

The Development of Honda Humanoid Robot

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Abstract

In this paper, we present the mechanism, system configuration, basic control algorithm and integrated functions of the Honda humanoid robot. Like its human counterpart, this robot has the ability to move forward and backward, sideways to the right or the left, as well as diagonally. In addition, the robot can turn in any direction, walk up and down stairs continuously. Furthermore, due to its unique posture stability control, the robot is able to maintain its balance despite unexpected complications such as uneven ground surfaces. As a part of its integrated functions, this robot is able to move on a planned path autonomously and to perform simple operations via wireless tele-operation.

1. Introduction

In December 1996, Honda announced the development of a humanoid robot with two arms and two legs called P2. [1],[2].

Research and development of this humanoid robot was initiated in 1986. The desired goal was to develop a robot able to coexist and collaborate with humans, and to perform tasks that humans cannot. In other words, to create a mobile robot which brings additional value to human society. Thus Honda aims to develop a new type of robot able to meet consumer needs, and not a robot that is limited to specialized operations.

We believe that a robot working within a household is the type of robot that consumers may find useful. It was named the "Domestic Robot". For such a robot, it is necessary to be able to move around the house, where many obstacles such as the entrance, a staircase, doors and furniture exist. In order to move in such an environment, which is made for humans, Honda believes that a robot with legs and arms, and which can walk like a human, is the most practical and suitable configuration.

The first two legged (biped) robot of practical size was developed by Kato and et al. [3]. Since then, much research in this field has improved the performance of walking robots. But at that time (1986) the understanding of legged locomotion appeared to be limited, and a practical biped robot that walks like a human was difficult to realize.

Consequently the design of the Honda Humanoid

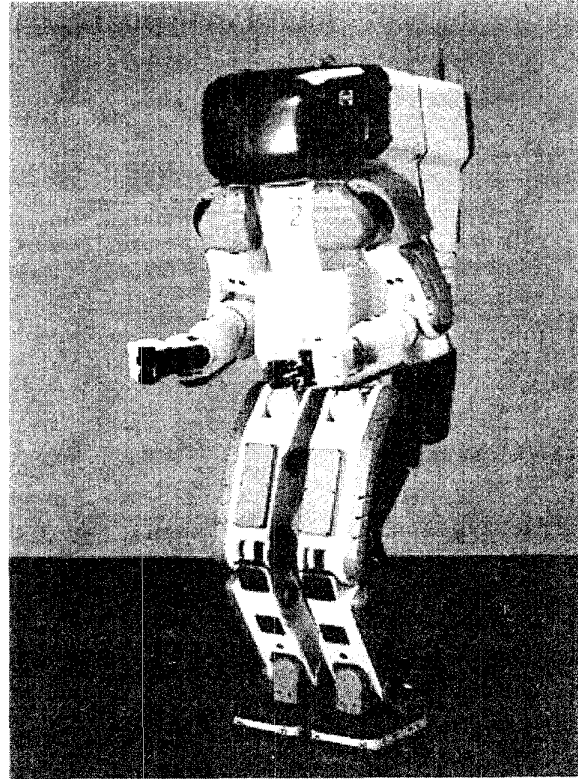


Figure 1 Honda Humanoid Robot

Robot started at the most basic level of research - a study of the biped walking mechanism.

2. Basic research and the Design policy

We analyzed the characteristics of a walking human, with experiments using ourselves as models. Based on these experiments, we developed the initial specifications of our robot.

An effort was made to set the location of the joints, their angles of rotation, dimensions and the center of gravity to be equivalent to a human leg. But it was difficult to satisfy all the conditions.

The number of leg joints was reduced to the minimum required for walking. It was set to 3 joints for the hip, 1 joint for the knee, and 2 joints for the ankle. The joints

equivalent to the toes were omitted. Hence it has 12 degrees of freedom in two legs. The joint torque was defined as being a level adequate to walk on flat surfaces and to go up and down stairs. The angles of rotation were set to satisfy the angles witnessed during the walking experiments.

Honda has developed several types of biped robot, and has performed research in the areas of high speed walking and increased payload. The maximum walking speed achieved by a specialized robot is 4.7 km/h. Another robot has walked with a payload of 70 kg. At the same time, we have achieved a robot posture stabilizing control similar to that of humans.

