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Biologically-Inspired Design of Humanoids

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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.

Interestingly, among the human-made inventions, the most challenging one will be humanoid robots (Hirai et al, 1998). One reason is that a humanoid robot is a unique platform which integrates both complex manipulation (i.e. dexterous grasping and motions) and complex locomotion (i.e. bipedal locomotion) (Ishida et al, 2004). Another reason is that a humanoid robot is a unique platform which helps us to discover the physical principles behind human-like skills and human-like intelligence (Xie et al, 2004). In the past twenty years, we have seen many humanoid robot projects around the world. Among them, we can mention HRP (Kaneko et al, 1998), BIP2000 (Espiau et al, 2000), ASIMO (Sakagami et al, 2002), QRIO (Ishida et al, 2004), HOAP (Kurazume et al, 2005) and HUBO (Kim et al, 2005).

In this chapter, 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.

2. Blueprint of Artificial Life

With the advance in mechanics, electronics, control, and information technology, it is natural for people to dream of creating artificial life, which could possess a sophisticated body, brain and mind (Xie, 2003). And, it is always the dream of human beings to create an artificial life called *robot*, which could help us to perform dirty, difficult, or even dangerous, jobs. Before we venture into the creating of artificial life, it is interesting to ask this question: *What is an artificial life?*

This is a difficult question. Only the designer of life is able to provide the full answer. However, from an engineering point of view, we can identify the key steps which evolve non-life into life.

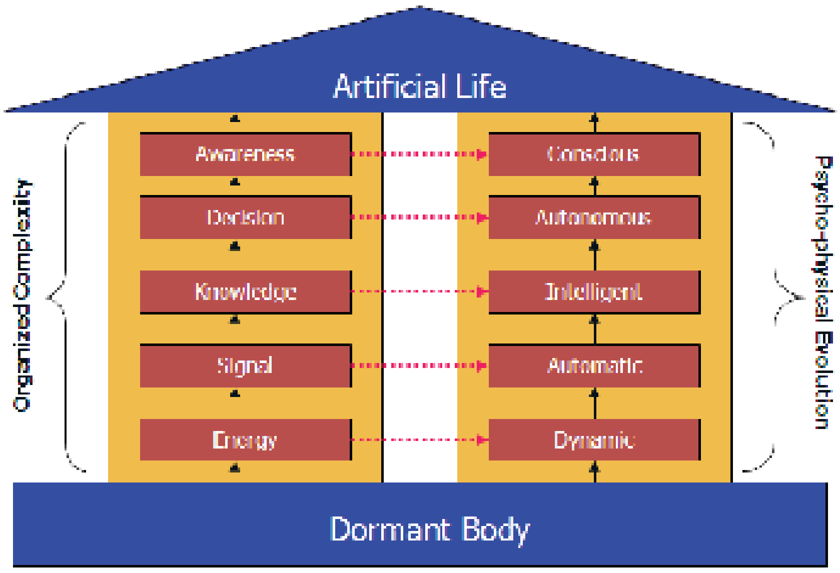


Fig. 1: Five steps leading to artificial life.

Refer to Figure1. 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

3.1 Blueprint of Body

In general, a humanoid robot's body will consist of structure and mechanism (Kim et al, 2005). The purpose of structure is to house a humanoid robot's computational modules, communication modules, actuation modules and sensing modules. And, the main structure will be located at the trunk of a humanoid robot. On the other hand, the purpose of mechanism is to produce motions which in turn enable a humanoid robot to perform actions. And, a mechnism is much more complex than a structure.

Since a humanoid robot has a human-like body, the blueprint of a humanoid robot's body will cover the mechnism of neck, the mechanism of arm, the mechnism of hand, the mechanism of waist, the mechanism of leg and the mechanism of foot. And, the generic design requirements for a humanoid robot's body include:

1. The payload and degrees of freedom at the neck.
2. The payload and degrees of freedom at each arm.
3. The payload and degrees of freedom at each hand.
4. The payload and degrees of freedom at the waist.
5. The payload and degrees of freedom at each leg.
6. The payload and degrees of freedom at eah foot.

In order to enable a humanoid robot to perform human-like motions, the layout of degrees of freedom and the angle ranges of these degrees of freedom must closely follow the corresponding data of a human being. However, a human being's body is a bio-mechanic system, which has redundancy in kinematics. Therefore, it is necessary to do some simplification. For instance, a humanoid robot's neck may just have two degrees of freedom. And, a humanoid robot's waist is good enough to have two degrees of freedom as well.

In mechanics, a degree of freedom indicates an allowable motion between two rigid bodies along, or about, an axis. In order to specify the orientation of an axis, it is necessary to define a global reference coordinate system as shown in Figure 2.

Refer to Figure 2. The global reference coordinate system is placed on a ground. The Z axis is perpendicular to the ground. The rotation about Z axis is called *Yaw*. The Y axis is in the coronal plane of a humanoid robot. The rotation about Y is called *Pitch*. And, the X axis is the in sagittal plane of a humanoid robot. The rotation about X axis is called *Roll*.

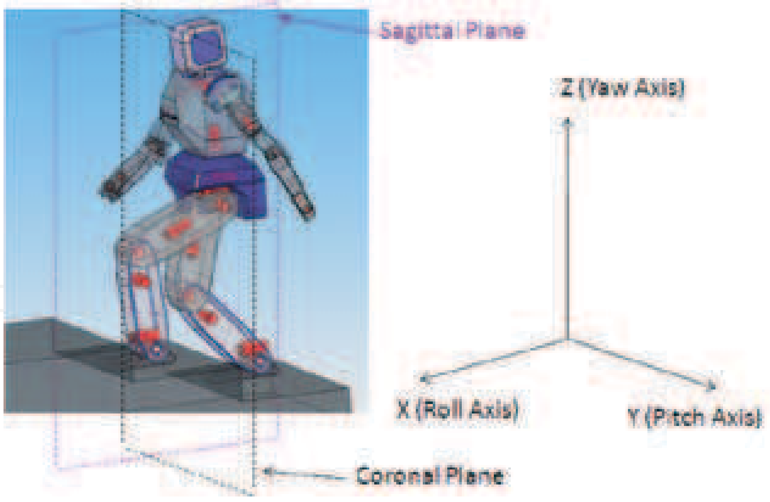


Fig. 2: Definition of reference coordinate system and (Yaw, Pitch, Roll).

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.

Figure3 shows a typical layout of the degrees of freedom in a humanoid robot.

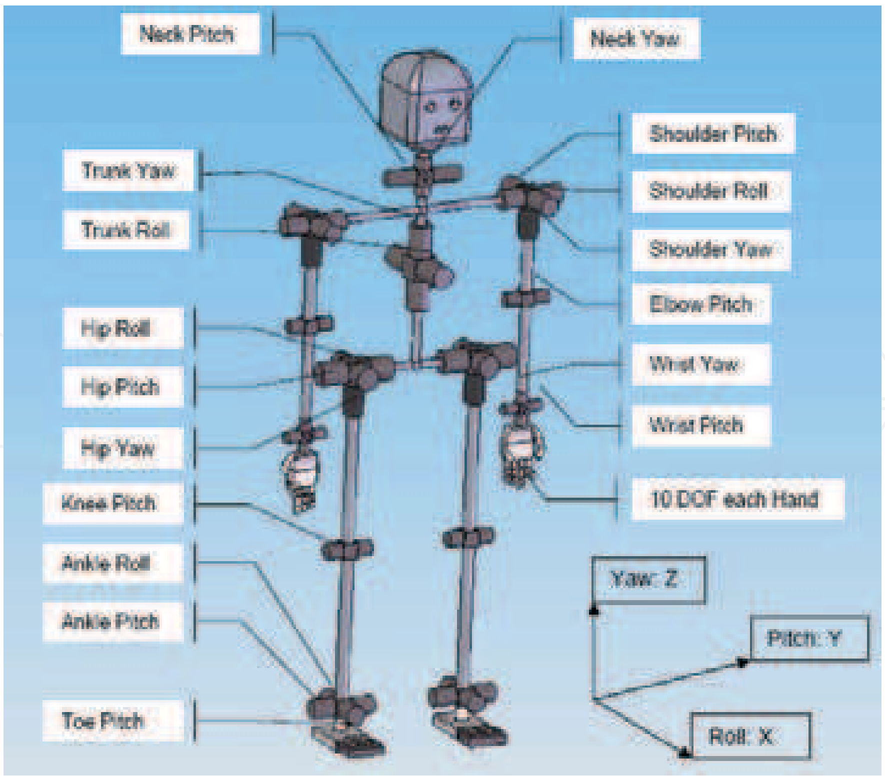


Fig. 3: Layout of degrees of freedom in a humanoid robot.
We can see that the orientations of these degrees of freedom are as follows:

