Birth of An Intelligent Humanoid Robot in Singapore

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Abstract. Since 1996, we have embarked into the journey of developing humanoid robots at Nanyang Technological University, Singapore. We have ventured into the various technical aspects of humanoid robot development. In particular, we have placed special emphasis on mechatronics design of humanoid robots, planning and control of biped walking, hand-eye coordination for humanoid robots, cognitive vision for humanoid robots, and cognitive speech for humanoid robots. Between 2006 and 2011, we have received a substantial amount of research grants and have developed two full prototypes of humanoid robots, which are about 1.8 meters in height and weigh about 80 kg each. And, each humanoid robot has 42 degrees of freedom with independent actuations. In this short paper and talk, I will share some various findings and results with the readers and audience.

Keywords: humanoid robot, cognitive vision, cognitive speech, hand-eye coordination, biped walking.

1 Introduction

Human beings are the most advanced creatures in the nature because of the combined abilities of learning and performing both physical and mental activities. In terms of physical activities, a human being is very skilful in undertaking both manipulation and biped walking. And, in terms of mental activities, two impressive behaviours are analysis and synthesis. Because of the mental power of doing analysis and synthesis, it is unique for human beings to achieve discoveries and inventions. For instance, human beings have gained a better understanding of the nature through a series of important discoveries, which in turn fuel human being's creativity leading to inventions. As result of human-made inventions, our lives are much enjoyable than before.

In this short paper, we will discuss the issues behind the blueprints of a humanoid robot's body, brain and mind. Also, we will show examples of solutions to these important issues, which are implemented on our LOCH humanoid robot.

adfa, p. 1, 2011.

2 Blueprint of Artificial Life

We believe that the evolution from non-life to life will go through the following five key steps:

- Step 1: To be a dynamic system.
  When a dormant body could respond to energy, such a dormant body will become a dynamic system. In engineering, the use of actuators to drive a mechanism is a typical example of creating a dynamic system which could respond to electric energy.
- Step 2: To be an automatic system.
  When a dynamic system could respond to signal, such a dynamic system will become an automatic system. By default, a dynamic system has its own transient and steady-state responses when energy is applied to it as input. In order to control a dynamic system for the purpose of achieving intended responses, it is necessary to create a feedback mechanism so that a dynamic system will be able to directly respond to signals, which in turn control the release of the energy. Such a feedback mechanism can be called a *behavioural Mind* which plays the role of doing sensory-motor mapping.
- Step 3: To be an intelligent system.
  When an automatic system could respond to knowledge extracted from signals, such an automatic system will become an intelligent system. And, it is necessary to know the principles behind the design of a *cognitive Mind*, which will have the ability of extracting knowledge from signals such as visual or auditory signals.
- Step 4: To be an autonomous system.
  When an intelligent system has the innate ability of making its own decisions and acts according to its own decisions, such an intelligent system will become an autonomous system. Therefore, an autonomous system must have a *creative Mind* which is able to manipulate knowledge so as to synthesize decisions.
- Step 5: To be a conscious system.
  Finally, when an autonomous system has a *conscious Mind* which is able to be aware of any consequence of doing (or being) and not-doing (or not-being), such an autonomous system will become a conscious system. When a dormant body reaches the level of being a conscious system, we can say that a life or artificial life is born.

These five steps are important to guide discoveries in science and inventions in engineering. For instance, the answer to the question of "what are the principles behind a human being's mind?" is yet to be discovered in science. And, the question of "how to create an artificial mind which could extract knowledge from signals?" is still a big challenge in engineering.

3 Blueprint of Humanoid Robot's Body

Fig.1 shows a typical layout of the degrees of freedom in a humanoid robot. In practice, a humanoid robot may have a distribution of degrees of freedom as follows:

a) Neck: Two degrees of freedom.
b) Arm: Six degrees of freedom so that the wrist can be in any orientation.
c) Hand: Ten degrees of freedom in total, and two degrees of freedom per finger.
d) Waist: Two degrees of freedom.
e) Leg: Six degrees of freedom so that the ankle can be in any orientation.
f) Foot: One degree of freedom.

