Development of New ASIMO
– Realization of Autonomous Machine –

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ABSTRACT

The new ASIMO was developed as a step toward the goal of achieving "a robot that coexists and cooperates with people and performs useful functions in society." The purpose was to give it the capability to sense changes in the circumstances of real-life environments where people are present, to take autonomous action, and to continue acting. New multi-modal sensing technology, situation estimation and prediction technology, and autonomous behavior generation technology were developed, greatly advancing the robot's ability to adapt to situations. The development of physical capabilities included a many-axis hand capable of independent control of five fingers and lightweight, highly responsive hardware with heightened agility to enable continuing operation in a mixed environment with people. In terms of human response functions, therefore, the robot became able to adapt to situations to work appropriately with people. In terms of walking functions, it became able to predict the movements of multiple people and cross their paths without stopping, as well as to maintain its balance even on irregularities or other changes in the road surface. In terms of work functions, it became able to hold an object with a stable grip and to manipulate things with its fingers.

1. Introduction

Honda has for a long time engaged in research on humanoid robots in its efforts to create further innovative forms of mobility. Such robots function usefully in society by coexisting and cooperating with people, which adds new value. Findings from analysis of how humans walk obtained in the course of research, designs for actuator mechanisms for bipedal walking, methods for controlling bipedal walking, and other such technologies were put to use in the world's first autonomous bipedal walking humanoid robot, the P2, the prototype of which was publicly announced in 1996(1). In November 2000, Honda introduced ASIMO, which was made a size adaptable to the human living environment with the aim of making it a genuinely useful robot that could function in close proximity to people(2). ASIMO was made available for rent on the Japanese market in 2001, and it was exhibited in 30 or more countries around the world in 2002. Honda has explored the interaction between people and robots in search of ways to make robots more useful in real-life situations, and has further equipped robots with human interactive functions, including the capability for recognizing people's posture and actions as well as distinguishing among individual people's faces so that robots could interact more smoothly with humans(3). In December 2005, Honda presented an ASIMO with body functions significantly enhanced by highly accurate, highly responsive hardware and new posture control technology that makes active use of bending and twisting of the upper body(4). It was also equipped with technologies for autonomous, continuous movement as well as for obstacle avoidance and track generation(4). In December 2007, ASIMO was given new functionalities for cooperative work, autonomous recharging, crossing paths without colliding, and obstacle avoidance, and operational testing in a real-life environment was begun. Through activities like these, Honda has sought to further its dream of a humanoid robot that functions together with human beings, to illuminate new frontiers for exploration, and to develop a wellspring of technological know-how.

This article presents an overview of the new ASIMO (Fig. 1) that was presented in November 2011.

Fig. 1 Humanoid robot "New ASIMO"

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2. Development Goals

Figure 2 shows a development roadmap that leads toward the ultimate goal for the ASIMO, which is to achieve “a robot that coexists and cooperates with people and performs useful functions in society.” The new ASIMO is positioned at the second step, aiming for the capability to engage in continuing work in a real-life environment where it coexists with people, though in a limited manner.

The previous model of ASIMO has been employed to date in operation tests of use as a reception guide and in a delivery service in office lobbies and other real-life environments. It was found through this testing that there are many situations in a real-life environment where a robot is unable to recognize the presence of people, and that the people a robot interacts with often do not act as anticipated. When the previous model of ASIMO, which acted automatically in accordance with scenarios defined in advance, encountered these situations, it was unable to act appropriately, making it necessary for an operator to intervene.

The aim in developing the new ASIMO, therefore, was to achieve an autonomous machine with the capability for autonomous decision-making and behavior in changing circumstances. The elements that are necessary to make a robot an autonomous machine were defined as:

1. External recognition: This capability detects people’s changing movements and other such actions around the robot using multiple sensors and integrates that data to infer the situation.
2. Autonomous behavior generation: This capability predicts the subsequent situation from collected data and autonomously makes decisions about its next behavior without the intervention of human operation.
3. High-level postural balancing: This is the robot’s capability to maintain a stable posture by quickly extending a foot forward.

The development effort was then directed toward technology that would achieve these three elements.

This paper introduces the main specifications of the new ASIMO in Chapter 3. Chapter 4 then describes the system architecture that provides the foundation technology for enhancement of robot intelligence, which achieves the external recognition and autonomous behavior generation noted above. This architecture integrates information obtained from external observation of people and things by multiple sensors, determines what action to take with regard to whom, and takes the action. Next, Chapter 5 describes the technology for adapting to exterior disturbances such as differences in level, unevenness, and other such changes in road surface conditions, in terms of the high-level postural balancing noted above. There will also be some description of local path planning technology used to move without stopping in a mixed environment with people. Chapter 6 will introduce the many-axis hand that was developed in order to support the increase in kinds of work objects and the diversification of positions and postures.

