Feature

The Honda humanoid robot: development and future perspective

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Abstract

Honda revealed a humanoid robot with two legs and two arms in December of 1996. The robot walks not only forward and backward but also diagonally either to the right or left and turns in any direction as well. The robot can also steadily walk up and down a staircase without missing a step and push a cart with coordinated movement of its legs and arms. This robot with its innovative posture stability control can keep its balance against such unexpected disturbances as irregularities and unevenness on the floor surface. The paper introduces an outline of the structure and joints of the robot along with the development history. The basic principle of the robot's posture recovery control is also briefly explained.

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1. Start of humanoid robot research

Honda publicly presented a humanoid robot having two legs and two arms in December of 1996. The research and development of this robot was initiated in 1986[1,2].

The key words were "intelligence" and "mobility", and our direction and thoughts were "to coexist and collaborate with humans, to perform things that the human is unable to do and to create a mobility which brings additional value to human society". That is to say, we aimed at developing a new type of robot to meet the consumer needs but not a robot for a special limited purpose.

We first planned a practical wheeled robot having two arms and a video camera installed on the upper body for recognition research which we thought would be very convenient to study such intelligence as judgment and recognition research.

However, as we gave careful thought to the meaning of a consumer type robot which we initially intended to develop, we came to a conclusion that it did not meet one of our key words "mobility". We then looked into a type of consumer robot which would better meet our initial objective.

If we were to look at a "Domestic Robot", for example, as a type of robot that consumers may use, it will be necessary for a robot to walk around the furniture and walk up and down the staircase inside a house. We found that a human with two legs is best suited for such movements.

At the same time, if we were able to develop a two legged (biped) robot technology, we believed that the robot should be able to move around the majority of earth environments including rough terrain.

Consequently, we reached a conclusion that the configuration of the lower part of the robot would be better if it had a two legged mobile mechanism which can walk like a human rather than a wheeled type.

We therefore decided to develop a robot by concentrating our effort on that objective. Once we established our direction, the next step was how to realize it.

We then began to conduct a study of two legged walking mechanisms by first analyzing actual human walking and taking ourselves as a model.

2. Study on robot's leg mechanism

The following seven subjects were selected to study the leg mechanism:
(1) Effectiveness of leg joints relating to walking.
(2) Locations of leg joints.
(3) Movable extent of leg joints.
(4) Dimension, weight and center of gravity of a leg.
(5) Torque placed on leg joints during the walking.
(6) Sensors relating to the walking.
(7) Grounding impact on leg joints during walking.

In the following, we would like to explain the result of our initial experiment.

Regarding the subject (1) of the leg joints above, we found that the walking was not affected even when there were no toes and that the roots of the toes and heel are more important for supporting body weight.

As far as the ankle joint and walking function are concerned, if the ankle joints are fixed:
(1) there will be a lack of contact feeling with ground surface and the fore-and-aft stability will be poor;
(2) standing still is difficult if eyes are closed; and
(3) when side crossing a sloped surface, the feeling of contact with ground surface and stability are poor.

As far as the knee joint, we found that if the knee joints were fixed, walking up and down staircase was not possible.

From the above observation, we decided to have joints equivalent to such joints as hip joints, knee joints and ankle joints but not toe joints.

In order to study the roles of hip and backbones, those areas were fixed and restrained from outside and we observed how these factors affect such walking patterns as S-curves, straight and turning. As a result, we found that the robot was able to walk at a speed of 8km/h even it was restrained.

Regarding the subject (2) of the locations of leg joints, we carefully observed human bone frames.

Regarding of the subject (3) of the movable extent of leg joints, we experimented with walking on flat surfaces and up and down staircases, measured the movement of joints and the extent of the movement of each joint of the robot.

Regarding the subject (4) of the center of gravity of each leg, we set our objective by referring to "the center of gravity of an actual human body".

Regarding the subject (5) of the torque placed on the joints, we found the torque of joints by measuring the ground reaction force and the movement of leg joints in human walking.

And regarding the subject (6) of the sensor, we made a careful study of the types of sensors that would be required by the robot.

A human has three senses for sensing equilibrium. One is the sensor to sense acceleration using the ear drum, the second is the sensor to sense the tipping rate by using semicircular canals and the third is the sensor to sense the angles of joints movement, angle acceleration, muscular strength, pressure feeling of foot sole and skin.

We also studied the visual sensor which complements and alternates the sense of equilibrium mentioned above and also manages walking information.