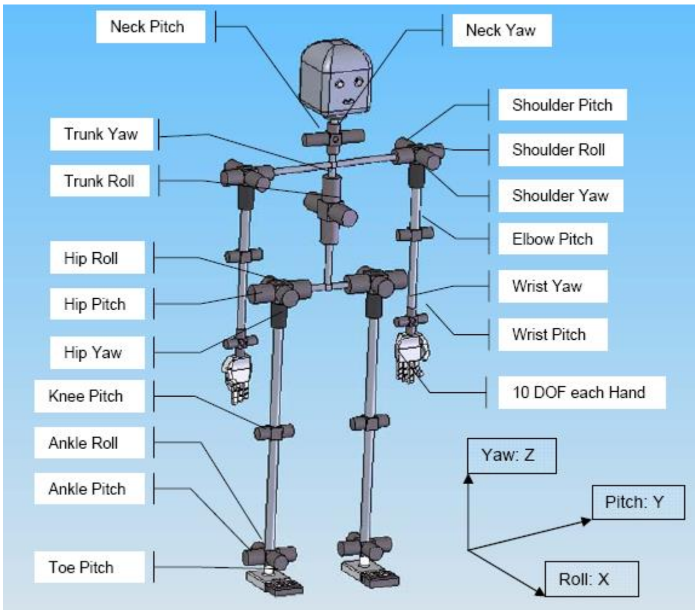

Figure 1: Layout of degrees of freedom in a humanoid robot.

4 Blueprint of Humanoid Robot's Brain

In a human being's brain, there are: a) cerebrum and b) cerebellum. The cooperation of these two organs makes a human being extremely powerful in undertaking: a) knowledge-centric activities and b) skill-centric activities. Interestedly, the knowledge-centric activities are orchestrated by the cerebrum. And, the neural system in the cerebrum is divided into different zones, each of which has a specific function such as speech, vision, reading, writing, smelling, reasoning, etc.

On the other hand, the skill-centric activities are controlled by both the cerebrum and the cerebellum. For instance, the cerebrum controls the skill-centric activities at the cognitive level, such as: planning, coordination, and cooperation. And, the cerebellum controls the skill-centric activities at the signal level with a network of feedback control loops, each of which consists of: a) sensing neurons, b) actuating neurons and c) control neurons.

In engineering terms, a human brain can be treated as a distributed system with two main controllers and many sub-controllers. Therefore, the blueprint of a humanoid robot could follow such a design, which is based on a network of distributed microcontrollers under the supervision of two main host computers, as shown in Fig.2.

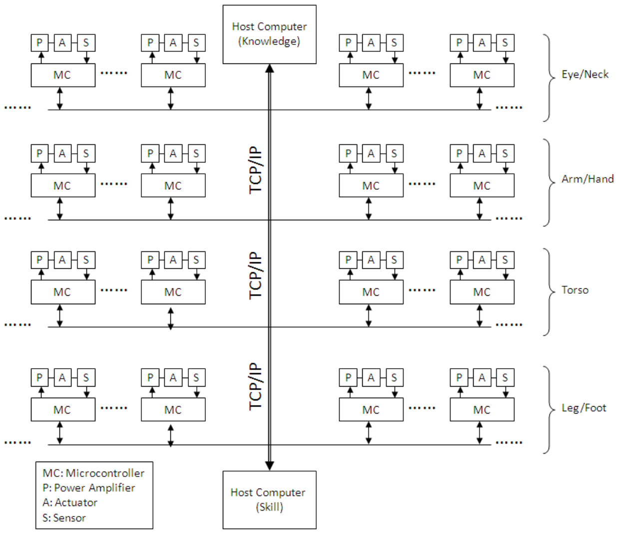

Figure 2: A network of distributed microcontrollers and two main computers.

Refer to Fig.2. Each microcontroller has the abilities to do: a) sensing, and b) control. And, each of the main computers will have the built modules for wired and wireless communications, which will enable a humanoid robot to act and interact with human beings or other humanoid robots.

5 Blueprint of Humanoid Robot's Mind

A human being has a powerful mind, which enables him/her to perform both mentally and physically challenging activities. Also, it is interesting to note that a human being's mind is a composite mind which consists of: a) behavioral mind, b) cognitive mind, c) creative mind and d) conscious mind.