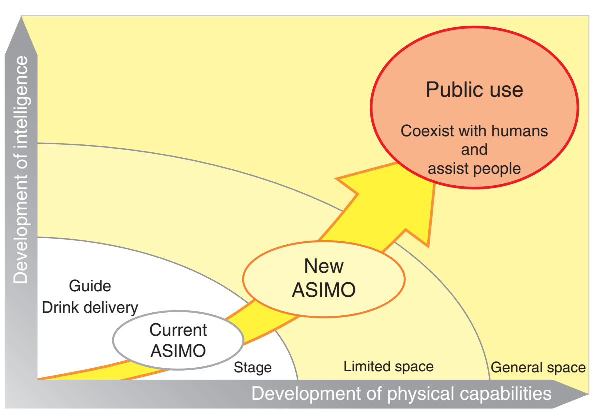

Fig. 2 ASIMO development roadmap

3. Main Specifications

3.1. Basic Specifications

Table 1 shows the main specifications of the new ASIMO. Its total height is 1300 mm and its weight is 48 kg. A weight reduction of 6 kg was achieved without altering the robot’s total height, which is the same as the previous ASIMO announced in December 2005. It was given a walking speed of 4.0 km/h, which is the same as normal human walking speed, in order not to hinder people’s walking. Its running speed was raised significantly, to 9.0 km/h, and the robot was also given the ability to move in reverse. The exterior design continues to express a harmony of innovativeness and familiarity while embodying evolution in terms of gentleness, comprehensibility, and distinguishability for the purpose of engaging with people.

3.2. Joint Configuration

The new ASIMO has been given a total of 57 degrees of freedom (Fig. 3) with the addition of one axis in the waist and 11 axes in each hand. The pitch axis in the waist was added to expand the robot’s range of work by including the ability to bend at the waist. The degrees of freedom in the hands were increased significantly by adding to the previous count of one axis in the thumbs and one axis in the four other fingers. The new configuration enables an optimal grasp of objects in accordance with their position and orientation, enabling the robot to grip objects of various shapes and pinch them with its fingertips, and enabling the manipulation of objects using a twisting motion.

The new ASIMO’s range of movement in each axis has also been expanded compared to the previous model. A wide-angle six-link neck construction with a changing instantaneous center was adopted to avoid interference with the chest from up-and-down movement of the head. This significantly (by a factor of 1.7) expanded the angles of movement from the previous 22 degrees up and 19 degrees down to 26 degrees up and 32 degrees down. The ability to

Table 1 Specifications for ASIMO

Height	1300 mm	(self-standing)
Weight	48 kg	
Speed	0 – 4.0 km/h	(Walk)
	9.0 km/h	(Run straight)
	3.0 km/h	(Run backwards straight)
Sensors	Dual resolution stereo camera	(in head)
	8-ch microphone array	(in head)
	G/Gyro	(in body)
	Floor mark sensing camera	(in waist)
	Force sensors	(in legs, wrists, hands)
	Tactile sensors	(in hands)

rotate the foot in the lateral direction at the ankle (tilting the foot so the sole will remain flat on a floor that slants upward or downward from left to right) is important to the cross-step leg movement, which expands the range of landing points for the feet. By reducing the link-leaning angle, the range of this lateral rotation increased from the previous ±24.5 degrees to ±32.5 degrees.

3.3. Configuration of the Electrical System

High-response systems that support all of the robot's recognition, movement, and work functions were achieved for the new ASIMO.

One of the pair of stereo cameras previously mounted in the head was made into a multiple resolution camera that uses a prism. This achieved a balance between recognition of objects across a wide range and face detection at a distance. Moreover, where the previous model had microphones mounted at three locations on the front of the head, the new ASIMO has them at eight locations around the head to enable detection of sound from the total periphery. Ring-shaped vibrating gyroscopes, which are less influenced by external shock and vibration, were used for acceleration and angular velocity sensors. This achieved a 95% reduction in volume compared to the previous model, contributing to the increased compactness of the system.