1. Neck: (Yaw, Pitch)
2. Arm: (Pitch, Roll, Yaw) at shoulder; Pitch at elbow; (Pitch, Yaw) at wrist.
3. Hand: (Yaw, Pitch) at thumb; (Pitch, Pitch) at other fingers.
4. Waist: (Yaw, Roll)
5. Leg: (Pitch, Roll, Yaw) at hip; Pitch at knee; (Roll, Pitch) at ankle.
6. Foot: Pitch.

3.2 Blueprint of 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 Figure4.

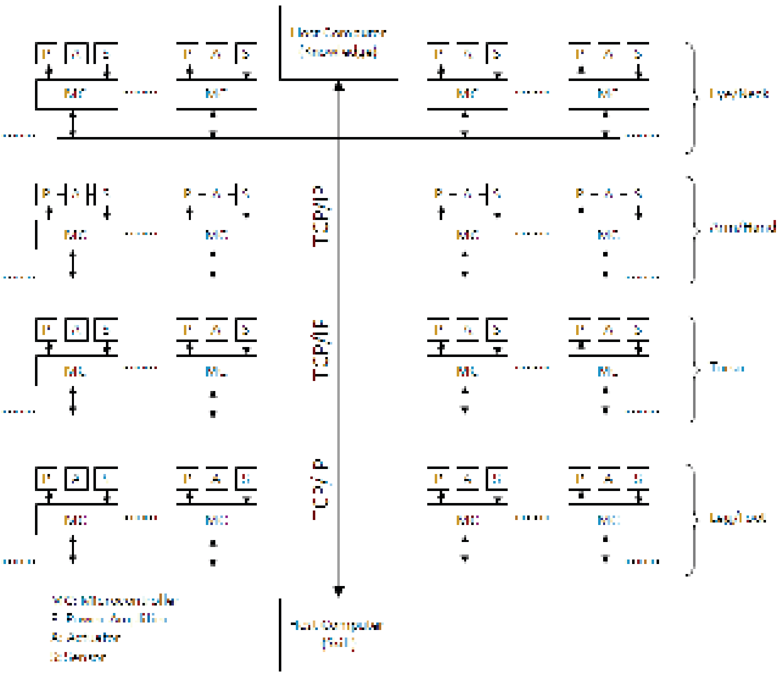


Fig. 4: A network of distributed microcontrollers and two main computers.

Refer to Figure4. 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.

3.3 Blueprint of 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 Figure 5.

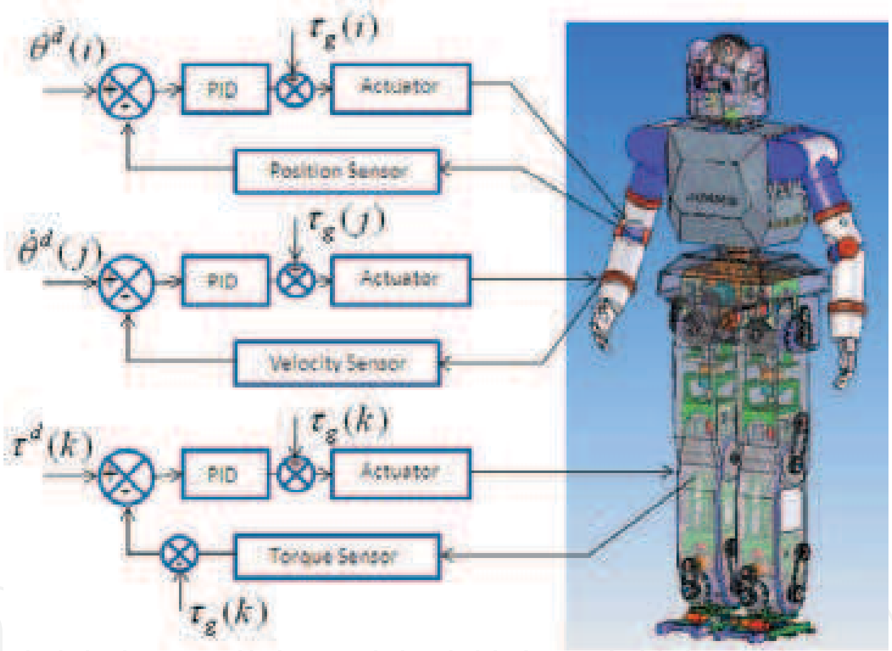


Fig. 5: Behavioral mind consisting of feedback control loops at the joints.

In Figure 5, $(\theta^d, \dot{\theta}^d, \tau^d)$ 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.

It is worthy noting that there is no significant progress in artificial intelligence, despite the huge amount of research efforts devoted to this field and other related fields such as cognitive sciences, machine learning, and natural language processing. This stagnation is largely due to the lack of clear statements of the fundamental questions to be faced by artificial intelligence. People fail to clearly define such fundamental questions because the main focus of the actual research efforts is on the so-called *computer-aided human intelligence*, which is real and not artificial. And, the typical example of such endeavour is the IBM's deep blue project, in which the computer has no intelligence at all.

Here, we believe that artificial intelligence literally means the self-intelligence in robots or machines. Therefore, the fundamental questions to be faced by artificial intelligence include:

- What is the physical principle behind the transformation from visual signals into the cognitive state of knowing the meanings behind these signals? And, how to implement this physical principle onto a robot or machine?
- What is the physical principle behind the transformation from auditory signals into the cognitive state of knowing the meanings behind these signals? And, how to implement this principle onto a robot or machine?
- What is the blueprint behind the representation of learnt meanings? And, how to implement this blueprint onto a robot or machine?
- What are the processes and their working principles, which manipulate the learnt meanings for various activities related to knowledge and skill?

It is interesting to note that human mind is implemented onto a human brain, which has a neural architecture. In addition, a human mind is very powerful in undertaking both knowledge-centric activities and skill-centric activities. However, these two types of activities are very different. Then, we may ask this fundamental question: *What are the models behind a neural architecture, which share a same hardware infrastructure?*

In (Xie et al, 2004), we first show that the mathematical principle behind a neural network and hidden Markov model has the root on the state space equation, which describes the dynamic behaviours of any dynamic system. In other words, the model of a neural architecture for skill-centric activities is rooted on the *state space equation*.

Also, in (Xie et al, 2004), we outline a meaning centric framework for the representation of learnt meanings. We believe that a natural language is the best solution of knowledge representation. The evidence is our libraries, in which all learnt knowledge is documented in natural languages. Therefore, one crucial issue in artificial intelligence is: *what is the universal principle for a human mind to represent a natural language*?

Here, we advocate a concept-physical principle for the representation of a natural language, as shown in Figure 6, 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.