Based on this information, we concluded that a robot in its system needs a G-sensor, six axis force sensor and gyrometer to sense its own posture, and joint angle sensor in order to grasp the leg movement when walking.

Next subject discussed was the ground reaction force; that is, impact force imposed on the foot during the walking. The human body is designed to absorb the impact force with the soft skin tissues surrounding the foot, arch frame of bones forming the foot, the roots of toe joints, and flexible movement of knee joints as the feet land on the ground.

As the walking speed increases, the reaction force becomes larger even with the human's impact damper mechanism. We found that at the walking speed of 2 to 4km/h, the load forced on the foot is about 1.2 to 1.4 times that of the body weight and at the walking speed of 8km/h, it is about 1.8 times.

Based on these results, we made an initial specifications for our robot.

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3. Development of biped walking robot

After trials with an experimental biped walking robot, we then refined the specifications to meet the following functions:
(1) to realize a walking speed of 3 km/h;
(2) for attaching arms and hands of the robot to the upper body;
(3) walking up and down a normal staircase.

For a research purpose, we began with static walk. However, since human walking is mainly of dynamic walking, we thought that the robot must also have a dynamic walking feature and therefore our research efforts have concentrated more on dynamic walking. As a result, our walking program is a dynamic walking program based on the human walking data and we conducted our experiment.

Based on our continuous research effort, we were able to consolidate those specifications mentioned above for a biped robot and complete a wireless robot movable with electric batteries mounted as shown in the Figure 1.

4. Start of flexible walking robot

Up to this point, the robot we developed was just able to walk on a straight line only. For the next stage, however, we began research and development of a biped robot which can steadily move around in a natural human environment without tipover or falling down and is especially maneuverable on different road surfaces, undulation, slope and steps. As a preparation for further study, we developed a walking simulator taking the mechanical characteristics into account.

5. Technical points for realizing stable walking

When a human is about to fall down while walking or standing straight, he pushes the ground hard with a part of his foot sole to resist the falling. But when he is no longer able to resist, then he tries to recover his posture by changing his body movement or by taking an extra step. We have tried to achieve a high posture stability by adopting a similar recovery ability for the robot[3]. Figure 2 explains the principle of robot posture recovery.

Figure 2 Dynamic balance while walking

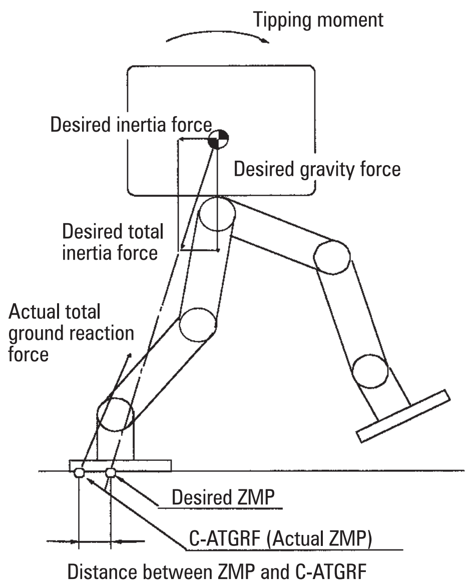
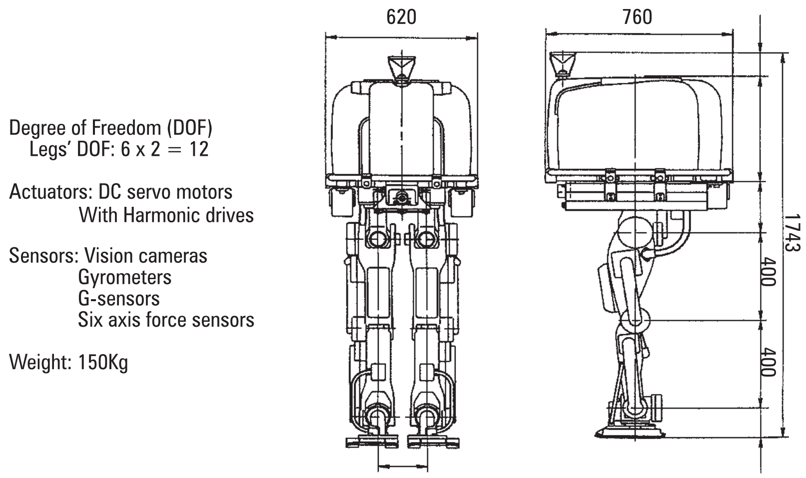


Figure 1 Biped walking robot



Basically, a robot is controlled to follow the angles of leg joints of an ideal walking pattern. A combined force of inertia force and gravity force of the desired walking pattern is called "desired total inertia force". The point on the ground surface where the moment of the desired total inertia force becomes zero except for the vertical element is called "Desired Zero Moment Point" or "Desired ZMP".