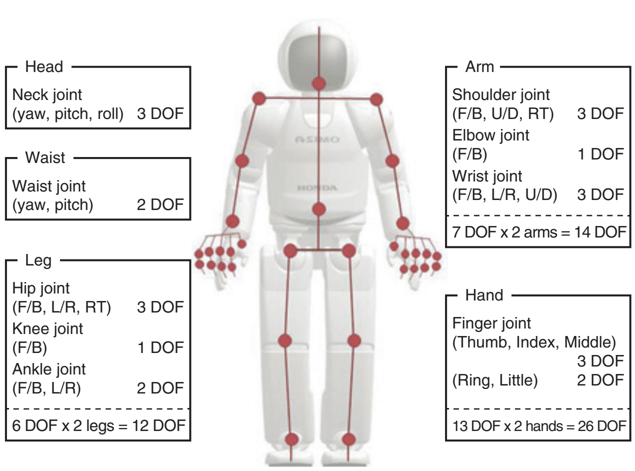

Fig. 3 Joint configuration and DOF (Degree of freedom)

In order to support the increased processing volume resulting from enhancement of the robot's functions, the central processing unit (CPU) parallelism was increased and a dedicated leg control CPU was added. A hierarchical memory structure using serial input and output was also adopted for the main CPU, achieving conflict-free memory access. The speed of the internal communications system linking the main CPU, sensors, and motor drivers was increased (by a factor of four relative to the previous model), as well, enabling synchronization of all 57 axes on a cycle of 250 μs.

4. Autonomous Behavior Control

A new system architecture for autonomous behavior control was built with the aim of giving the new ASIMO a heightened ability to adapt to situations. Working on the assumption that the robot would be assigned to office reception, a system applying this architecture to human response functions (interaction at encounter, interaction by trigger, guiding), interactive explanation functions (presentation question and answer (Q&A)), and work functions (drink delivery) was first created (Fig. 4).

4.1. Sensing

In order for the robot to act in a manner appropriate to changing circumstances, it is necessary for the robot to have an accurate grasp of the circumstances around it. In addition to the sensors mounted on the previous robot body, sensors were placed in spaces for the new ASIMO in order to detect conditions in the total space where the robot operates, not just in its immediate vicinity.

4.1.1. Spatial sensing

Two types of sensor were used: Lateral laser range finders (LRF) that conduct one-dimensional scans were placed mainly on wall surfaces, and vertical LRF that conduct two-dimensional scans were placed on ceilings. These measure distances from the sensors to an object. The differences between those measured distances and the distances to the background measured in advance when there were no moving bodies present are obtained. The vertical LRF further help eliminate data that does not match with people's heights. The remaining data is subjected to clustering by the lateral LRF on the basis of adjacency of data and by the vertical LRF on the basis of distance between data. Those clusters that are determined not to be people due to the distances between data on either end of the clusters are eliminated from the clusters created by the lateral LRF. The centers of the clusters that remain after this processing are output as the locations of people.

4.1.2. Image recognition

Office reception areas are unlike an area under controlled illumination, such as a stage, because their lighting environment generally varies significantly with the weather and the time. Such areas therefore call for image sensing that remains robust against varying illumination. A technology for automatically adjusting shutter speed in coordination with face recognition at the time of image acquisition was developed for the new ASIMO.

In cases when the robot is interacting with multiple people, it is not necessarily the case that the face of the person the robot should be interacting with will always be directly in front of the robot. A facial image recognition technology was therefore developed that would enable face detection, face direction estimation, and face identification regardless of the person's location in the camera's field of view. Instead of the previous method, which took the center of the image as the center for application of distortion correction to the entire image field, this technology uses a method of distortion correction known as virtual pan and tilt, which virtually directs the camera to the face location and places the face at the center (Fig. 5).

4.1.3. Audio recognition

Taking proxemics as a reference, the distance between the robot and people it converses with was set at 1-2 m for the new ASIMO. The aim was to recognize only utterances by people who are at this distance from the robot. Given that there is some breadth to the distance, and that, unlike demonstrations on stage, the people interacting with the robot will not all speak at the same volume level, the audio intensity input to the robot will vary considerably. In the conventional audio recognition method that is generally used, sounds that have multiple envisioned signal-to-noise (S/N) ratios are given as individual models to be learned, and the model that is considered optimal in terms of distance and loudness of the voice is selected. The distance and loudness of voice can vary dynamically, however, which means that the optimal model cannot necessarily be chosen in every case, and there was therefore a risk that the recognition rate would decline.

In order to deal with these varying circumstances, a technology was developed for the new ASIMO that uses a single model to learn sounds over a wide range of S/N ratios. Compared to audio recognition that uses individual models for each distance, this method has achieved a favorable recognition rate using a single model for sounds at every distance.

