

# Soccer playing humanoid robots: Processing architecture, gait generation and vision system

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## ABSTRACT

Research on humanoid robotics in Mechatronics and Automation (MA) Laboratory, Electrical and Computer Engineering (ECE), National University of Singapore (NUS) was started at the beginning of this decade. Various research prototypes for humanoid robots have been designed and are going through evolution over these years. These humanoids have been successfully participating in various robotic soccer competitions. In this paper, three major research and development aspects of the above humanoid research are discussed. The paper focuses on various practical and theoretical considerations involved in processing architecture, gait generation and vision systems.

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## 1. Introduction

In the world we live in, many areas are created or configured for human access such as catwalks, tunnels, ladders or other restricted areas. Such areas can only be accessible by biped humanoids with a structure similar to humans. Recently, research on biped robots has attracted a lot of interest. The studies on biped robots are generally undertaken along two directions: (a) to elucidate the locomotion mechanism of humans from (robotics) engineering viewpoints, and (b) to impart intelligence for reproducing human-like activities.

### 1.1. FIRA and RoboCup

There are several international robotic soccer competitions for humanoid robots. RoboCup ([www.robocup.org](http://www.robocup.org)) and FIRA ([www.fira.net](http://www.fira.net)) act as fuel to draw the worldwide attention for the research and development on humanoid robots. These competitions help to exchange various technologies among the research communities.

### 1.2. The NUS humanoid robot

The research on humanoid robots in MA Laboratory, ECE, NUS started in early this decade. The first generation of autonomous soccer playing humanoid robot, MANUS (Fig. 1(a)), was released in 2001. MANUS has 17 degrees-of-freedom (DOF) and is capable of performing various complex soccer playing tasks such as penalty striker and dynamic balancing. Over the years, research has been undertaken towards implementing several soccer playing tasks,

and modifications are made to improve the existing humanoid platform. The latest prototype, GENUS (Fig. 1(b)), was released in 2007. With 21 DOF GENUS is capable of many features required in soccer playing. It operates as either a striker or a goalkeeper. It can dive and recover from a fallen position.

The research and development on the humanoid robots in NUS is not confined to theoretical, simulation and experimental studies. Humanoid research is kept abreast by actively participating at various competitions such as FIRA and RoboCup to compete with the contemporary humanoid platforms. MANUS is the overall humanoid champion at FIRA RoboWorld Cup competition in the years 2003, 2005 and 2006. It has won first runner up in the FIRA RoboWorld Cup competition 2004. GENUS is the first runner up for the FIRA RoboWorld Cup competition 2007 in the robot dash category.

In this paper, the evolution of three major aspects of humanoid research is discussed: processing architecture, gait generation, and vision. Section 2 discusses related works reported in the literature to define the scope of the paper. The evolution of processing architectures over the years is discussed in Section 3. Various gait generation techniques, used in the humanoids, are explained in Section 4. Section 5 provides an insight into the vision system used to achieve better image data acquisition. The paper is concluded in Section 6.

## 2. Related works

### 2.1. Processing architecture

The processing architecture has a severe impact on real-time decision making and task execution performed by humanoid robots. Generally, the architecture comes under two categories: Multi-Processing and Multi-Tasking.

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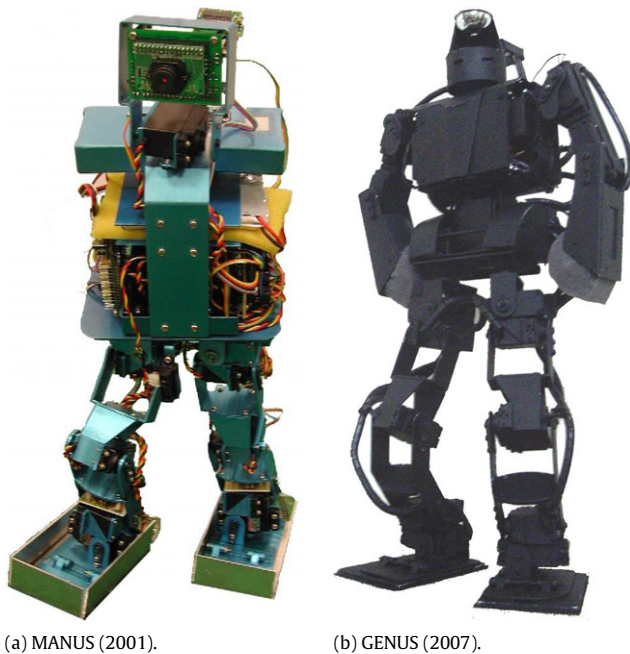


Fig. 1. The NUS humanoid robots.