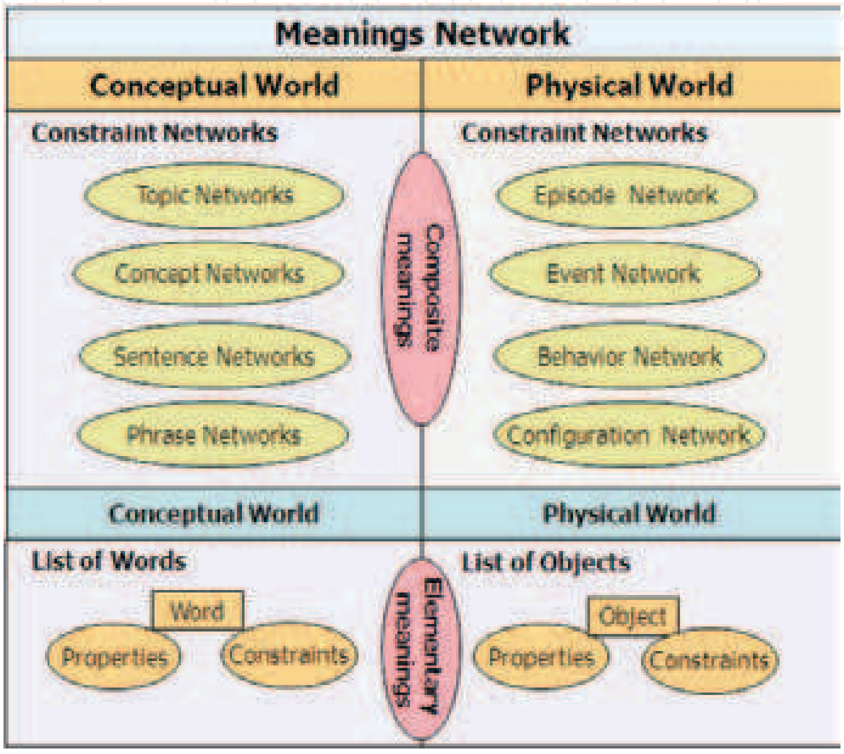


Fig. 6: Knowledge representation by meaning network.

In Figure 6, we have clearly defined what the knowledge (i.e. meanings) is. And, features 6, 7 and 8 solve the important problem of symbol grounding faced by the old paradigm for the study of natural language understanding.

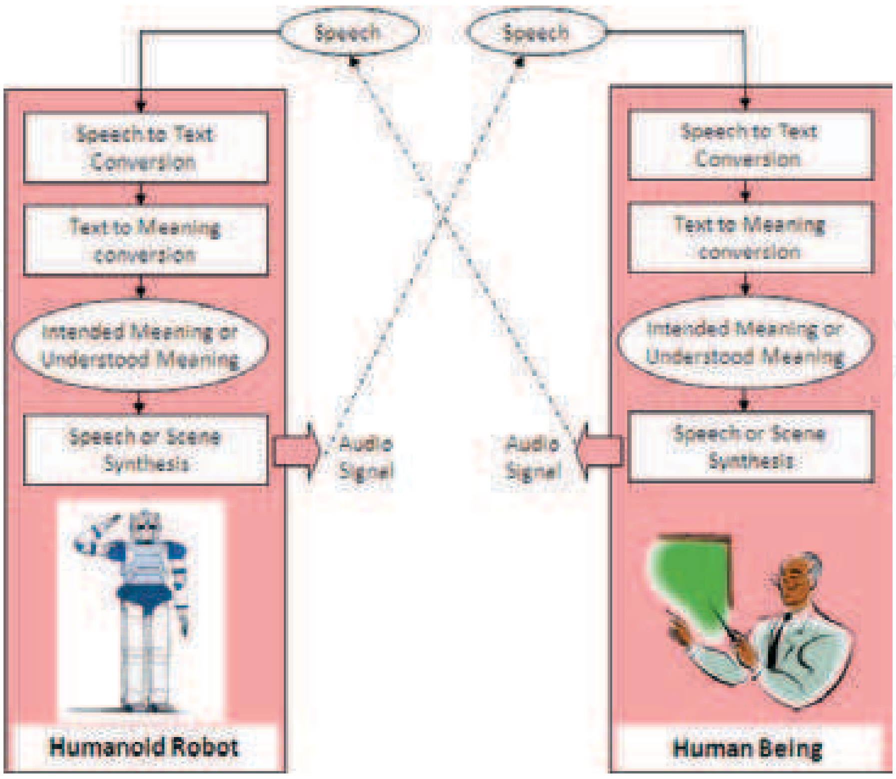


Fig. 7: Scheme of conversational dialogue with a natural language.

With the implementation of such a meaning network as shown in Figure 6, it becomes possible for robots to learn and converse in human language, insead of making human beings to continue to learn and program in machine language. Most importantly, the ability of undertaking conversational dialogues with a natural language, as shown in Figure 7, will be a decisive step for humanoid robots to be deployed into home enviroment for various services.

In summary, the blueprint of a human-like mind is two fold. First of all, the model for skill-centric activities is rooted on state space equation, which is effective in describing the dynamic response of any dynamic system. Second, the model for knowledge-centric activities is rooted on meaning network, which enables a range of mental processes to do jobs such as learning, analysis, synthesis, understanding, decision-making, and inference.

4. Design Considerations

When we implement the generic blueprints of body, brain and mind, we must consider several issues which may not be trivial.

4.1 Actuation by the Principle of Many-to-Many Coupling

Although it is relatively easy to choose materials and to size the motors during the detailed design of a humanoid robot's body, the issue of actuation is generally overlooked. One reason is because many researchers and engineers believe that the solution to actuate a joint is simply to use an actuator. However, careful analysis will revieal that there are different ways of actuating the joints in a body.

For instance, a human body's skeleton is actuated by musles. And, it is interesting to note that some joints are actuated by multiple muclses in order to achieve the redundancy in actuation. In this case, when one mucle faces a problem, a joint will not be handicaped in general. Such a scheme of coupling many muscles with many joints is useful in achieving reliable actuation. In engineering terms, the idea of coupling many actuators with many joints can be depicted in Figure 8.

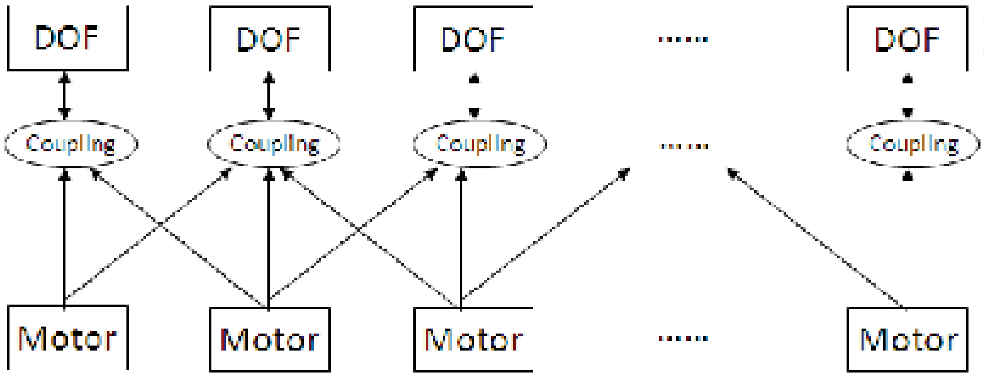


Fig. 8: Actuation scheme of coupling many actuators with many joints.

Another example is to use a single actuator to independently drive many joints in a robot (Zhu et al 2000; Xie, 2003). Such a scheme of coupling one actuator with many joints is useful if we want to reduce the weight and cost.

Unfortunately, today's robots are still follow the old scheme of coupling one actuator with one joint. This scheme has the least reliability. When one actuator fails, a joint will systematically fail. As a result, a robot will fall as shown in Figure 10, in which the knee joint of the robot's right leg fails during the climbing of staircase.