In addition, acoustic feature, sound volume, and fundamental frequency are used to detect word lengthening within audio. This has achieved elimination of misrecognition caused by the filled pauses that occur frequently in speech.

4.2. Situation Estimation

Situation estimation uses spatial sensing information

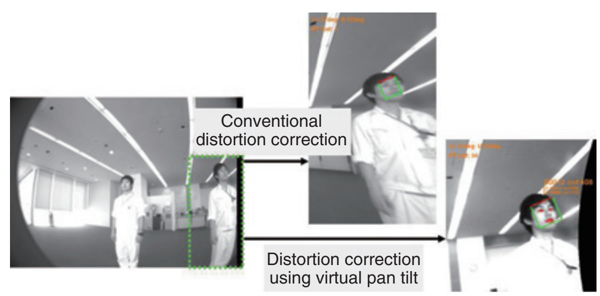

Fig. 5 Correction of image distortion

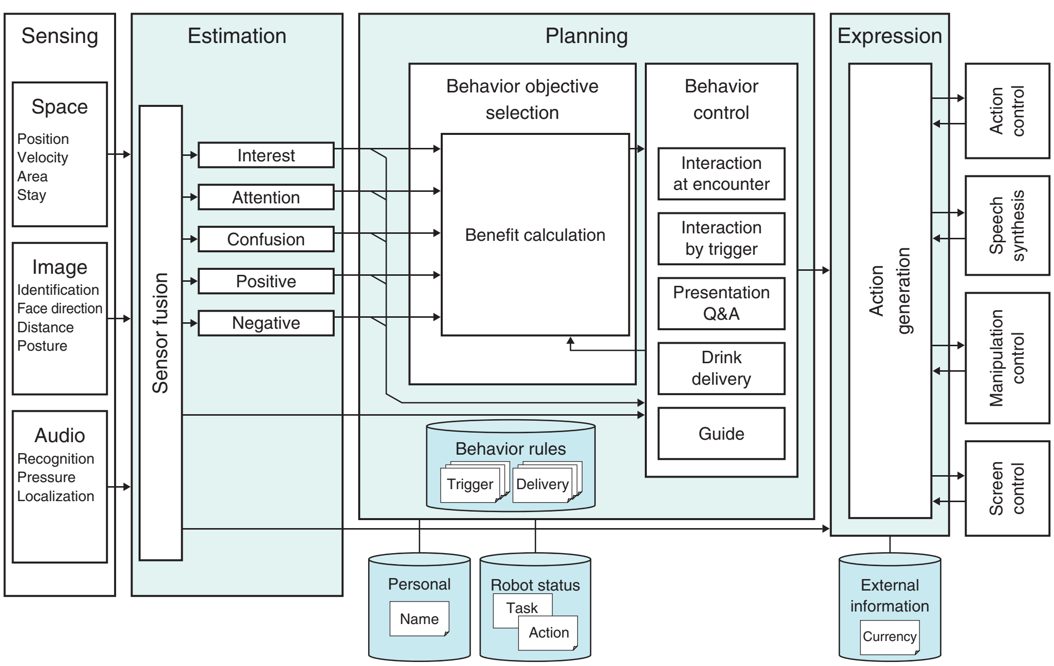

Fig. 4 Interaction system architecture

as a basis for estimating people's attributes that are needed in the robot's interactions with people. Here, people's attributes refers to the states of people, including stopped, coming closer to the robot, going farther away from the robot, facing the robot, arriving at the workplace, leaving, and waiting. This is information needed to determine the robot's course of action. The previous ASIMO could interact only with people who came close to it. By using this information, however, the new ASIMO has become able to approach people on its own.

The system uses a Bayesian network that takes the audio, image, and spatial sensing information as input and provides the situations of the people as output in the form of probabilities. Then it extrapolates where the people in the vicinity of the ASIMO are directing their attention and how much interest they are showing in the ASIMO, and it outputs this to the behavior generation unit, which is described below.

4.3. Behavior Generation

An example of the operation of behavior generation will be explained using Fig. 6. This scenario has five people designated A-E as candidates for interaction with the robot. The behavior objectives are of five types: interaction at encounter, interaction by trigger, acting as a guide, presentation Q&A, and drink delivery.