In engineering terms, a behavioral mind is responsible for the control and coordination of skill-centric activities such as grasping, manipulation, walking, and running, etc. And, the basic principle behind a behavioral mind is the feedback control mechanism.

For a humanoid robot, the coordinated control of the motions at the joints will give rise to a complex behavior. And, at each, there are two types of motion: a) unconstrained motions and b) constrained motions. Therefore, at each joint, there must be three feedback control loops such as a) position control loop, b) velocity control loop and c) torque control loops as shown in Fig. 3.

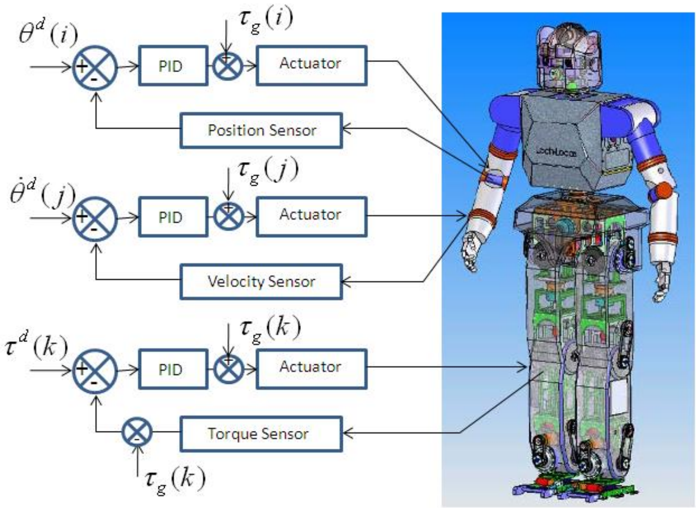

Figure 3: Behavioral mind consisting of feedback control loops at the joints.

In Fig.3, $(\theta^d, \dot{\theta}^d, \tau^d)$ is a set of desired joint angle, desired joint velocity and desired joint torque. And, $\tau_g(i)$ is the torque for gravity compensation by joint i.

Due to the advance in control engineering, the principle behind a behavioural mind is well-understood. However, it is still a challenging to discover the principles behind a cognitive mind, a creative mind and a conscious mind.

Here, we advocate a concept-physical principle for the representation of a natural language, as shown in Fig.4, in which the main features are:

1. Meanings can be divided into two levels: a) the elementary meanings and b) the composite meanings.
2. A real world is composed of two related worlds, namely: a) physical world and b) conceptual world.
3. A physical world exists because of the existence of physical entities, which include nature-made objects and human-made objects.
4. A conceptual world exists because of the existence of conceptual entities, which include the words in natural languages.
5. The elementary meanings in the physical world refer to the properties and constraints of the entities in the physical world, while the elementary meanings in a

conceptual world (note: each natural language depicts one conceptual world) refer to the properties and constraints of words in a conceptual world.
6. Each physical entity has at least one corresponding word in a conceptual world.
7. Each property of a physical entity has at least one corresponding word in a conceptual world.
8. Each constraint of a physical entity has at least one corresponding word in a conceptual world.
9. Interactions among the physical entities due to the constraints will create the composite meanings such as configurations, behaviours, events and episodes.
10. Interactions among the conceptual entities due to the constraints will create the composite meanings such as phases, sentences, concepts and topics.

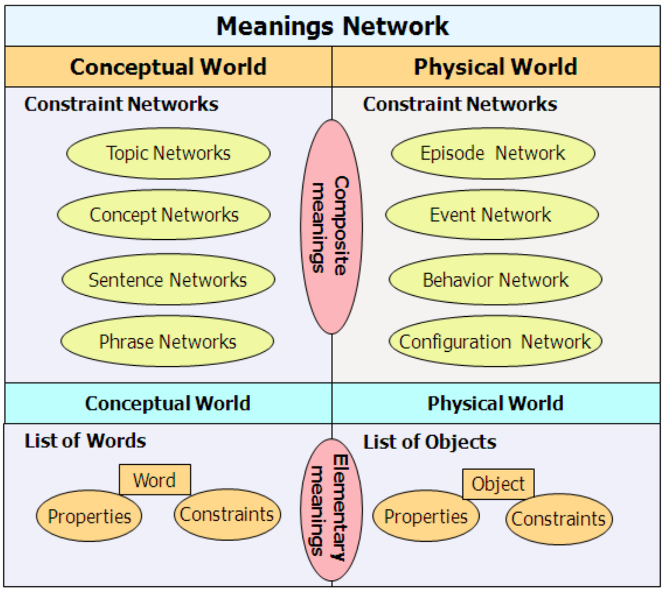

Figure 4: Knowledge representation by meaning network.