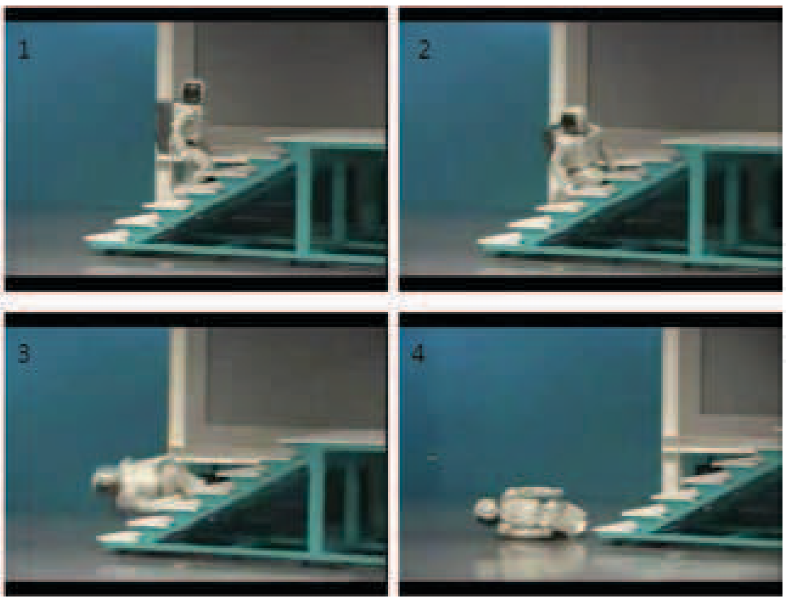


Fig. 9: Failure due to actuation scheme of coupling one actuator with one joint.

In engineering terms, the idea of coupling one actuator with one joint is simple to be implemented. Figure 10 illustrates the actuation scheme of coupling one actuator with one joint.

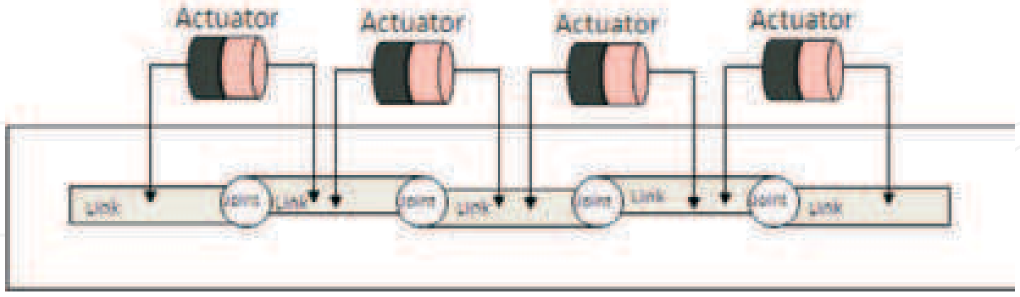


Fig. 10: Actuation scheme of coupling one actuator with one joint.

4.2 Foot with Variable Length

A human being's foot is not a single rigid body. It has at least one pitch joint (Bruneau, 2006). Interestingly, such a design enables a foot to have a variable foot length, which in turn will have two advantages.

First of all, a larger foot helps increase the stability of a humanoid robot during standing or walking. Second, a smaller foot (i.e. a shorter foot length) helps a humanoid robot to run/jump at ease. As shown in Figure 11, when a humanoid robot is lifting up the body, the lifting force comes from the torque at the ankle joint (or knee joint). From the relationship between force and torquem, it is clear that the shorter the foot length is, the larger the lifting force will be, when the torque remains the same.

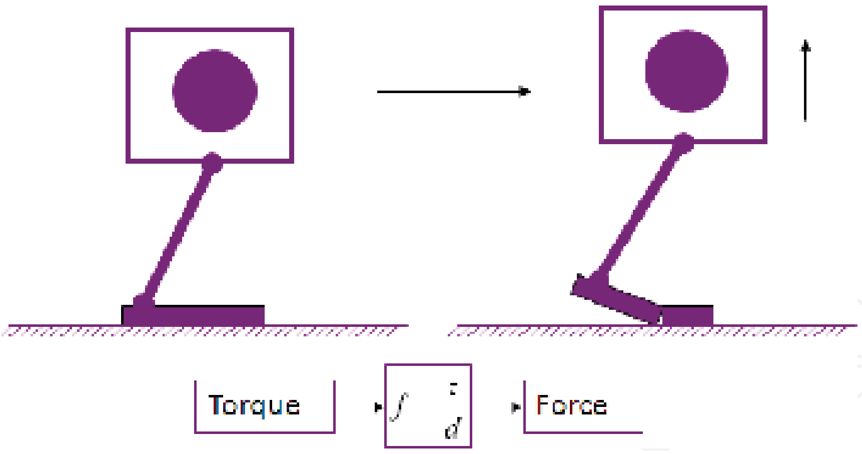


Figure 11: A variable foot length helps generate larger lifting force.

Similarly, when a humanoid robot lands with a same impact force, the shorter the foot length is, the smaller the impact torque at the ankle joint will be.

In pratice, we can design a humanoid robot's foot with two rigid bodies. When a humanoid robot's foot consists of two links with the lengths of (l_1, l_2), the foot could have three possible configurations of length, such as: a) $l_1 + l_2$, b) l_1, and c) l_2.

4.3 Body with Massive Network of Sensors

A human being's body is not only agile in performing motions, but also sensible in capturing visual, auditory, kinesthetic, olfactory, taste, and thermal signals. Most importantly, a human being's body is a massive network of sensors. Such a massive sensing capability helps simplify the complexity of decison-making in undertaking appropriate actions in response to sensed signals.

Due to cost, today, it is still difficult to develop a humanoid robot which is as sensible as a human beings.

4.4 Behavioral Control

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 Figure 12(a).
- Action selection among the generic actions of manipulation as shown in Figure 12(b).
- Motion description for a selected action.

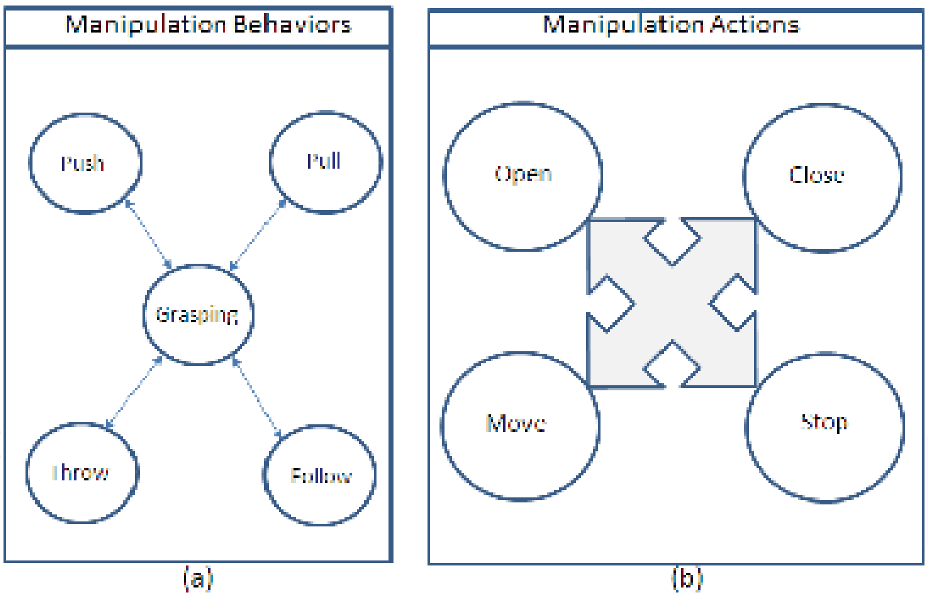


Fig. 12: Generic behaviours and actions for manipulation.

On the other hand, in the effort toward the design of planning and control algorithms for biped walking, not enough attention has been paid to this top-down approach of behavioral control. For instance, a lot of works is focused on the use of ZMP (i.e. zero-moment point) to generate, or control, dynamically stable gaits. Such stability-centric approaches do not answer the fundamental question of how to walk along any intended trajectory in real-time and in real environment. Because of the confusion on the relationship between cause and effect, one can hardly find a definite answer to the question of how to reliably plan and control a biped walking robot for any real application.

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 Figure 13(a).
- Action selection among the generic actions of a leg shown in Figure 13(b).
- Motion description for a selected action.