In behavior objective selection, the effectiveness of behavior is first calculated for each behavior objective according to the situations of people output from situation estimation and the robot's action history. There are combinations formed from multiple people and multiple behavior objectives. From among those, the robot selects the target person and behavior objective that yields the greatest benefit of behavior. In Fig. 6, the robot chooses to engage in interaction at encounter with person C. The robot's choice of an action with greater benefit of behavior enables the robot not to continue speaking to a person who does not respond no matter how many times the robot speaks to him/her, and instead to change its action to work with a different person.

Next, in behavior control, the decision is made on specifically which action to take among those behavior objectives. The choice of action is made here on the basis of predefined action rules and under constraint conditions, which are that the same thing is not said twice and another action that uses the same part of the robot's body is not performed simultaneously.

The system allows parallel processing and interrupt processing to occur in multiple behavior controls, and when the robot is taking a certain action, it can, according to the circumstances of use of the robot's resources, continue that action or temporarily suspend it and undertake a separate action. Specifically, this means that when someone says "thank you" to the robot while the robot is placing a tray on a table during drink delivery, the robot now has the capability to respond, "you're welcome" at that time, and when a person asks the robot a question during the robot's explanation of a presentation, the robot now has the capability to answer the question at that time.

5. Mobility Functions

In a real-life environment, the positions of people and obstacles change dynamically. There may also be cases when people cannot readily predict the robot's movement, resulting in situations when the people's movements and the robot's intersect. The new ASIMO has been given significantly enhanced capability for detection of obstacles, including people, relative to the previous model, and new leg control technology has been developed to serve as the basis for smooth movement that will not confuse people.

5.1. Dynamic Route Guidance

The new ASIMO has been equipped with new local path

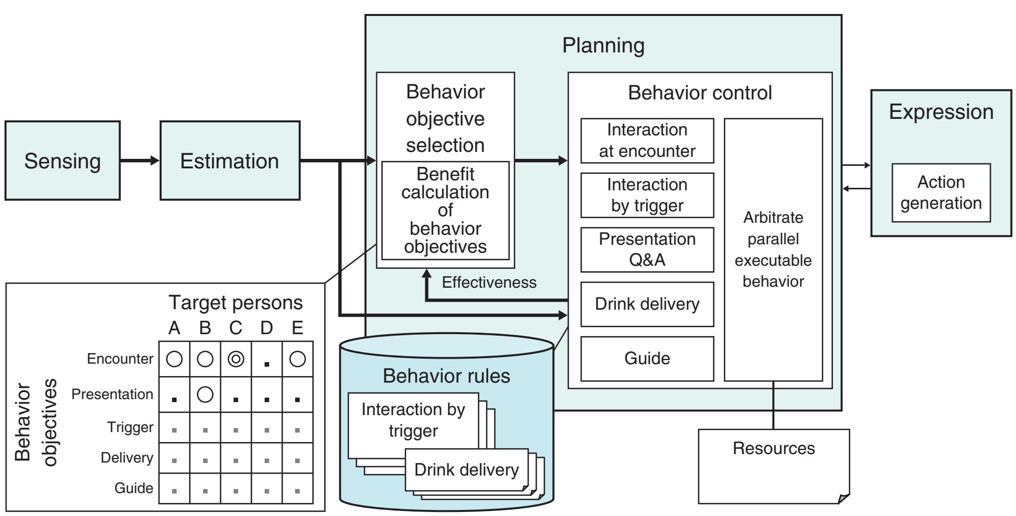

Fig. 6 Behavior control

planning technology and upgraded detection functionality for obstacles including persons. The purpose was to enable the robot to generate a path that allows it to accelerate, decelerate, change course, and so on without stopping, even in a location where multiple robots and multiple people are present.

5.1.1. Person and obstacle detection by spatial sensors

Detection was previously conducted by sensors on the body of the robot, so that only people and obstacles that were at close proximity and to the front could be detected. Since courses were generated on the basis of information from such an extremely narrow range, the robot sometimes moved jerkily or it would move toward a person behind it because it could not detect a person in that location. For the new ASIMO, therefore, new spatial sensing was introduced in order to detect the approach of people from the rear and the movement of people in blind spots, not just in the direction the robot is moving. Since the robot is able to detect people at an earlier stage, a smoother walking path can be generated for it.

5.1.2. Local path planning

The robot's path was previously decided as a matter of keeping the predicted locations of people and the path of the robot from overlapping on a two-dimensional plane. When a person was walking on a path that would cut across the robot's path, therefore, as in Fig. 7 (left), the robot would be unable to generate a course that avoided the person. Also, as explained in the previous section, the new ASIMO detected the movements of people in the entire space, so that when multiple people were present in the vicinity of the robot, the further increased likelihood that a path could not be generated would be anticipated. For the new ASIMO, therefore, a technology was developed for seeking paths whereby the person's predicted location and the robot's location would not overlap within a three-dimensional space that included time, as shown in Fig. 7 (right).

