second control loop for dynamic stability or 'stabilizer' maintains postural balance during locomotion by means of ZMP and CoM allocation control. The first loop corresponds to the internal PID control of each individual joint. It is performed by the driver device that actuates every degree of freedom. Due to this nature, it is impossible to perform whole body postural corrections only with this loop. On the opposite, the 'stabilizer' considers the robot as a whole and it supervises the parameters influenced by the body dynamics. These parameters can be computed online thanks to the use of a simple inverted pendulum model that reduces significantly the processing time.

Another important aspect of this architecture is the availability of sensor data and its treatment. The only sensor devices integrated in the kinematic chain of the RH-1 robot are incremental encoders used to measure joint angles. This kind of sensors does not provide information about the dynamics of the robot. The use of the simplified model of the robot body helps to estimate the dynamics and its influence in balance. The unfeasibility of obtaining direct sensor data regarding the body dynamics, such as limb accelerations, forces exerted on the body, etc., causes an increase of computing time. Due to this, the admissible level of perturbation is lower and the time to reaction higher.

Apart from the restrictions in control, RH-1 robot presented great limitations which did not allow a correct motion performance in terms of mechanical robustness (high joint looseness), stability, and energy consumption (necessity to be connected to the electrical net since battery could not supply the required energy for more than a while), not to mention the realization of high-level tasks such as manipulation, complex gait generation, or complex human-robot interaction [41].

TEO robot comes to substitute RH-1 humanoid robot to overcome its limitations. The design of the new platform turns the humanoid robot into a cognitive robot that enables the implementation of human inspired concepts. The novel PC architecture proposed for TEO humanoid robot is compounded by two differentiated parts: the feedback and the feedforward control loops. It is shown in Fig. 6.

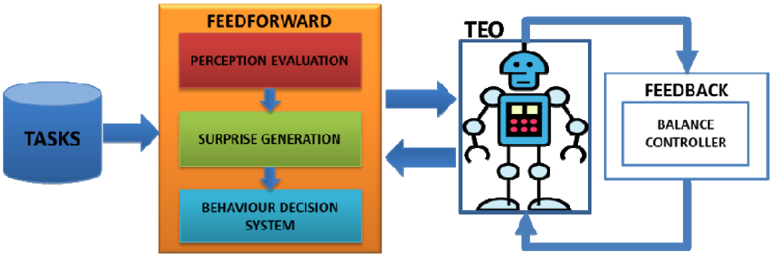

Fig. 6. TEO High level control architecture

The feedforward control loop shown in Fig. 6 has been inspired in the architectures for human PC system stated in previous sections. As commented before, human body has different levels of reaction depending of the required response velocity. Automatic and reflex acts are the fastest levels of reaction against disturbances. These reactions are activated by the inputs coming from the corresponding sensorial organs. The information from these organs is transmitted to the processing centres in which the reaction is built. Once the response is composed it is sent to the muscles to perform the programmed action.

The novel TEO postural controller has been inspired in this operation and the robot mechatronic systems have been designed to support these functions.

3.3 Perceptual Evaluation

Apart from the levels of motor reaction, the basis of the PC is the sensorimotor integration and the way of enabling it. As reviewed before, several theories have been developed to explain how the sensorial information is captured, processed and, executed through the corresponding action. Multiple systems are involved in PC in a multilevel structure. Taking this into account, it has been established a sensorial evaluation module to compute the input information and to compose the named 'perceptions'.

The exoceptive perception will capture the external perturbations (Table 2). This perception is composed by different sensor devices that accomplish the same function as one system of the human body. Then, the sensorial information detected is integrated task-dependant Fuzzy systems.

Table 2. Human vs. humanoid exoceptive perception

Exoceptive Humanoid System	Exoceptive Human System
Inertial Measurement Unit (IMU)	Vestibular System
Force / Torque Sensors (F/T)	Muscles / Skin
Vision (3D cameras)	Vision

The proprioceptive perception measures the internal body status. The sensorial data is provided by joint position and velocity sensors (Table 3).

Table 3. Human vs. humanoid proprioceptive perception

Proprioceptive Humanoid System	Proprioceptive Human System
Relative Encoder	Joint Velocity
Absolute Encoder	Joint Position

The result of the sensor data evaluation depends highly on the task being performed. It means that the resulting perception will not be the same if the task performed is, for instance, pure manipulation or pure locomotion. It is the task oriented perceptual system which filters the information and uses it in the proper way. Taking this into account, two premises can be established for TEO robot perceptual evaluation:

- Same sensorial inputs will produce different perception depending on the task performed.
- Exoceptive and proprioceptive perceptions will be composed by different sensorial sources depending on the task performed.

The first premise means, following psychophysical principles, that the processor centres filters the sensorial information to speed the result of the evaluation up and to produce an accurate response (detection, identification, discrimination and scaling). Second premise remarks the task dependant nature of the perception production as well. For instance, the use of data related with equilibrium is unnecessary in a manipulation task when the robot is seated.