As a result of this research, it was concluded that the robot system requires a body inclination sensor, and a ground reaction force sensor for each foot. We learned that it is also important to absorb the landing-impact ground reaction force, and that an impact absorption mechanism is required.

As the next step, the Honda team developed humanoid robots. We defined the functional specifications of this humanoid robot as follows.

The robot should be of such a type that it can automatically perform certain tasks in a known environment, and other tasks, with assistance from a human operator, in an unknown environment.

We determined the robot width using the dimensions of a typical door through which our robot will pass. The length of the leg link was determined so as to be able to negotiate typically sized stairs. In the same way as the leg, the number of the arm joints was reduced to a minimum. It was set to 3 joints as the shoulder, 1 joint as the elbow, and 3 joints as the wrist. Hence it had 14 degrees of freedom in two redundant arms. The length of the arm

was determined by the required ability to pick up an object on the floor when the robot is in a squatting posture. Each arm was equipped with a hand. Its hands were designed for simple work, and for assisting locomotion, for example, clearing obstacles from the path of the robot. A force and torque sensor was also required for each wrist for the force control of the arms. The schematic view is shown in figure 2. The robot has also video cameras for the vision processing of robot or target position estimation, for inspection (for example the inspection of a chemical plant equipment) and for tele-operation.

3. Mechanism and System configuration of P2

P2 is a self-contained humanoid robot with two arms and two legs, and may be operated via wireless communication. The overall height is 1820mm, the width is 600mm (as shown in Figure 3), and the weight is 210 kg.

From the functional specifications we said before, its legs have 12 degrees of freedom in two legs and its arms have 14 degrees of freedom in two arms. The hand is similar to a two fingered gripper with 2 degrees of freedom. It is able to open and close between its thumb and the other fingers, which form a single moveable digit. Furthermore, by rotating the position of the thumb, it is able to grasp an object in other ways.

Each joint is actuated by a DC motor with a harmonic-drive reduction gear. Within its body is a control computer with four microprocessors (micro SPARC II) running the real-time operating system VxWorks. The processors are used for the arm control, leg control, the local control of the joints, and the vision processing respectively. Also within the body are DC servo amplifiers, a NiZn battery for the electronic