By means of this technology, the robot became able to generate a path of movement such that the robot could pass the person's path ahead of the person, or slacken its speed to allow the person to pass in front of it. The robot was thus enabled to continue walking without pointless stopping even if circumstances changed.

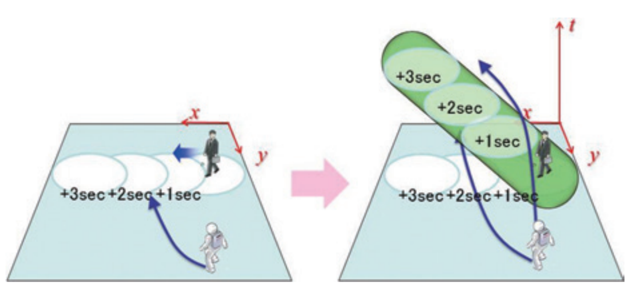

Fig. 7 Local path planning

5.2. Leg System

The previous model of ASIMO was limited in its ability to deal with changes in circumstances for various reasons. For instance, it could not generate more than one type of gait at a time, it could not adjust its landing point while it was moving, and it could not exert restoring force with regard to inclination errors due to external disturbance except within the area covered by its feet.

The new leg system configuration shown in Fig. 8 was adopted for the new ASIMO in order to overcome these issues. This system conducts gait generation in parallel and in real time so that the optimal gait pattern can be selected at any time from among walking, running, and hopscotch movements. This has also yielded significant enhancements in the robot's ability to exert restoring force when inclination error occurs not only by staying on its foot, but also by changing its landing point in real time by means of the horizontal acceleration of its upper body and by bending at the hip.

5.2.1. Expansion of landing points

It is important that the robot be able at any time to change the landing point where it places its foot and the timing of that action in order to reinforce its capability for dealing with external disturbances. Figure 9 shows the range within which the foot can be placed on the next step when the left leg is the supporting leg. The range of possible landing points for the previous ASIMO is the red area in the

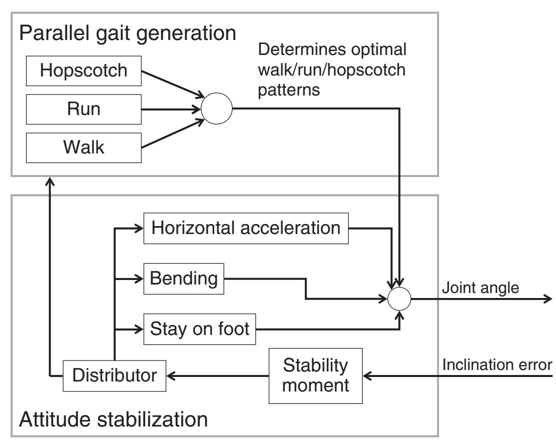

Fig. 8 Leg control system

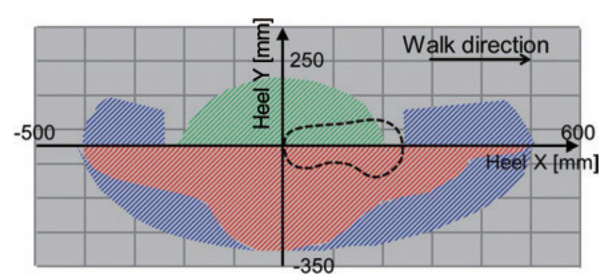

Fig. 9 Extended foot landing position

figure. The foot and leg cannot be extended in the direction of the supporting leg (positive direction on the Y axis), and there was therefore a risk that the robot would fall over if it were subjected to an external disturbance on the supporting-leg side. The new ASIMO has been given the capability to move laterally toward the supporting leg by means of the cross-step leg movement and hopscotch movement. The blue areas show the idling-leg landing area, which has been expanded by the new ASIMO's cross-step leg movement. The green area shows the landing area for the supporting leg from the hopscotch movement. The cross-step leg movement and hopscotch movement have added a remarkable degree of stability when the robot is subjected to external disturbance in the direction of the supporting leg.