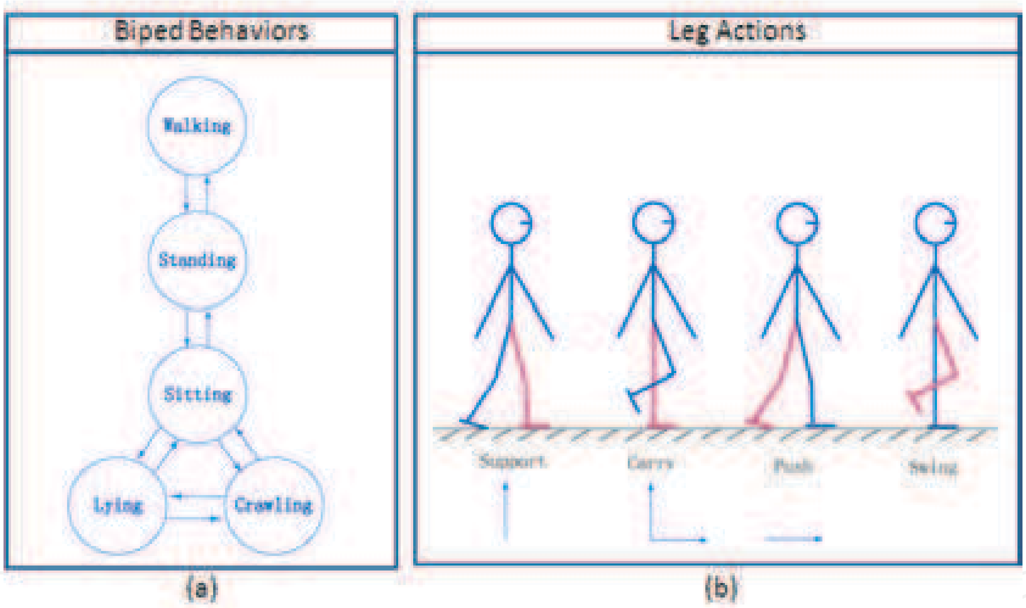


Fig. 13: Generic behaviours and actions for biped locomotion.

In order to show the importance of top-down approach for behavioral control, we would like to highlight the following correct sequence of specifying the parameters of walking:

- Step 1: To determine the hip's desired velocity from task, intention, or sensory feedback.
- Step 2: To determine the step length from the knowledge of the hip's desired velocity.
- Step 3: To determine the walking frequency (i.e. steps per unit of second) from the knowledge of the hip's desired velocity and the chosen step length.

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 Figure 14.

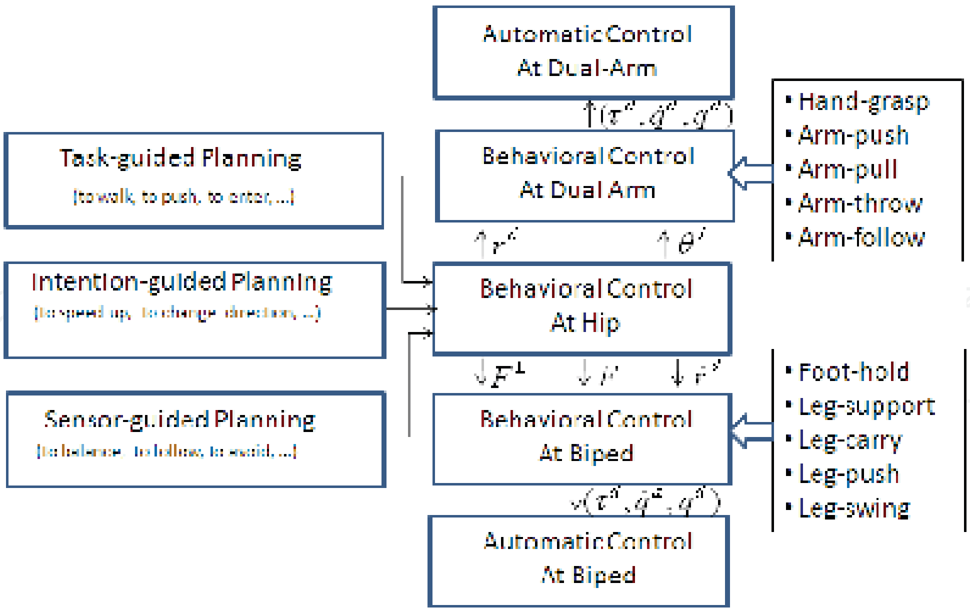


Fig. 14: Interface between behavioural control and automatic control.

4.5 Cognitive Vision

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.

4.6 Cognitive Linguistics

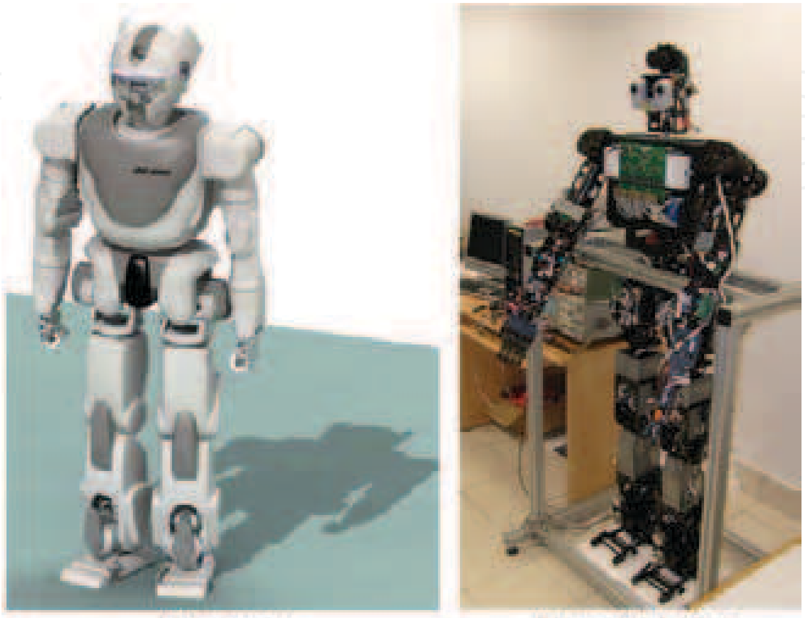
Human beings can communicate effectively in using a natural language. And, the instructions to human beings can be conveyed in both written and spoken languages. In engineering terms, such a process of instructing a human being on what to do is very much similar to programming. But, this type of programming 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.

5. Implementations

5.1 Appearance and Inner Mechanisms

Our LOCH humanoid robot has the appearance and inner mechanisms as shown in Figure 15. And, the general specifications of the robot body are given in Table 1.



(a) Appearance (b) Inner Mechanisms

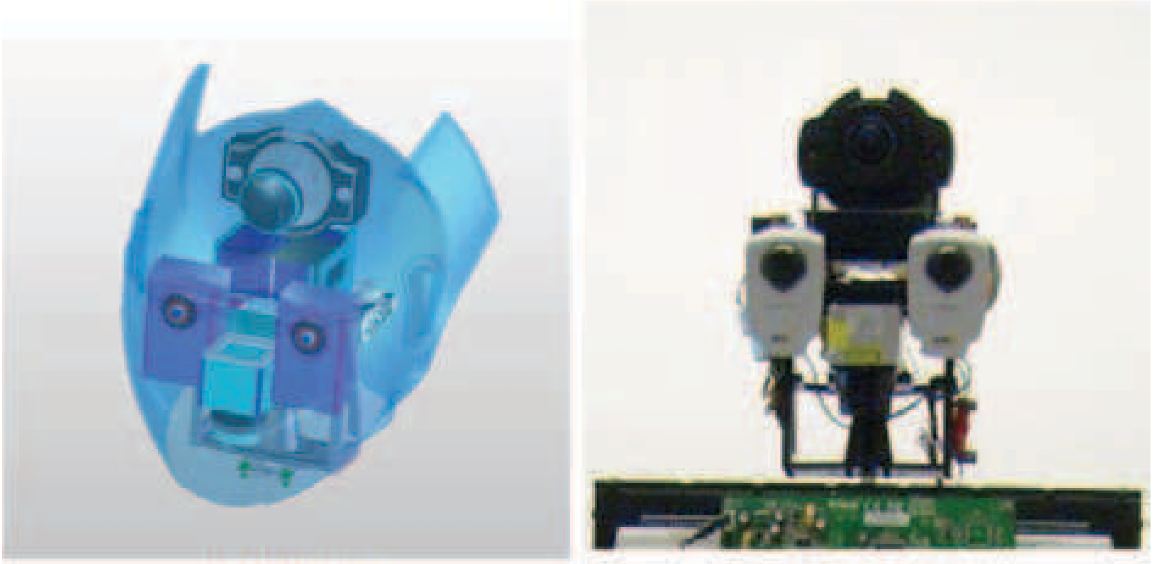
Fig. 15: LOCH humanoid robot: a) appearance and b) inner mechanisms.