Summarizing, not all information might be used in all cases and the information might not be applied in the same way in every task. Fig. 7 shows the modules in charge of perceptive evaluation in TEO control architecture. Sensations composed by the information captured by sensory devices are evaluated forming the proprioceptive and exoceptive perceptions. Both sets of perceptual information is then available in the system to be used depending of the PC necessities.

3.4 Surprise Generation

It has been described how sensory information can be processed and converted into perceptions. They are parameters that relate posture and sensorial incomes. In this stage the main problem is how to apply all this information in PC.

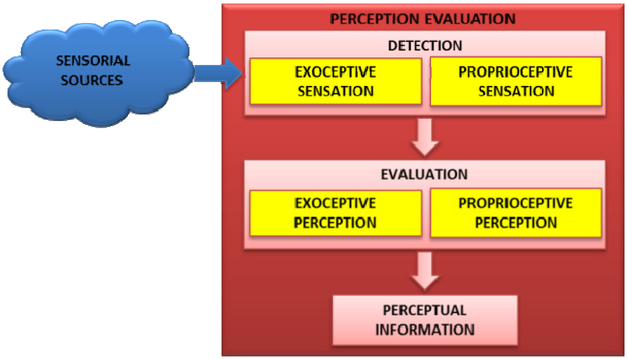

Fig. 7. Perception evaluation

The mechanism established in the feedforward loop to trigger reactions is based on the evaluation of surprising events. Perturbations can be considered as unexpected events and, the output of its processing, the activation of a surprise [15]. Then, the information from perceptions is the base for this evaluation. The system selects and combines information from the available sets, depending on the necessities of pre-established output surprises.

Nevertheless, the concept of surprise is a high level envelope that explains the process of any kind of unexpectedness. Taking this into account, surprisingness is generated by lower level mechanisms called expectations. The failure of a determined expectation elicits a surprise event. The expectation failure can be classified in:

- Active expectation failure or prediction failure. It is produced when a prediction about an outcome has not been produced by an input proposition.
- Passive expectation failure or assumption failure. It is caused when an outcome, originated by a determined input proposition, is not predicted but some assumptions about it can be established. If this output doesn't fit into these assumptions, the surprise should be elicited.
- Unanticipated incongruity. It is related to unexpected events never experimented before.

Then, reaction movements can be considered as reactions driven by surprise events. Passive and active expectations require a certain degree of previous knowledge about the matter that can cause surprise. These two forms of expectation failures have been considered to be applied for surprise generation in TEO robot. Unanticipated incongruity implies the integration of other kind of intelligent module that will be able to classify the event and to learn about it.

In this way, passive expectation failure sub-system will produce surprise events when some predefined thresholds will be exceeded by the input proposition. In the case of active expectation, predictions about critical issues related with tasks performance are continuously verified. Then, the surprise event is triggered if these predictions fail, always taking into account the task context.

3.5 Behaviour Decision System

At this stage, there has been described how perturbations are perceived by the sensorial system. After that, it has been introduced the system which transforms sensations into 'understandable' information (perceptions). At last, perceptual information is interpreted and converted into surprise events that will be used by the control system to act against perturbations.

However, the anticipated actions deployed by the decision system can be defined as reactions against future consequences evoked by sensorial stimuli. That is, given a determinate task, it is possible to know so the correct behaviour as the deviation caused by determined perturbations. It means that the perceptual knowledge will drive the decision because the consequence of the perturbation is previously known. Then, it is possible to say that the anticipative PC system reacts against the future task state.

Therefore, inside the behaviour decision module, the surprise events are processed to decide:

- If any kind of future action or reaction is needed.
- The kind of reaction that would be the most appropriate.
- How the selected reaction should be performed.

By means of evaluating the information from active and passive expectations (surprise events), it can be determined if a reaction might be selected and executed. The reaction is selected among all available motor synergies related with the corresponding task. These synergies are motion patterns that will be filled in using the results from the expectations evaluation (surprise task parameters). The outcome of this module will be a parameterized synergy that could be executed to enhance PC.

4 Conclusions

This paper presents the novel high level PC architecture for the humanoid robot TEO. Specifically, it has been exposed the guidelines for the development of the new human inspired anticipative system. It has been outlined the human PC system as design basis of a novel humanoid anticipative control system. From perturbations and sensation detection to control signal generation, the new control system established taking into account the way human's body performs these processes. This high level architecture is the framework to develop all necessary human reasoning inspired subsystems to process task information.

Acknowledgements. The research leading to these results has received funding from the ARCADIA project DPI2010-21047-C02-01, funded by CICYT project grant on behalf of Spanish Ministry of Economy and Competitiveness and from the RoboCity2030-II-CM project (S2009/DPI-1559), funded by Programas de Actividades I+D en la Comunidad de Madrid and cofunded by Structural Funds of the EU.

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