5.2.2. Real-time gait generation

Even the previous ASIMO had the conceptual approach of overall stability, which seeks to stabilize the robot against inclination error by bending at the hip or accelerating the upper body. Since it did not have lateral movement or real-time gait generation, however, its capability for stabilization was low and the circumstances under which the capability could be used were limited.

Figure 10 shows the landing point determination method used when exerting restoring force against inclination error. When the zero moment point (ZMP), calculated from the moment of the restoring force required when trying to land the foot at the desired landing point in the diagram, goes beyond the foot, the sensitivity of the landing point and ZMP compensation is calculated and the ZMP landing point is decided analytically.

The new ASIMO has achieved overall stability that can be used on uneven road surfaces and other such real-life environments. It was achieved by this real-time gait generation technology as well as by the expansion of the range within which the foot can be placed by means of the cross-step movement and hopscotch movement, as described in the previous section.

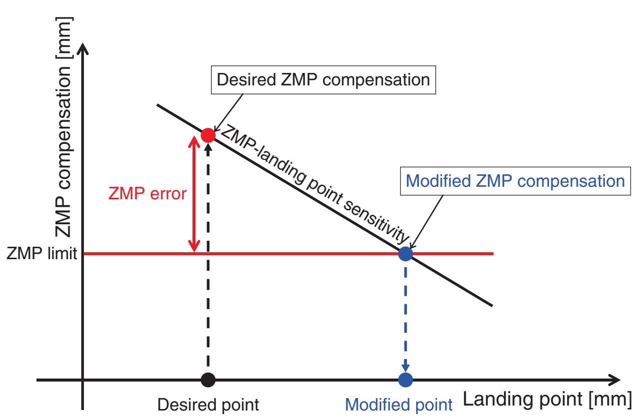

Fig. 10 ZMP landing point compensation

6. Compact, Hydraulic Many-Axis Hand

The previous ASIMO's hands were grippers with two degrees of freedom that did not even have sensors. Consequently, they were only capable of gripping a limited range of objects in a fixed manner. In working toward achievement of work that is in the interest of coexisting with people and performing useful functions, it becomes necessary to increase the types of object and to enable manipulation even when object positions and postures become more diverse. With the new ASIMO, therefore, the number of degrees of freedom in the hand was increased significantly without undercutting its design quality. Control for a stable grip using sensor information and degrees of freedom was also developed.

6.1. Hardware

The enhanced compactness of every functional component in the new ASIMO achieved multiple degrees of freedom in the ASIMO-sized hands. A mechanism was adopted that uses hydraulic pressure to transmit driving force from the motors, which support each axis on a one-to-one basis[5]. The hydraulic pressure master cylinders for all 26 axes were made more compact by means of a newly developed motor integrated with a ball screw, a 13-axis motor driver, and the integration of multiple axes in one. The master cylinders are mounted inside the robot torso, as shown in Fig. 11. Each finger uses low-expansion, small-diameter, flexible mesh-reinforced tubing to provide full responsiveness under the increase in pressure that occurs when the crank is made more compact.

Newly developed, compact six-axis force sensors were mounted at the fingertips of all five fingers on each hand. Tactile sensors were also placed under the skin on the palms of the hands. These together with the six-axis force sensors on the wrist provide 96 channels of signals. A compact electronic control unit that can capture these signals on a cycle of 250 μs and be mounted in the hand was also developed.

Measures were also taken to enable diverse manipulations of work objects. The angular mobility of the wrists was increased 90% in the vertical direction and 60% in a twisting direction compared to the previous model, significantly increasing the degree of postural freedom of

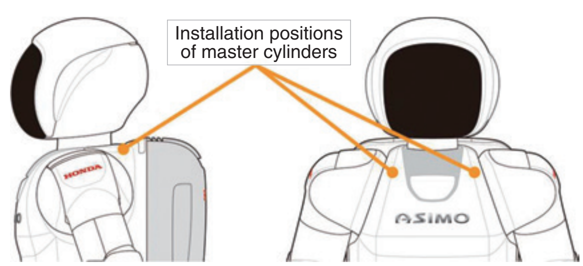

Fig. 11 Installation positions of hydraulic pressure master cylinders

the hands.

Application of these technologies achieved a compact hand weighing 0.38 kg and capable of gripping 1.8 kg, an increase of 360% over the previous capability.

6.2. Stable Grip and Shift of Grip

In order to secure a stable grip on an object, it is necessary to distribute finger forces properly to every finger so that the object will not slip. Determination of the internal forces for the new ASIMO required development of a method for formulating the grip conditions in terms of force distribution such that the contact point on the finger side and the contact point on the object side have a relative velocity of zero. This method remains effective even if the number of contact points is increased.