Body weight:	80 kg
Body height:	1.75 m
Body width:	0.60 m
Body depth:	0.25 m

Table 1: Specifications of body.

5.2 Robot Head

The primary function of robot head is to sense the environment in which a humanoid robot is going to perform both manipulation and location. In our design, we have incorporated four types of environmental sensing capabilities, namely: a) monocular vision, b) stereovision, c) distance finder (up to 200 meters) and d) laser range finder (within 4 meters). Figure 16a shows the CAD drawing of the robot head, while the real prototype without external cover is shown in Figure 16b. And, the specifications of the robot head are listed in Table 2.



(a) CAD Model (b) Actual Prototype

Fig. 16: Head of LOCH humanoid robot: a) CAD model and b) actual prototype.

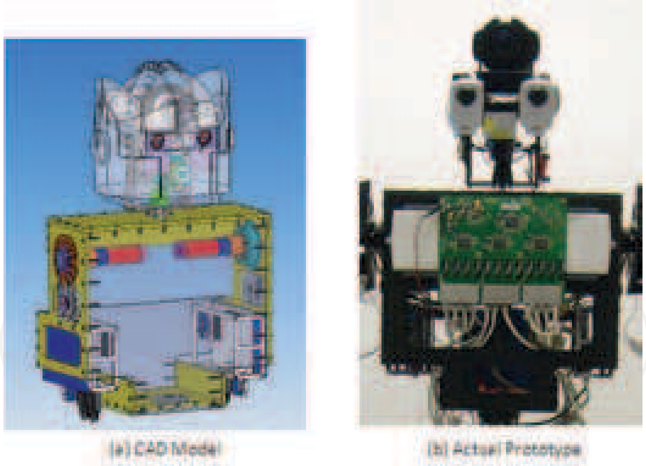
Weight:	4 kg
Height:	22 cm
Width:	25 cm
Depth:	25 cm
Degrees of Freedom:	● Two DOFs at the neck (Yaw + Pitch)
Sensors	● One PTZ camera ● Two stereo cameras ● One distance finder ● One laser range finder ● Absolute encoder at each neck joint
Actuators:	● Two DC brush motors ● Two low-power amplifiers ● One micro-controller
Functions	● Visual perception ● Nod ● Gaze

Table 2: Specifications of Robot Head

5.3 Robot Trunk

The primary function of robot trunk is to house the host computers and power units. In addition, the robot trunk has two degrees of freedom which enable a humanoid robot to turn left and right, and also to swing left and right.

In Figure 17, we can see both the CAD model of the robot trunk and the real prototype of the robot trunk. And, the specifications of robot trunk are listed in Table 3.



(a) CAD Model (b) Actual Prototype

Fig. 17: Trunk of LOCH humanoid robot: a) CAD model and b) actual prototype.

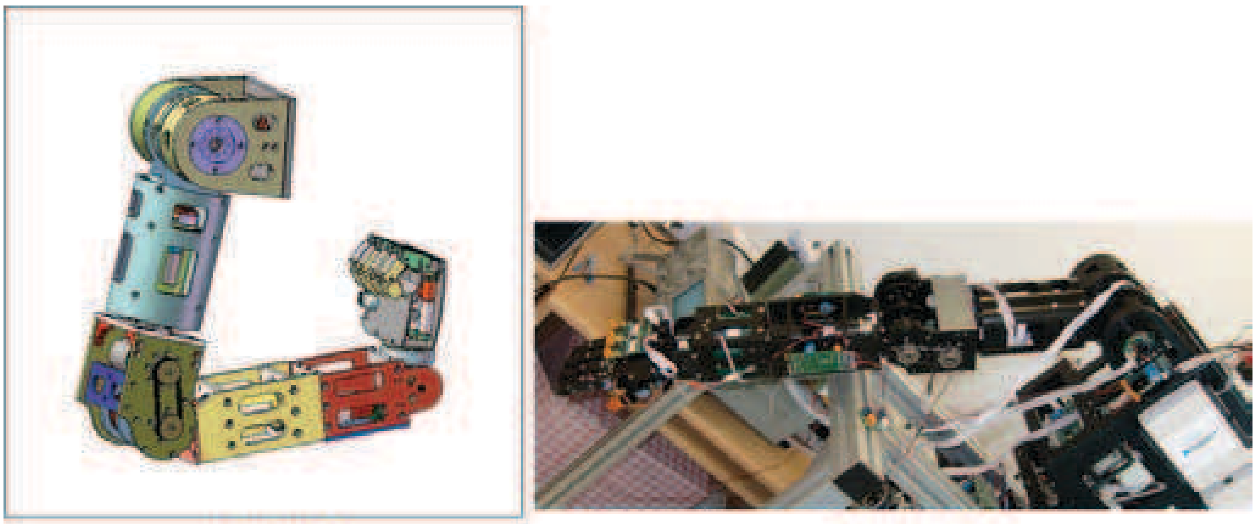
Height:	58 cm
Width:	40 cm
Depth:	20 cm
Weight:	24 kg
Computing Units:	● Two PC104 ● One wireless hub
Power Units:	● Capacity: 20 AH at 48 VDC ● Current: 20 A ● Voltage: 5V, 12V, 24V and 48V ● Weight: 15 kg
Degrees of Freedom:	● Two DOFs at the waist (Yaw + Roll)
Sensors:	● One 3-axis GYRO/Accelerometer ● Three microphones
Actuators	● Two DC brush motors ● Two low-power amplifiers ● One microcontroller
Functions	● Torso turn ● Torso swing

Table 3: Specifications of robot trunk.

5.4 Arms and Hands

Arms and hands are very important to a humanoid robot if it will perform human-like manipulation. And, the design of arms and hands should enable a humanoid robot to achieve these five generic manipulation behaviors: a) grasp, b) push, c) pull, d) follow and e) throw.

In Figure 18, we show both the CAD model and the real prototype of LOCH humanoid robot's arms and hands. We can see that LOCH humanoid robot has human-like hands, each of which has five fingers. And, the specifications of arms and hands are shown in Table 4.



(a) CAD Model (b) Actual Prototype

Figure 18: Arms and hands of LOCH humanoid robot: a) CAD model and b) actual prototype.

Length:	● Upper arm: 32 cm ● Forearm: 28 cm ● Hand: 16 cm
Weight:	● Upper arm: 2.0 kg ● Forearm: 2.5 kg ● Hand: 1.8 kg
Degrees of Freedom:	● 3 DOFs in shoulder ● 1 DOF in elbow (Pitch) ● 2 DOFs in wrist (Pitch + Roll) ● 2DOFs in the thumbs ● 2 DOF in other fingers (one DOF is passive)
Sensors:	● 6-axis force/torque sensor at each wrist ● Absolute encoder at each arm joint ● Potentiometer at each hand joint ● Incremental encoder at each joint ● Pressure sensors at palm and fingers
Actuators:	● Six DC brush motors for each arm ● Six DC brush motors for each hand ● Six low-power amplifiers for each arm ● Six low-power amplifiers for each hand ● Three microcontrollers for each

	arm ● Three microcontrollers for each hand
Functions:	● Grasp ● Pull ● Push ● Move ● Throw ● Hand-shaking ● Hand gesture ● Handling soft objects

Table 4: Specifications of robot arms and hands.