**Multi-Processing:** In multi-processor architecture, more than one processor is utilized to handle the processing requirement for accomplishing a particular task. In humanoid robots, the requirement of parallel processing arises frequently. For example, information gathering from sensors, decision making based on them and gait generation for motion are expected to be pursued in parallel. The multi-processing architecture enhances the processing capabilities of such systems. However, use of multiple processors leads to increased complexity, space and resource overhead. Use of multi-processors in humanoid robots with height less than 60 cm is often restricted by its space and weight constraints. Moreover, multi-processor architecture needs a proper communication protocol for information exchange among different processing units.

**Multi-Tasking:** In single processor architecture, where task execution is often done sequentially, a certain task is executed after the completion of another. In the case of humanoids, different sensor data are very often read sequentially. The major disadvantage of such architecture lies in the bottleneck of sensors' feedback latency time and the resulting delay in decision making.

## 2.2. Gait generation

The motion of a humanoid robot comprises of time functions, trajectories, corresponding to angular positions and velocities of the robot's joints. Motion generated, as a combination of all these trajectories, is known as gait. The most noticeable difference between gait generation, in biped and multi-legged or wheeled locomotion, is the stability aspects. Generally, biped gaits are referred as stable when they are able to keep the structure upright. There are several analytical methods to verify the stability of certain biped gait. Zero-Moment-Point (ZMP) [1–7] is one of the most frequently used concepts in stability analysis. ZMP is defined as the point on the ground where the net moment of the inertial forces and the gravity forces have no component along the horizontal axes. Sufficient conditions for stable locomotion is to have the ZMP within the support polygon, the convex hull of the foot-support area, at all stages of the locomotion gait [8].

Based on the above analysis, biped gait generation is classified into three categories: trajectory-based, dynamic-based and the hybrid combination of trajectory-based and dynamic-based.

**Trajectory-based Gait Generation.** In Trajectory-based gait, biped robots use gaits that are generated from actual human walking. Several reported works on this method utilize additional control units to augment the reference joint trajectories [9]. A common form of augmentation is to use the Zero Moment Point (ZMP) to compute a desired stable foot placement [5]. Postural stability of bipeds are ensured by keeping the ZMP within the support polygon formed by the feet.

Central Pattern Generators (CPG) is another example of trajectory based approach. CPGs have been identified in most animals as being responsible for controlling many oscillatory activities like walking, swimming etc. They are mathematically formed by a set of coupled oscillators, some of which are excitatory and others inhibitory in nature. These oscillators, when configured properly, generate complete walking patterns. Many CPG models are proposed to explain the mechanism of motion pattern generation in humans. In [10], user supplied commands generate basic CPG. Cerebellar Model Articulation Controller (CMAC) [11, 12] neural network is used to generate joint angles for the proper balancing of a biped walking robot. Zheng [13] proposed a CPG which uses Van Der Pol oscillators to generate stable gait data for each joint.

Learning techniques such as neural network [14,15] and reinforcement learning [16] are used to generate walking gaits. Using feedback data and the learned parameters, the robot is able to control its stability when it is walking on uneven or inclined surface terrain.

A major drawback in using the trajectory-based control is the need for a large database to store the gaits required and very often the amount of motion data becomes insufficient to generate proper motion gaits. Nevertheless, trajectory-based control has achieved notable success in biped locomotion.