6 Planning and Control of Humanoid Robot's Manipulation

A human being can perform a wide range of manipulation tasks through the execution of motions by his/her arms and hands. Hence, it is clear that the motions at the joints of hands and arms are dictated by an intended task. In industrial robotics, it is well-understood that the inputs to the motion control loops at the joint level come from a decision-making process started with an intended task of manipulation. And, such a decision-making process includes:

- Behavior selection among the generic behaviors of manipulation as shown in Fig.5(a).
- Action selection among the generic actions of manipulation as shown in Fig.5(b).
- Motion description for a selected action.

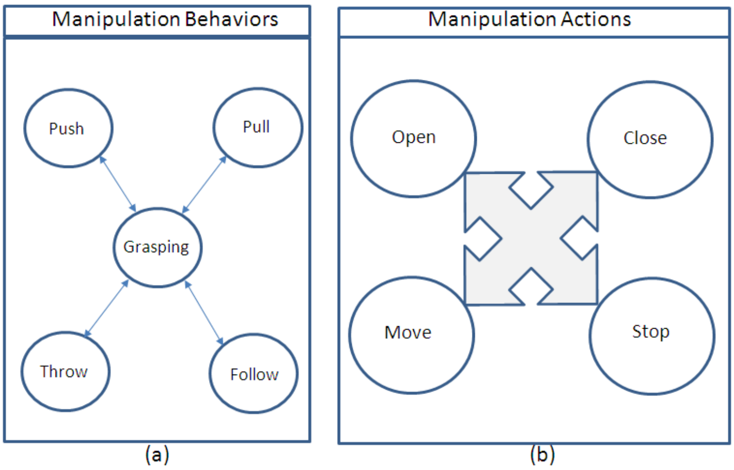

Figure 5: Generic behaviours and actions for manipulation.

7 Planning and Control of Humanoid Robot's Biped Walking

Here, we advocate the top-down approach to implement the behavioral control for biped locomotion. And, the inputs to the decision-making process for biped walking can be one, or a combination, of these causes:

- Locomotion task such as traveling from point A to point B along a walking surface.
- Self-intention such as speed-up, slow-down, u-turn, etc.
- Sensory-feedback such as collision, shock, impact, etc.

The presence of any one of the above causes will invoke an appropriate behavior and action (i.e. effect) to be undertaken by a humanoid robot's biped mechanism. And, the mapping from cause to effect will be done by a decision-making process, which will also include:

- Behavior selection among the generic behaviors of a biped mechanism as shown in Fig.6(a).
- Action selection among the generic actions of a leg shown in Fig.6(b).
- Motion description for a selected action.

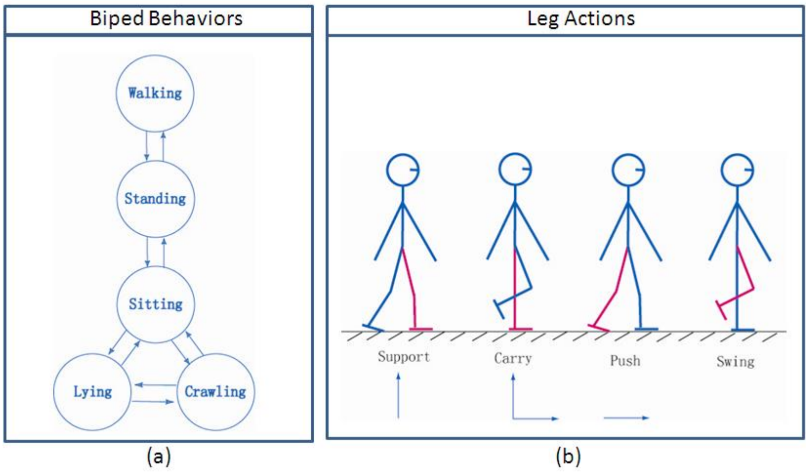

Figure 6: Generic behaviours and actions for biped locomotion.