5.5 Legs and Feet

Legs and feet are unique features which differentiate a humanoid robot from an industrial robot. And, it is also very important to design legs and feet so that a humanoid robot could perform human-like biped walking/standing.

In Figure 19, we show both the CAD model and the real prototype of LOCH humanoid robot's legs and feet. It is worthy noting that LOCH humanoid robot has a ZMP joint in each joint, which is implemented by a six-axis force/torque sensor. This ZMP joint allows the control of the so-called in foot ZMP for leg stability (Xie et al, 2008). And, the specifications of arms and hands are shown in Table 5.

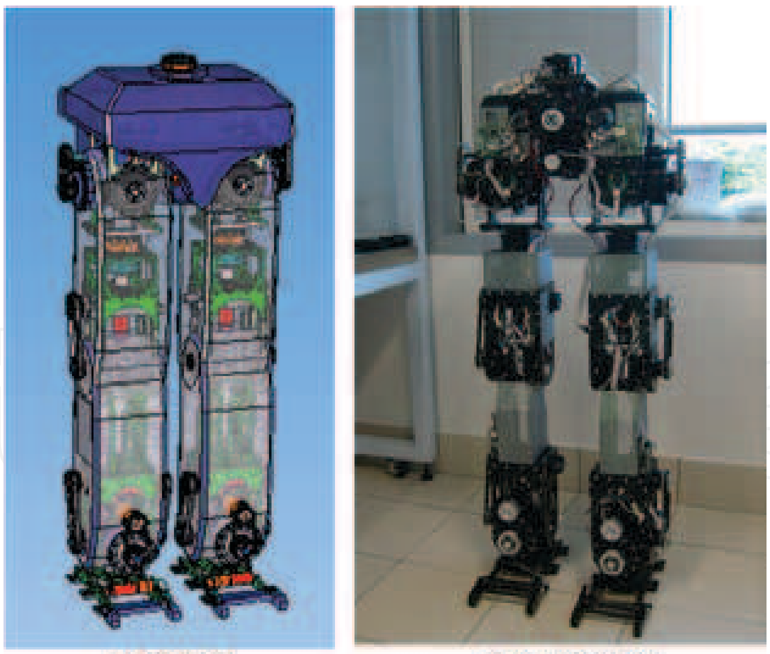

(a) CAD Model (b) Actual Prototype

Figure 19: Legs and feet of LOCH humanoid robot: a) CAD model and b) actual prototype.

Length:	● Thigh: 42 cm ● Shank: 42 cm ● Foot: 31 cm

Weight:	● Thigh: 8.0 kg ● Shank: 6.0 kg ● Foot: 2.2 kg
Degrees of Freedom:	● 3 DOFs in each hip joint ● 1 DOF in each knee joint (Pitch) ● 2 DOFs in each ankle joint (Pitch + Roll) ● 1 DOF in each foot
Sensors:	● 6-axis force/torque sensor below each ankle joint ● Absolute encoder at each joint ● Incremental encoder at each joint ● Six pressure sensors below each foot
Actuators:	● Five DC brushless motors for each leg ● One DC brush motor for hip yaw ● One DC brush motor for each foot ● Five high-power amplifiers for each leg ● One low-power amplifier for hip yaw ● One low-power amplifier for each foot ● Four microcontrollers for each leg/foot
Functions:	● Foot-hold ● Leg support ● Leg carry ● Leg push ● Leg swing ● Standing ● Sitting ● Stepping ● Walking ● Running ● Climbing ● Crawling ● Entering/exiting car

Table 5: Specifications of robot legs and feet.

6. Discussions

A good design will enable a sophisticated analysis, control and programming of a humanoid robot.

6.1 Kinematics

In terms of analysis, two important aspects are kinematics and dynamics. As a humanoid robot can be treated as an open kinematic chain with bifurcation, the tools for analysing industrial arm manipulator are applicable to model the kinematics of a humanoid robot (Xie, 2003).

However, one unique feature with a humanoid robot is that there is no fixed base link for kinematic modelling. Therefore, an interesting idea is to describe the kinematics of a humanoid robot with a matrix of Jacobian matrices. For instance, if a humanoid robot has N coordinate systems assigned to N movable links, a NxN matrix of Jacobian matrices is sufficient enough to fully describe the kinematic property of a humanoid robot. And, in Figure20, J_{ij} refers to the Jacobian matrix from link i to link j.

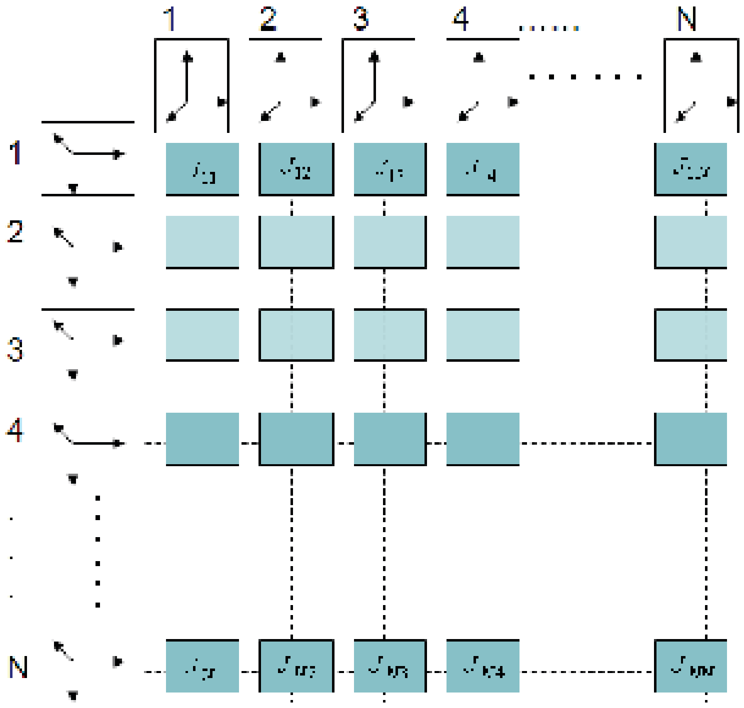
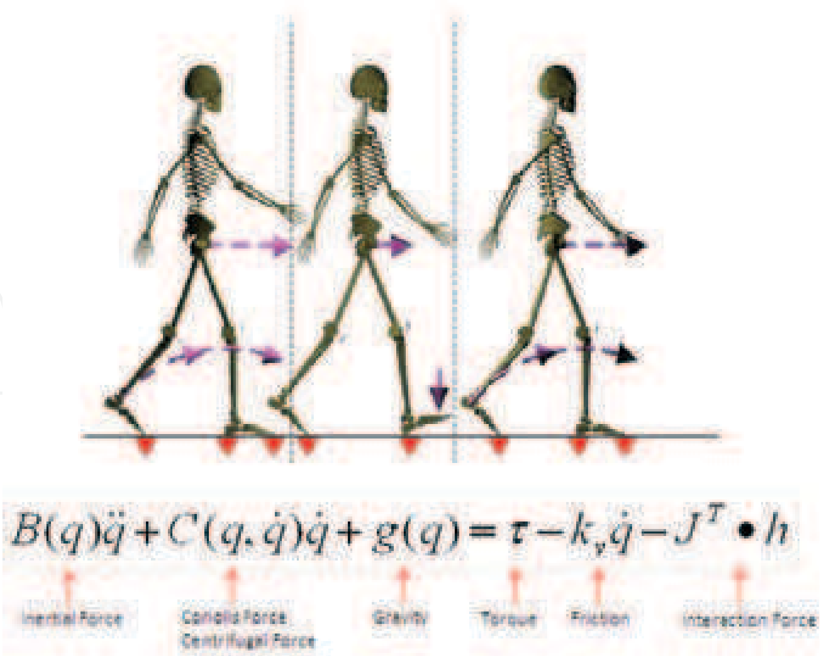


Fig. 20: A matrix of Jacobian matrices to describe the kinematics of a humanoid robot.