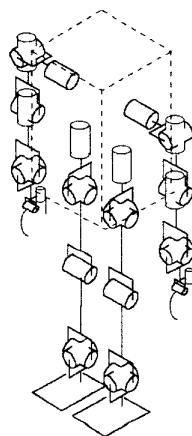


Figure 2 Schematic view of humanoid robot

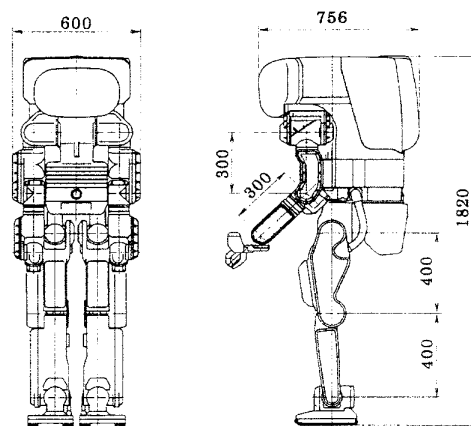


Figure 3 External shape of P2

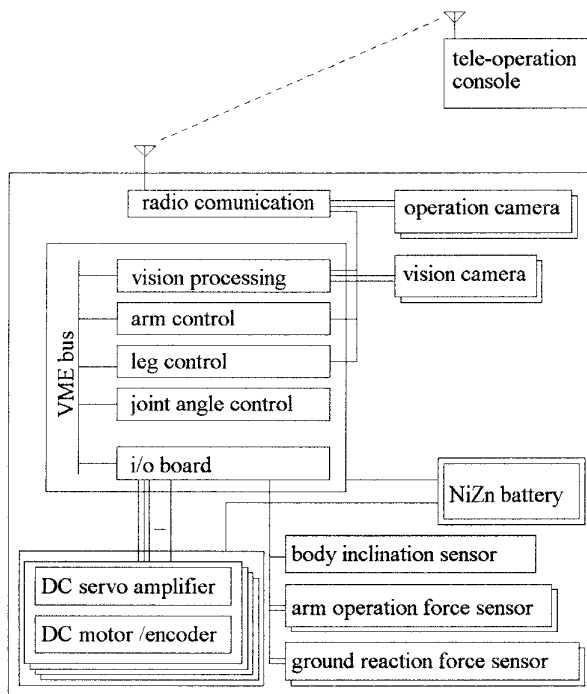


Figure 4 Overall system configuration of P2

components and actuators, and a wireless ethernet modem. The weight of the battery is approximately 20 kg. It is able to drive the robot for about 15 minutes. The use of an external power supply is also possible.

The sensors are as follows. The body is equipped with an inclination sensor which consists of three accelerometers and three angular rate sensors (optical fiber gyros). This

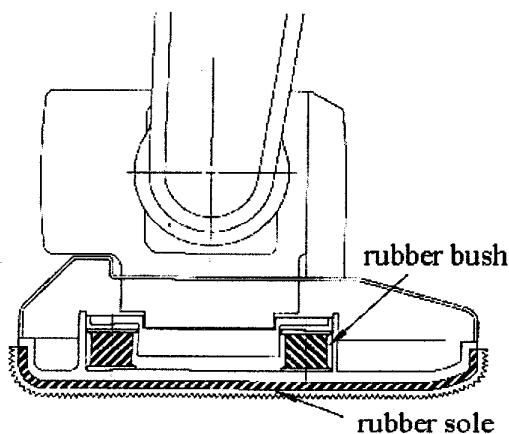


Figure 5 Structure of the foot of P2

is also used as a navigation sensor. Each foot and wrist is equipped with a 6-axis force sensor (a 3-dimension force and 3-dimension moment sensor). In the head of the robot, there are four video cameras. Two are used for vision processing, and can pan and tilt independently. The other cameras are used for the tele-operation. Figure 4 shows an outline of the overall system configuration of P2.

4. Impact Absorption Mechanism

For the practical biped robot, it is very important to absorb the landing-impact force. P2 has impact absorption mechanisms in its feet, as shown in Figure 5. The impact absorption mechanism is formed from rubber bushes inserted into a guide. It deforms elastically in the vertical direction upon a force being transmitted from the sole. With this arrangement, we have reduced the transmission of impact forces. Furthermore, it acts as a mechanical lowpass filter which prevents the vibration of leg compliance control.

5. Principle of the Posture control

5.1 Outline of the principle

To avoid tipping over, a walking or standing human will first push down hard on the ground with a part of the sole of the foot. Then, when the tipping force can no longer be resisted, a change in the body position or an extra step may be required to recover the correct, or balanced, posture. P2 has been designed to maintain a stable posture by adopting human-like movements.

Basically, the local controller controls the

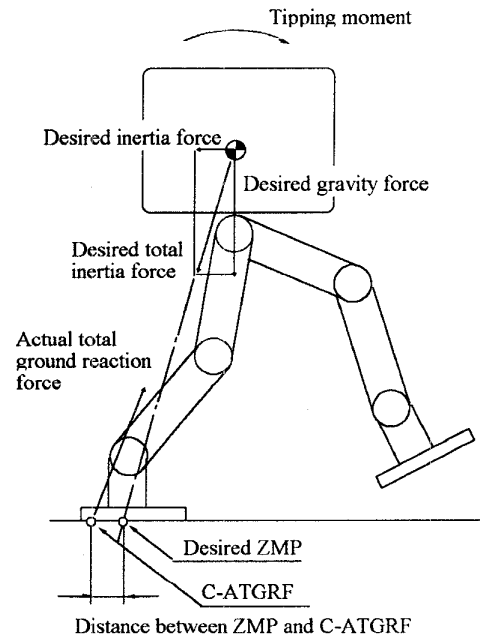


Figure 6 Dynamic Balance while Walking

displacement of the electric motor actuators so that the robot can follow the leg joint angles of the desired walking pattern.