In the above discussions, the motion description inside a behavioral control is to determine the desired values of joint positions, joint velocities, and/or joint torques, which will be the inputs to the automatic control loops at the joint level, as shown in Fig.7.

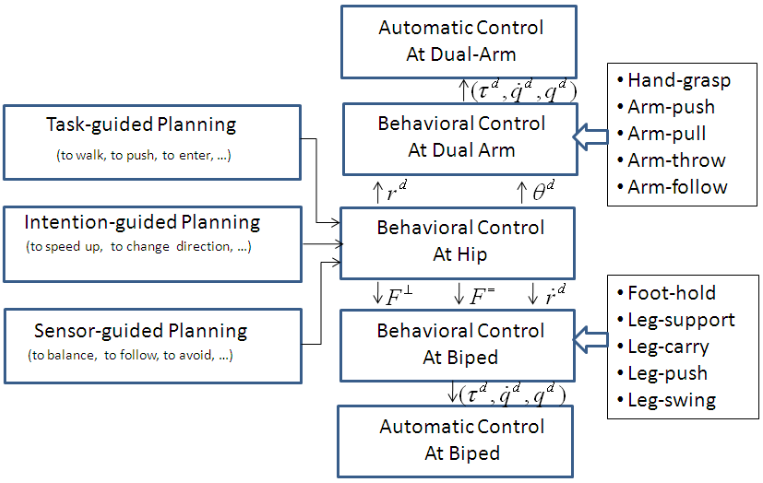

Figure 7: Interface between behavioural control and automatic control.

8 Cognitive Vision of Humanoid Robots

The behavioral mind of a humanoid robot will enable it to gain the awareness of its stability, and the awareness of its external disturbance. However, a human being is able to autonomously and adaptively perform both manipulation and location in a dynamically changing environment. Such an ability is quite unique due to a human being's vision which is intrinsically cognitive in nature.

In engineering terms, if we will design a humanoid robot with the innate ability of gaining the awareness of its workspace and/or walking terrain, it is necessary to discover the blueprint behind a cognitive vision and to implement such a blueprint onto a humanoid robot.

9 Cognitive Speech of Humanoid Robots

Human beings can communicate effectively in using a natural language. And, the instructions to human beings can be conveyed in both written and spoken languages. In engineering terms, such a process of instructing a human being on what to do is very much similar to programming. But, this type of programming is at the level of a natural language. This is why it is called a linguistic programming. And, the purpose of linguistic programming is to make a human being to be aware of next tasks that he or she is going to perform.

Today, it is still a common practice for a human being to master a machine language in order to instruct a robot or machine on what to do. Clearly, this process of using machine language in order to communicate with robots has seriously undermined the emergence of humanoid robots in a home environment. In near future, it is necessary to design a humanoid robot which incorporates the blueprint of cognitive linguistics (yet to be discovered) so that it can gain the awareness of next tasks through the use of natural languages.

10 Results and Conclusions

Fig. 8 shows the first version of our full-sized humanoid robot which has 42 degrees of freedom, and has the capabilities such as biped walking, hand-eye coordination, grasping, manipulation, and conversational dialogues in English. Although tremendous progresses have been made by Honda Co. Sony Co. Boston Dynamics Co., and many universities around the world, there are still many rooms for furthe research and investigations. For example, in the domain of humanoid robot's motion, solutions for reliable and redundant actuations are still epected. In the domain of humanoid robot's intelligence, solutions for cognitive visions are still expected. And, solutions for cognitve speech still have serious limitations. Last but not the least, we are still in the quest of discovering the blueprint of human mind, and the physical principles behind the blueprint of human mind. Nevertheless, humanoid robots are ideal platforms for us to further venture into the discovery and inventions which will certainly lead to the answers about human being's mind and the developments of commercially viable humanoid robot products of various sizes.

Figure 8. First Version of Full-sized Humanoid Robot at Nanyang Technological University.

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