The ground reaction force has an affect on each leg of an actual robot for which the combined force is called "Actual Total Ground Reaction Force" or "ATGRF". The point on the ground surface where the moment of ATGRF becomes zero except the vertical element is called the "Center of ATGRF" or "C-ATGRF".

If the actual robot walks in an ideal manner, ZMP and C-ATGRF will be at the same point. In reality however, even though the body posture is in accord with the desired posture and the joint angles are following the desired joint angles, C-ATGRF is off the desired ZMP as it is shown in the figure because of the irregular terrain. In this state, since the action lines of ATGRF and the desired total inertia force do not agree, a couple force produced by these forces acts upon the robot and the robot's entire posture tends to tipover. This couple force is called "Tipping Moment" which is calculated with the following equation.

Tipping moment = (Desired ZMP – C-ATGRF) * Vertical element of desired total inertia force

By observing this equation, we had the idea that if the distance between the desired ZMP and C-ATGRF were actively controlled, the tipover posture of a robot can be recovered by conversely utilizing the tipping moment. We believe that this is a basic principle for recovering the robot's tipover posture. The control to operate C-ATGRF is called "Ground Reaction Force Control" and the control to operate the desire ZMP is called "Model ZMP Control".

The ground reaction force control controls C-ATGRF by sensing with six axis force sensors and by modifying the desired position and posture of the feet.

The model ZMP control is to control the shifting of the desired ZMP to an appropriate position in order to recover the robot posture by changing the ideal body trajectory when the robot is about to tip over (that is, when there is a difference between the inclination of the body of actual robot and that of the desired body).

For an example, when the body of a robot tips forward, the model ZMP control system increases the acceleration of the desired body. As a result, the magnitude of the desired inertia force changes and the desired ZMP shifts its position to behind the original desired ZMP to recover the robot posture.

If the desired body position of the model changes, the spatial configuration of the desired body and feet will be immediately off the ideal state. In order to bring the robot back to the ideal state gradually, the landing positions of the feet are changed.

By having the controls described above working simultaneously, we were able to give the robot the same posture stabilizing control as a human.

6. Progress toward humanizing

The next step was to realize a humanoid robot. We defined the functions of this humanoid robot as follows. The robot should be of such a type that it can automatically perform a certain type of work under the known environment and perform uncertain types of work with assistance from a human operator under unknown environments. The first experimental humanoid robot had an overall length of 1,915mm and weight of 185kgf.

We had first concentrated our study on how to realize the coordinated movement of legs and arms and therefore the computers for image processing and action plan, electric power supply, etc. were not installed on the first robot.

Through the experiment with this robot, we studied a coordinated movement of the robot to perform such tasks as turning a switch on and off, grasping and turning a door knob and holding and carrying an object.

In the next stage, we developed a wireless humanoid robot as shown in the Figure 3 which was publicly revealed by Honda as mentioned earlier. The overall length was 1,820mm with weight of 210kgf.

Computers, motor driver, batteries as a power source and transmitter were installed inside the robot. The main functional specifications are listed below.

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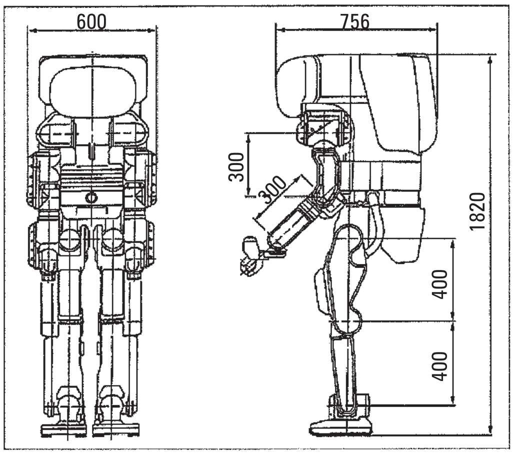
Figure 3 Humanoid robot P2

Degree of Freedom (DOF)
Leg's DOF: 6 x 2 = 12
Arm's DOF: 7 x 2 = 14
Hand's DOF: 2 x 2 = 4

Actuators: DC servo motors
With Harmonic drives

Sensors: Vision cameras
Gyrometers
G-sensors
Six axis force sensors

Weight: 210Kg



Mobility performance – the robot should be able to:

- Move around on normal flat surfaces. Example: plastic tiles, paved road, grazing, etc.
- Pass through a narrow opening: Width of the opening to be 850mm.
- Step over and cross over steps and mounds. Example: step over steps with a height of about 200mm; cross over steps of 150mm height and 150mm length.
- Walk up and down normal staircases at a human speed. Example: staircase with 200mm height and 220mm depth of each step.
- Walk on a known slope of about 10 percent.