6.2 Dynamics

Given an open kinematic chain, the dynamic behaviour can be described by the general form of differential equation as shown in Figure21.

However, biped walking is not similar to manipulation. As a result, a common approach is to simplify a biped mechanism into a model called *linear inverted pendulum*. And, a better way to understand inverted pendulum model is the illustration by the so-called cart-table model (Kajita et al, 2003).



$$B(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=\tau-k_v\dot{q}-J^T\bullet h$$

Fig. 21: General dynamic equation of an open kinematic chain.

Here, we believe that we can treat a leg as an inverted arm with the foot to serve as the base link. In this case, the leg supporting the upper body of a humanoid robot is undergoing a constrained motion. And, it has both horizontal and vertical dynamics as shown Figure22.

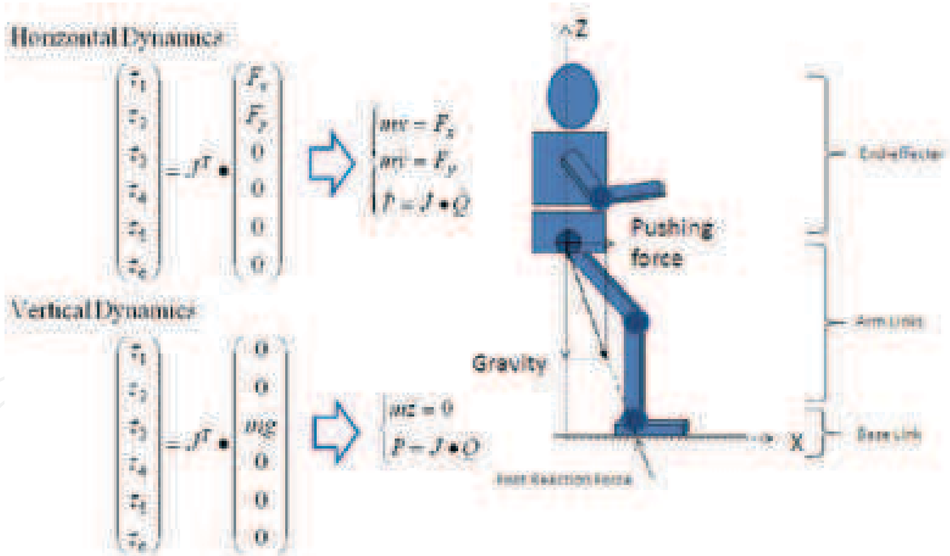


Fig. 22: Inverted arm model to describe the dynamics of a biped mechanism.

In Figure22, we assume that a leg has a six degrees of freedom. J is the Jacobian matrix of a leg. $\dot{P}$ is the hip's velocity vector and $\dot{Q}$ is the vector of the joint velocities of the leg. And, m is the mass of a humanoid robot's upper body.

6.3 Human-Aided Control

Today's robots still have limited capabilities in gaining the situated awareness through visual perception and in making meaningful decisions. Therefore, it is always useful to design a humanoid robot in such way that a human operator can assist a humanoid robot to perform complex behaviours of manipulation and/or biped walking.
Therefore, it is interesting to implement virtual versions of a real humanoid robot, which serve as the intermediate between a human operator and a real humanoid robot, as shown in Figure23.

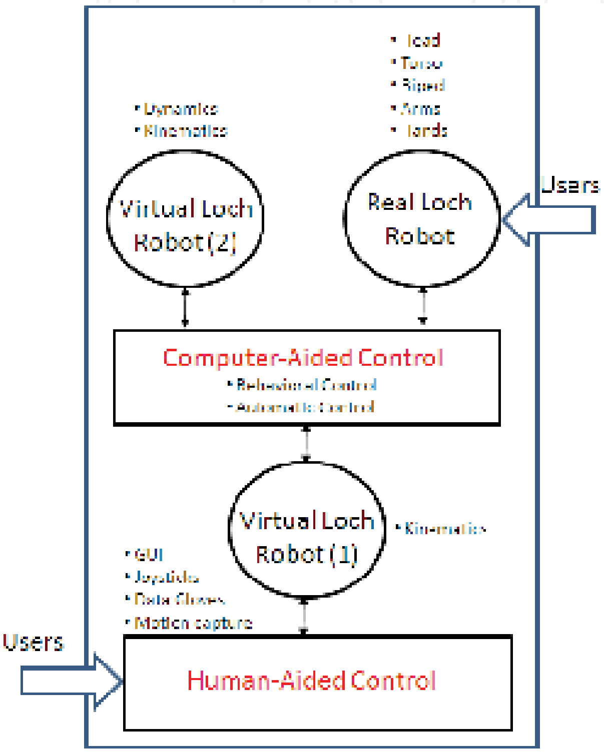


Fig. 23: Human-aided control through the use of virtual robots.

Refer to Figure 23. A human operator could teach a virtual robot to perform some intended tasks. Once a virtual robot has mastered the skill of performing a task, it will instruct the real robot to perform the same task through synchronized playback. On the other hand, a virtual robot could also play the role of relaying the sensory data of a real humanoid robot back to a human operator so that he/she will feel the sensation of interaction between a humanoid robot and its working environment.

7. Summary

In this chapter, we have first highlighted some characteristics observed from human abilities in performing both knowledge-centric activities and skill-centric activities. Then, we apply the observations related to a human being's body, brain and mind to guide the design of a humanoid robot's body, brain and mind. After the discussions of some important considerations of design, we show the results obtained during the process of designing our LOCH humanoid robot. We hope that these results will be inspiring to others.

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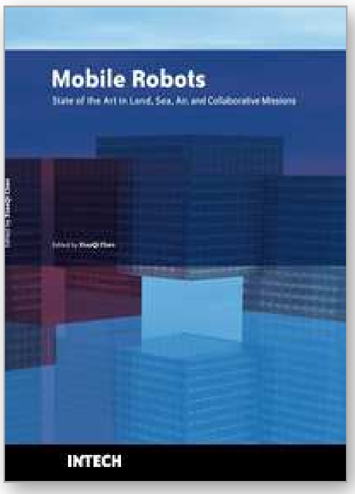

Mobile Robots - State of the Art in Land, Sea, Air, and Collaborative Missions
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Since the introduction of the first industrial robot Unimate in a General Motors automobile factory in New Jersey in 1961, robots have gained stronger and stronger foothold in the industry. In the meantime, robotics research has been expanding from fix based robots to mobile robots at a stunning pace. There have been significant milestones that are worth noting in recent decades. Examples are the octopus-like Tentacle Arm developed by Marvin Minsky in 1968, the Stanford Cart crossing a chair-filled room without human assistance in 1979, and most recently, humanoid robots developed by Honda. Despite rapid technological developments and extensive research efforts in mobility, perception, navigation and control, mobile robots still fare badly in comparison with human abilities. For example, in physical interactions with subjects and objects in an operational environment, a human being can easily relies on his/her intuitively force-based servoing to accomplish contact tasks, handling and processing materials and interacting with people safely and precisely. The intuitiveness, learning ability and contextual knowledge, which are natural part of human instincts, are hard to come by for robots. The above observations simply highlight the monumental works and challenges ahead when researchers aspire to turn mobile robots to greater benefits to humankinds. This book is by no means to address all the issues associated mobile robots, but reports current states of some challenging research projects in mobile robotics ranging from land, humanoid, underwater, aerial robots, to rehabilitation.

Xie M., Xian L. B., Wang L. and Li J. (2009). Biologically-Inspired Design of Humanoids, Mobile Robots - State of the Art in Land, Sea, Air, and Collaborative Missions, XiaoQiChen (Ed.), ISBN: 978-953-307-001-8, InTech, Available from: http://www.intechopen.com/books/mobile-robots-state-of-the-art-in-land-sea-air-and-collaborative-missions/biologically-inspired-design-of-humanoids

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