**Dynamics-based Gait Generation.** The dynamics-based control generates the joint time trajectories by solving inverse kinematics to maintain the physical stability of the humanoid based on system dynamics [17,18]. With an increase in DOF of the robot, it becomes computationally impractical to compute inverse kinematics. Moreover, such an approach often results in unnatural-looking motions and energy inefficiency. However, these approaches are suitable for off-line generation of joint trajectories.

The idea of dynamics-based control is modified and implemented by different approaches using natural dynamics in [19,20]. In these approaches, robots walk with natural gaits and energy efficiency. The advantage of dynamics-based control lies in the concept of using the passive effects of gravity and inertia to generate the gaits.

Hybrid approaches use a combination of both dynamics and trajectory based methods for gait generation. One such example is to use inverse kinematics to solve the joint angles. The inverse kinematics is solved and the solution is optimized, considering dynamics-based criterion such as ZMP to find out optimal gait [5].

## 2.3. Vision systems

In any intelligent system such as a humanoid robot, a vision system is necessary to provide information about the surrounding. A vision system may have either eye-to-hand configuration or eye-in-hand configuration. If a camera is fixed within the workspace, the vision configuration is called eye-to-hand or passive configuration. If a camera is mounted on the robotic system, it is an eye-in-hand or active configuration. In humanoid robots the camera is generally mounted on the robot's head and the vision system falls under the active-vision-system category.

In certain applications, it is desirable to extract three-dimensional information of the real-world from the corresponding two-dimensional image. Calibration is an obvious process to

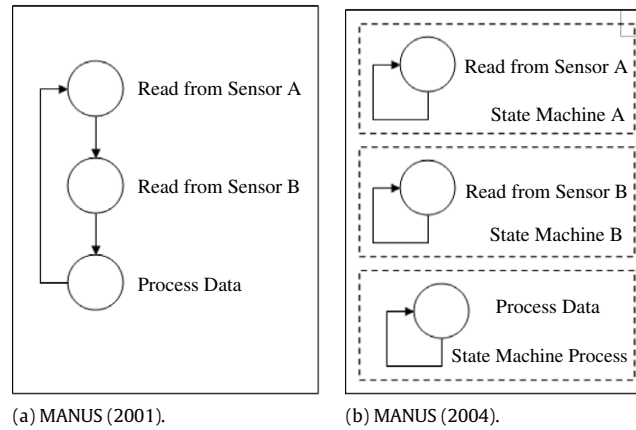


Fig. 2. The tasking architecture of the humanoid robots.

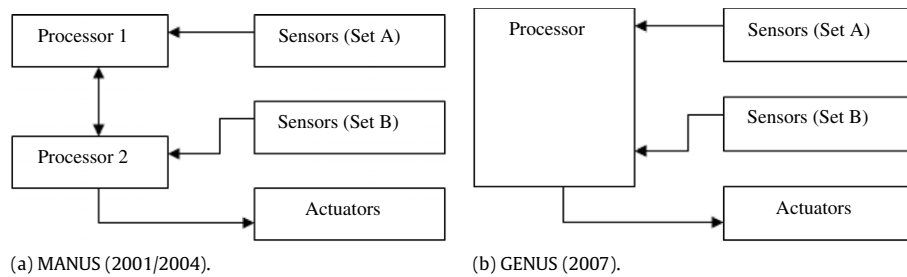


Fig. 3. The processor configuration of the humanoid robots.

address this issue. Calibration of any vision system involves parameter identification of two different natures: (a) Intrinsic parameters: parameters determining internal camera geometric and optical characteristics, (b) Extrinsic parameters: parameters to map the three-dimensional position and orientation of the real-world plane to the image-plane.

Vision-system calibration techniques can roughly be classified into two categories: photogrammetric calibration [21,22] and self-calibration [23,24]. The photogrammetric calibration methods use a known and well-structured object (called calibration reference) to determine the vision system parameters by matching the image-plane features to those on the calibration reference. Self-calibration uses the image of the environment instead of a calibration reference.

### 3. Processing architecture

The processing architecture in the humanoid robots such as MANUS and GENUS has been going through an evolution over the years. The computational requirement changes with time, bringing the processing architecture into consideration.