Working ability – the robot should be able to:

- grasp and hold an object with weight of about 5kgf;
- perform light work using such a tool as a wrench by remote control.

The robot operating system is as follows. Robot operation may be performed by working with a computer mouse. A live view through the eyes of the robot is shown on a workstation screen. When an operator clicks the mouse at a destination point on the screen, the robot begins calculation of the steps required to reach the destination point based on its measurement between current position and the destination. Any command from the workstation to the robot is transmitted by radio control.

The operator is also able to directly control the arms of the robot through a dedicated workstation in master-slave communication based on visual information through the stereo cameras of the robot.

7. P2 robot problems

The robot P2 has attained a good reputation, being the first autonomous humanoid robot in the world, which moves in a manner very similar to that of a human being. However, the robot has some problems. It is too big and heavy (1,820mm in height and 210kg in weight) for the realistic working environment shared with human beings, particularly from a Japanese standpoint.

Related to this problem is its large energy consumption: (2750W) when walking. P2's large size and weight requires the use of electric motors as large as 300W.

Carrying a battery weighing 20kg, the robot can operate only for 15 minutes.

Additional problems include the use of motors with brushes, which degrade its service life, and complicated internal wiring which lowers its reliability and serviceability.

8. Honda humanoid robot P3

In trying to solve the problems, we have developed a new robot, P3 (Figure 4), which is of a more acceptable scale for human cooperation, and is easy to handle in research.

The new robot P3 is 1,600mm in height and 130kg in weight.

The degrees of freedom of the legs, arms and hands of P3, as well as the sensory devices used, are the same as those of P2. P3's

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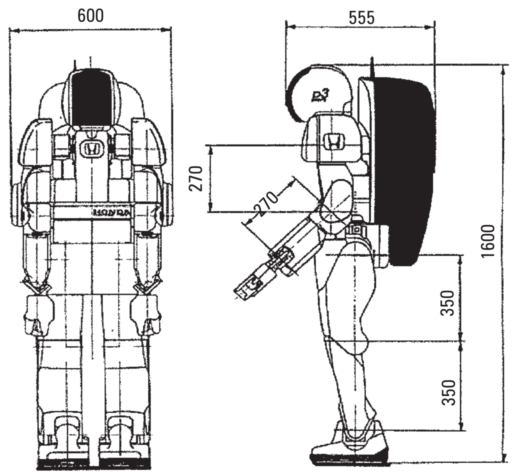
Figure 4 Humanoid robot P3



functions are equal to and in some ways improved over those of P2.

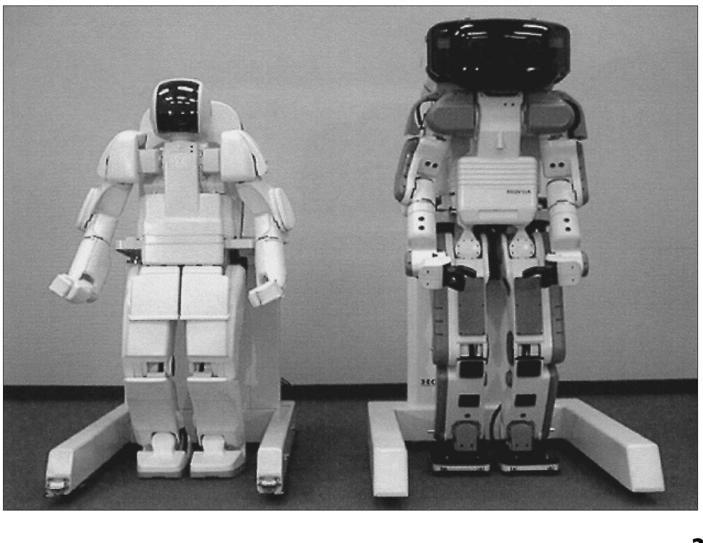
While P3's weight stands officially at 130kg, its actual weight is down to 118kg, and less than 100kg without its battery.