The balance of a walking robot from the viewpoint of dynamics is examined, as shown in Figure 6. The combination of the ideal walking pattern's inertia force and gravity force is called the 'desired total inertia force'. The point on the ground at which the moment of the desired total inertia force becomes zero, is called the 'Desired Zero Moment Point' or 'Desired ZMP'. A ground reaction force acts on both feet of the robot. The combination of these forces is referred to as the 'Actual Total Ground Reaction Force' or 'ATGRF'.

The point on the ground where the moment of the ATGRF becomes zero is called the 'Center of Actual Total Ground Reaction Force' or 'C-ATGRF'. If the robot is walking in ideal conditions, the desired ZMP and the C-ATGRF will be at the same point. In reality, however, terrain is often irregular. This means that the C-ATGRF may differ from the desired ZMP, (even though the joint angles may be ideal). In this case, the line of action of the ATGRF and that of the desired total inertia force separate. As a result, the force couple produced, referred to as the 'tipping moment', acts on the robot, and its posture will tend to rotate. The 'tipping moment' is calculated with the following equation.

$$\text{Tipping moment} = (\text{Desired ZMP} - \text{C-ATGRF}) \times \text{Vertical element of desired total inertia force.} \quad (\text{Equation 1})$$

This equation shows a basic principle which can be applied to recover the robot's posture. This involves the use of a counteracting tipping moment initiated through active control of the distance between the desired ZMP and the C-ATGRF. The control to operate C-ATGRF is called 'Ground Reaction Force control' and the control to operate the desired ZMP is called 'Model ZMP Control'.

The Ground Reaction Force control modifies the desired position and posture of the feet and acts to control the C-ATGRF sensed by the 6-axis force sensors. The Model ZMP control changes the ideal body trajectory to shift the desired ZMP to an appropriate position. By doing so, the robot posture is recovered when the robot is about to tip over. If the body position of the model changes in conjunction with the Model ZMP, the spatial configuration of the body and feet will differ from the ideal state. In order to gradually bring this back to the ideal state, the landing position of the feet is changed. This is called 'Landing Position Control'.

5.2 Ground Reaction Force control

To recover the robot's posture, the 'ground reaction

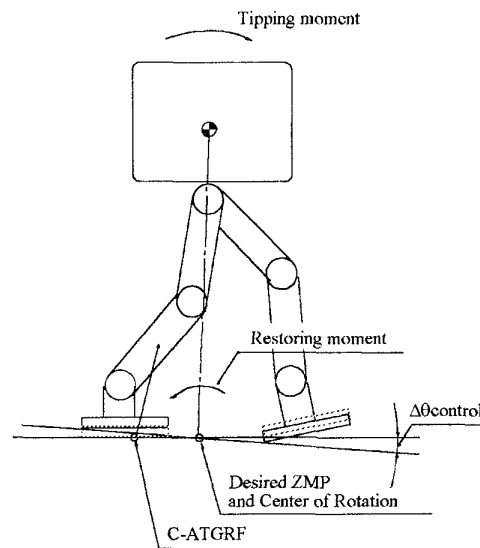


Figure 7 Ground Reaction Force control in the two leg support phase

force control' shifts the C-ATGRF to an appropriate position by adjusting each foot's desired position and posture.

During the single support phase, the C-ATGRF is controlled with a rotation of the supporting foot posture around the desired ZMP. When the robot's body tips forward, the robot lowers the front (toe) section of the supporting foot. When the robot's body tips backward, the robot lowers the rear (heel) of the supporting foot to shift the C-ATGRF rearward.

Similarly, during the double support phase, the C-ATGRF is controlled by rotation or movement of the posture and position of both feet around the desired ZMP. By doing so, the robot can be regarded as an inverted pendulum, and is controlled in the same way as in the case of one leg support. When the body tips forward, the robot lowers its front foot and lifts its rear foot, as shown in Figure 7. Thus it is able to produce a restoring moment according to the controlled angle of rotation, $\Delta\theta_{\text{control}}$ in Figure 7, to recover the stable posture.

Even if the ground surface is inclined, the 6-axis force sensors in the feet detect changes in the ground reaction force. Using these changes, the ground reaction force control controls the C-ATGRF to the appropriate position that produces the appropriate restoring moment which is determined by the body inclination control.