#### 3.1. Dual processor configuration (MANUS-2001)

Two processing units (Motorola DSP56F807 MPU, 16 bit 80 MHz processor) are used in MANUS: high level processor and lower body processor. The two processors communicate through a Serial Peripheral Interface (SPI) and are connected to various sensors (Fig. 3).

The high level processor processes information from various sensors. After processing the information from the sensors and deciding on the appropriate action to be taken by the robot, the high level processor sends the respective action commands to be executed by the low level processor via the SPI.

The low level processor controls the actuators for appropriate gait generation. As real-time computation and gait updates are

required during task execution, certain sensors (tilt and force sensors) are connected to the low level processor to reduce the latency time for processing the information required for decision making.

The advantage of the multi-processor configuration in MANUS is the decentralized processing architecture with increased processing capabilities.

#### 3.2. Dual processor configuration and virtual parallel machine architecture (MANUS-2004)

A noticeable feature of the Motorola DSP56F807 MPU processor is the multi-tasking programming paradigm called Virtual Parallel Machine Architecture (VPMA). Independent state machines can be built and executed in parallel in VPMA programming architecture. VPMA is a useful and effective technology for humanoid robots because of its need to integrate many different sensors and process sensor information in real-time (Fig. 2).

Unlike VPMA, the procedural programming architecture does not have parallel processing power. Procedural programs execute sequentially, i.e. each sensor is activated and read one-after-another which means the humanoid can only do single task at a time. Thus, reaction time of the robot is slower while using procedural programs.

Using VPMA, for every sensor on board, one state machine is built to control one sensor. The state machine is responsible for continuous monitoring and reading from that particular sensor. Thus, the main program is able to access the data of each sensor simultaneously during task execution, making the system response faster. For example, if there is a need to get information from the camera, the sequential approach halts the program and reads data from the camera. However, in a VPMA based architecture, the data retrieval is done by the dedicated state machine while the main program continues execution. With this architecture, a task program just needs to accomplish a particular task without consideration of organizing the sensor activation sequence. It acts as a library of real-time information stored in the database and

the main program simply needs to access the library for any information it needs about the environment.

### 3.3. Single processor configuration and virtual parallel machine architecture optimization (GENUS-2007)

In the dual processors configuration, in spite of higher processing capabilities, the need of communication between the two processors causes information latency. The speed with which information is shared is dependent on the communication protocols. The use of two processors also means a higher resource overhead and maintenance.

A single processor can be used to improve the utilization of the memory and computation power of the processor. The processing power is optimized by proper scheduling of the state machines for the sensors and gait generation by using the timer monitoring function embedded in the processor. By monitoring the timers, the state machine interval is kept consistent and any lapse in the state machine interval is immediately rescheduled to maintain the integrity of the timing.

Optimizing of the memory and computations are performed by using complexity analysis of the programs. Operational redundancy is reduced in the state machine for gait generation which is used for various computations of the trajectories. Memory pointers are dynamically repositioned to free memory banks that are not directly available in various part of the memory space to improve memory utilization.

The major advantages in using a single processor board are the elimination of inter-processor communication and the latency issues. In addition, a centralized control system provides better handling and processing of information among the state machines, leading to faster decision making and execution. Moreover, resource overhead is reduced without compromising the advantages of the multi-tasking feature of the VPMA paradigm.

## 4. Gait generation

### 4.1. Trajectory based gait generation utilizing ZMP criterion (MANUS-2001)

The robot's walking gait on a flat surface was first realized using a trajectory based gait generation algorithm. The walking gait is determined by the hip trajectory and the swing foot trajectory. The stability of the walking algorithm is characterized by the ZMP criterion.

The sagittal motion control algorithm includes the following steps:

- For each step, the desired final state, speed and position of hip and swing foot  $(v_{xhe}, v_{zhe}), (v_{xfe}, v_{zfe}), (x_{he}, z_{he}), (x_{fe}, z_{fe})$  and step length  $L_s$  (Fig. 7) are specified.
- The desired  $\theta_e$  (Fig. 8) is specified. The hip height adapting to the terrain is derived using the optimal hip height principle (4.1.9).
- The hip and foot trajectories are generated for the two parts of a single support period  $(T_1$  and  $T_p)$  (4.1.15).
- Change the parameters and repeat step i, ii, iii. The trajectory with satisfied ZMP trajectory is selected.
- The desired state at the beginning of a walking cycle is derived by Lemma 4.1.
- The double support phase drives the robot into the desired initial state.