The photo-comparison clearly shows that P3 has been reduced in scale to a fair extent from P2 (Plate 1).

I wish to explain how we accomplished P2's reduction. As shown, the robot is scaled down overall. The legs and arms are shortened by 10 percent. The depth of P3 (its size in the to-and-fro direction) is greatly reduced owing to the decentralization of computers.

Instead of a central cluster computer, small computers have been dispersed at several locations within P3. In order to achieve a substantial and advantageous reduction in weight, components made largely of magnesium have replaced many which, in P2, were composed of aluminum.

Plate 1 Photo-comparison



The P2 robot has a computer board (of a commercially available type) at its back, which is directly connected to each joint motor driver, requiring a total of 650 wires.

The P3 robot, on the other hand, has computers located at the corresponding leg and arm joints to control the joint's motion. These computers are inter-connected as a LAN (Local Area Network).

With this arrangement, the related number of wires is significantly reduced; from 650 to 30. As a result of scale-down, P2's energy consumption is greatly reduced to one third of the earlier level, i.e. 786W, down from 2,750W (in P2). This gain in efficiency has doubled the operation time, using a battery of the same capacity as that in P2.

Also due to the scale-down, the load placed on the motors is decreased. This fact, complemented by the use of brushless motors, results in an extension of the intervals between necessary maintenance procedures.

Relating to the reduction of the number of wires used, the number of connectors and contacts is reduced from 2,000 to only 500.

While we have often experienced troubles related to contacts in P2, the problem will be greatly reduced. Practical reliability will therefore be much improved.

These improvements are all in the hardware configuration. By placing an emphasis here we have achieved a meaningful result, in that the overbearing or difficult-to-manage physical dimensions of the robot, notable in work among human beings, is markedly reduced.

This aspect is significant in moving towards the adoption of a humanoid robot for applications within human society. People will be less overawed or intimidated by the presence of such a robot.

9. Problems in applications

We think that it is most important to determine the first areas for humanoid robot application very carefully. Since the robot has a humanoid configuration, it will be well suited to tasks performed by humans.

However, it will take a long time before the robot might perform a job in a manner better than humans. If applications are improperly determined, the robot will not perform as intended, resulting in disappointment. Such mistakes will not further development.

The area or field of application should accordingly be one most suitable and effective for the humanoid robot, and must contribute to human needs and human society. We will be apt to apply the robot to dangerous or dirty work (which most humans do not like to do). I believe, however, that we should not focus on this sort of area in these initial stages of humanoid robot development.

10. Future development

Our humanoid robot functions well. However, this robot has now attained only basic functions of motion which are necessary for such a humanoid robot.

Many problems remain, and we are working to find the best possible solutions. There are several problems to be faced in the continued development of hardware configurations.

Firstly what is required is to achieve a further scale-down of the robot. With regard to height, we think that the current value of 160cm is appropriate to our present needs.

Needless to say, different sizes will, in the future, be called for by different circumstances. We can foresee both smaller robots, perhaps child-sized, as well as bigger ones of, for example, 2m. Smaller sizes will introduce particular design challenges. Shorter leg length, for instance, makes the task of negotiating stairs much more difficult.

Our continued scale-down efforts should ideally include a further reduction in weight, to perhaps half of our present achievement, although we have no specific strategies for realizing this goal at present.

The second hardware issue for examination is the task of making manipulation simpler, while at the same time developing functions which enable the robot to make autonomous judgement. Presently, one operator gives instructions to the robot on-screen at a working station to manipulate the robot (Plate 2). The operator must have advanced knowledge and skills to carry this out. Improvements should allow anybody to use the robot comfortably, just as they do a laptop computer.

To this end, the robot should be provided with autonomous judgement functions, mainly using visual information, in order that it can avoid obstacles, determine its path of travel, etc., so as to decrease the burden on the operator.

Plate 2 Operator control

An advanced problem is enabling the robot, via hardware and control algorithms, to cope with difficult situations and, for example, pick itself up when toppled.

11. Future plan

In the long term, we believe that increasing the physical versatility by way of mobility improvement and environmental adaptability, made possible by hardware and software technology advancement, as well as improving the autonomous mobility without detailed human instructions are important.

We also hope to develop technologies so that the humanoid robot can function not only as a machine, but blend in our social environment and interact with people, and play more important roles in our society.

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