Figure 12 shows the relationships of forces when multiple fingers grasp an object. The blue in the figure signifies the designed finger forces, the red signifies the combined force of those forces, and the black signifies gravity. The internal forces are distributed so that the grip on the object will be stable even if the number of gripping fingers changes. In the horizontal direction, the forces of the fingers cancel each other out, and in the vertical direction, the combined forces balance out with the force of gravity. A divergence between the designed grip point and the actual grip point occurs when the object is actually gripped, so that the anticipated center of gravity and the actual center of gravity diverge. In order to extrapolate this divergence and compensate for it, the model of the object is corrected using a center of gravity error that is obtained as the difference between the designed finger force value and the actual value. Gripping force transition control that determines the gripping force by continuously changing the constraining conditions was also incorporated.

The hardware described in the previous section together with these items of control technology enabled the robot to perform the task of using one hand to pick up a drinking flask from a tabletop, unscrewing the cap, and pouring a drink from the flask into a cup that was picked up with the other hand.

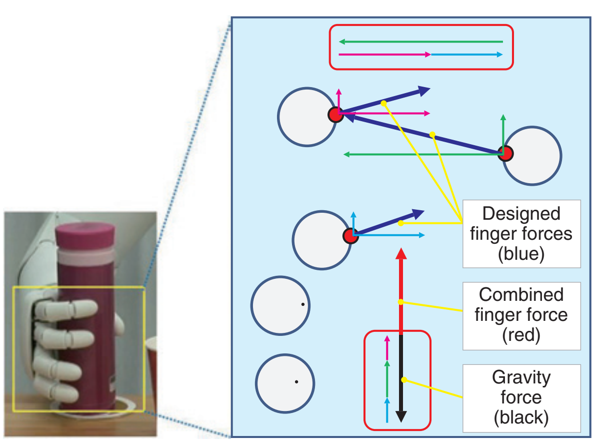

Fig. 12 Multi-finger grasping

6.3. Sign Language

The aim for the ASIMO is to achieve a high level of expressiveness that communicates readily to people using the robot's body and taking advantage of its humanoid characteristics. Sign language was selected as the means for expression by the new ASIMO, which was equipped with the actions to express greetings, self-introduction, and comments on the weather, which are frequently used in everyday life (Fig. 13). Sign language is a means of communication that functions through bodily expressiveness, and it includes large numbers of effective mechanisms, schemes, conventions, and other such resources that can be applied to bodily expression technology for robots.

The sign language words and messages that were created were then tested on a native user of sign language. This confirmed that fully adequate expression was taking place.

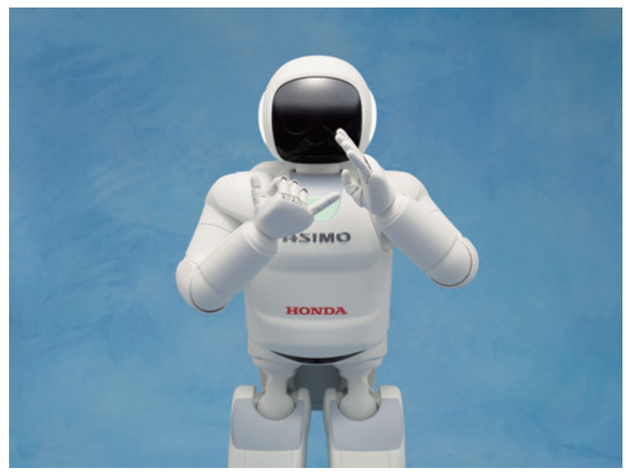

Fig. 13 Sign language "family"

7. Conclusion

The new ASIMO was developed with the capability for continued working in a real-life environment where it coexists with people. This was a step toward achieving "a robot that coexists and cooperates with people and performs useful functions in society." The new ASIMO represents an evolution from an automatic machine that performs fixed actions to an autonomous machine that matches its actions to changes in surrounding circumstances. This resulted in a system built with an architecture that constitutes the foundation technology for enhancement of robot intelligence, and it established the fundamental technology for engaging in appropriate action toward people in changing circumstances. In terms of bodily abilities, the development of lightweight mechanisms with a wide range of movement, high-response electrical systems, and new control technologies achieved an agility capable of dealing with changing circumstances.

Our intention at Honda is to make use of operational trials in real-life environments to further refine the robot's capability for adapting to circumstances within environments where it coexists with humans, and to expand the locations in which the robot can operate.

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