*Single and double support phases.* A walking cycle can be divided into a single support phase and a double support phase. In Fig. 4, from point 1 to 2 is the single support phase, and from point 2 to 3 is the double support phase. In the single support phase, the support foot is stationary on the ground. The other foot swings from the back to the front. The hip also moves along a trajectory. The double support phase starts from the forward foot touching the ground and ends with the rear foot leaving the ground. During

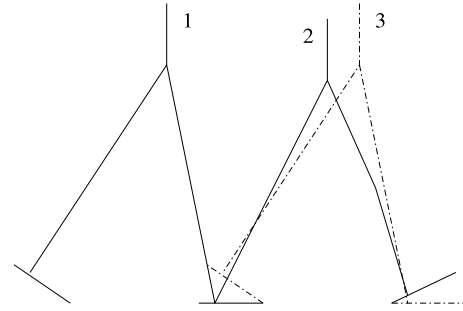


Fig. 4. Walking cycle: single and double support phase.

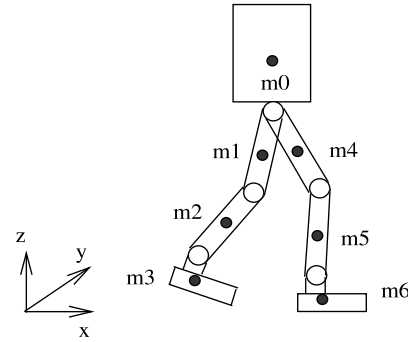


Fig. 5. Biped robot model.

the double support phase, the weight transfers from the rear foot to the forward foot. This phase is known as the weight acceptance phase [25].

To achieve continuous and dynamic walking, the transfer between single support phase and double support phase has to be smooth. At the beginning of the double support phase, the impact when the forward foot contacts the ground is very large and affects the walking stability. Force feedback control is used to resolve and minimize the reaction force to reduce instability during walking.

*ZMP and ankle torque.* The ZMP is the point on the ground where the sum of all the moments of the active forces equals zero. Under the assumption that no external force exists, the ZMP can be computed by [26]:

$$x_{zmp} = \frac{\sum_i m_i(\ddot{z}_i + g)x_i - \sum_i m_i\ddot{x}_i z_i - \sum_i I_{iy}\ddot{\theta}_{iy}}{\sum_i m_i(\ddot{z}_i + g)} \quad (4.1.1)$$

$$y_{zmp} = \frac{\sum_i m_i(\ddot{z}_i + g)y_i - \sum_i m_i\ddot{y}_i z_i - \sum_i I_{ix}\ddot{\theta}_{ix}}{\sum_i m_i(\ddot{z}_i + g)} \quad (4.1.2)$$

where  $(x_{zmp}, y_{zmp}, 0)$  is the coordinate of the ZMP,  $(x_i, y_i, z_i)$  is the mass center of link  $i$  on a Cartesian coordinate system.  $m_i$  is the mass of link  $i$ ,  $g$  is the gravitational acceleration.  $I_{ix}$  and  $I_{iy}$  are the inertia components,  $\ddot{\theta}_{iy}$  and  $\ddot{\theta}_{ix}$  are the angular speed around axis  $y$  and  $x$  about the center of mass of link  $i$  (Fig. 5).

Shown in Fig. 6, for the sagittal plane, the ZMP is derived directly through dividing the ankle torque by reaction force:

$$x_{zmp} = \frac{\tau_x}{\sum_i m_i(\ddot{z}_i + g)}. \quad (4.1.3)$$

Therefore, the ankle torque can be written as:

$$\tau_x = x_{zmp} \cdot \sum_i m_i(\ddot{z}_i + g). \quad (4.1.4)$$