By implementing these movements, the robot is able to maintain a stable posture while walking on an inclined surface as well as an even surface.

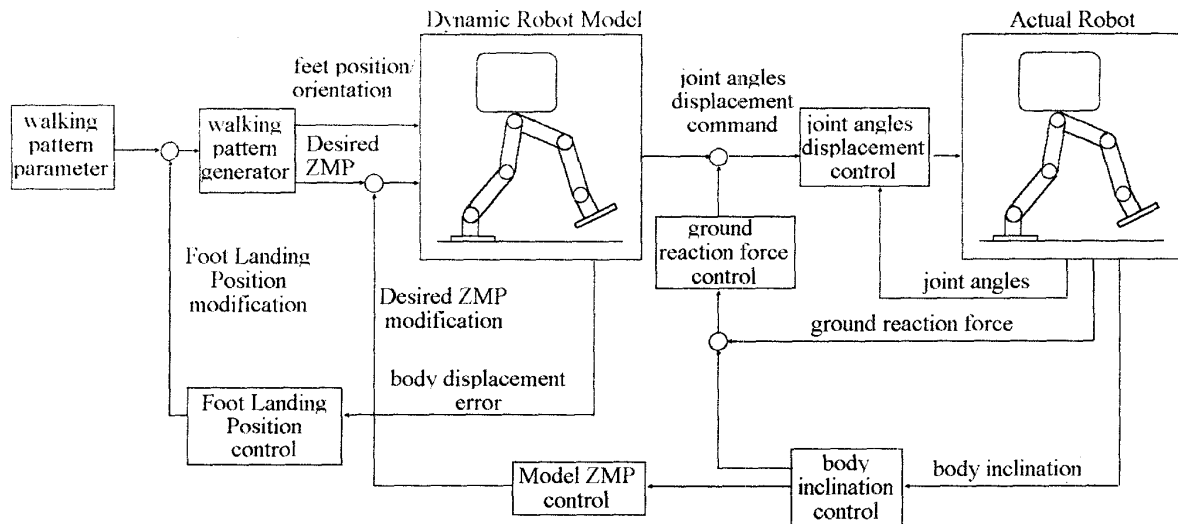


Figure 8 Overall block diagram of posture recovery control

5.3 Model ZMP control

The Model ZMP control is used to control the shifting of the desired ZMP to an appropriate position in order to recover the robot posture. It does this by changing the ideal body trajectory when the robot is about to tip over.

We demonstrate this principle with an example in which the upper body of the actual robot is inclined forward. Even if the desired ZMP and the C-ATGRF are at the same point, the robot will tip over unless posture control is initiated.

The Model ZMP control increases the magnitude of the desired inertia force by strongly accelerating the desired upper body position forward, according to the inclination of the upper body. This changes the direction of the desired total inertia force, and as a result, the position of the desired ZMP is shifted backward from the original desired ZMP.

However, in reality, the ground reaction force continues to act on the original desired ZMP via the ground reaction force control. This means that the lines of action of the desired total inertia force and the ground reaction force remain apart. These forces generate a moment that rotates the body backward. Consequently, the posture of the robot will gradually recover.

5.4 Foot Landing Position control

The Foot Landing Position control corrects the relative position of the upper body and the feet in conjunction with the Model ZMP control.

In the previous example, the Model ZMP control recovered the robot's upper body posture. However, the acceleration forces the upper body position forward and

the distance between the upper body and the next foot landing position is thus decreased. As a result, the geometric arrangement precludes the robot from maintaining the desired posture.

As a solution, the Foot Landing Position control lengthens the stride. It corrects the relative positions of the next supporting foot and the upper body. The stride then gradually recovers to its original state.

Thus, this control can only bring the relative positions of the upper body and the feet back to their ideal walking pattern position. It cannot in itself recover the actual robot posture.

By having the three controls described above working simultaneously, Honda has achieved a robot with a posture stabilizing control similar to a human. A basic overall block diagram of the posture recovery control is shown in Figure 8.

6. Integrated Function

6.1 System integration

Using the posture recovery control detailed above, the team has constructed an integrated system for the prototype humanoid robot which can automatically perform certain tasks in a known environment, and other tasks, with assistance from a human operator, in an unknown environment.

The integrated system consists of the robot itself and its tele-operation console as shown in Figure 9. The function modules of the robot consist of the dynamics control module of arms and legs which includes the stabilizing control that has been previously explained, the real time action scheduler which executes the action

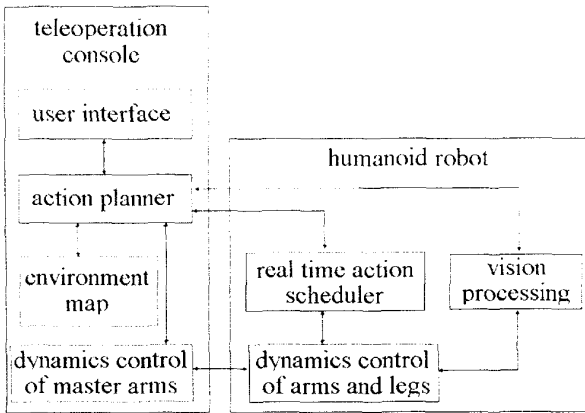


Figure 9 Configuration of the Integrated system

command from the action planner, and the vision processing module which finds the known landmarks using a template and measures the relative robot position from the landmarks within a precision of 10 mm and 1 degree.

The function modules of the tele-operation console consist of the user interface, action planner, environment map and dynamics control module of master arm. The operator inputs the basic plan of locomotion path and action to the user interface. The action planner modifies that basic plan by the vision processing result and sends the basic action commands such as 'go straight', 'turn', 'go up stairs', and so forth. In the environment map, there are the information of the position of landmarks, the shape parameters of stairs, and so forth. Using these function modules, the robot is able to walk autonomously. The master arms are used for the master slave control of robot arms. As a practical feature, the operator is able to perform a series of operations such as power on, stand by, working at tasks, and power off, at the tele-operation console alone.

6.2 Realized Functions

The main functional specifications are listed below.

Walking Performance:

- (1) Being able to move on normal even surfaces.
For example: on plastic tiles, a paved road, a metal grate, etc.
- (2) Being able to pass through a narrow opening.
Width of the opening being 850 mm.
- (3) Being able to step over and cross over (straddle) steps and mounds.
For example: to negotiate steps with a height of about 200mm and to cross over steps of 150mm height and 150 mm length.

- (4) Being able to walk up and down the staircase of typical buildings at a normal human speed.

For example: a staircase with a 200 mm height and 220 mm depth of each step.

- (5) Be able to walk on a known slope of approximately 10%.

Operational Performance:

- (1) Being able to grasp and hold an object with a weight of approximately 5kgf.
- (2) Being able to perform light work, by a remote control, using tools such as a wrench.

7. Future Plans

The future development will be divided into short term and long term plans.

For the short term, emphasis will be placed on hardware improvement, such as;

- 1) A smaller, more compact robot.
- 2) Walking performance improvement.
- 3) Operability improvement

For the long term, we believe that increasing the physical versatility as well as the level of machine intelligence is important. Greater physical versatility will be achieved by the improvement of environmental adaptability and walking and operational performance. An advancement of hardware and software technology will be necessary for these improvements. In the areas of machine intelligence, the improvement of autonomous functions, for example, operation without detailed human instruction, is expected. The effort in these two areas will realize a practical and useful robot that will meet consumer needs.

Furthermore, we also hope to develop technologies so that the humanoid robot can function not only as a conventional machine, but also as a new type of machine which blends into our social environment and interacts with people, thereby plays a more important role in our society.

References

- [1] Hirai, K., "Current and Future Perspective of Honda Humanoid Robot", In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.500-508, 1997
- [2] Hirose M., "HUMANOIDE ROBOT", In *Journal of the Robotics Society of Japan*, Vol.15 No.7, pp983-985, 1997
- [3] Kato, J., et al., "Pneumatically Powered Artificial Legs Walking Automatically Under Various Circumstances", In *Proc. of 4th Int. Symposium in External Control of Human Extremities*, pp.458-470, 1972