Design, Implementation, and Remote Operation of the Humanoid H6

Satoshi Kagami Koichi Nishiwaki James J. Kuffner Jr.
Tomomichi Sugihara Masayuki Inaba Hirochika Inoue
Dept. of Mechano-Informatics, Univ. of Tokyo.
7–3–1, Hongo, Bunkyo-ku, Tokyo, 113–8656, Japan.
{kagami,nishi,kuffner,zhidao,inaba,inoue}@jsk.t.u-tokyo.ac.jp

Abstract: The paper describes the humanoid robot "H6", which was designed to serve as a platform for experimental research on the development of advanced humanoid-type robots. The key features of the design of H6 include: 1) complete, 35-DOF human-shaped body with joints having sufficient torque to support full-body motion, 2) high-performance PC/AT compatible on-board computer running RT-Linux, a real-time OS that facilitates simultaneous low-level and high-level control, 3) fully self-contained on-board power supply and wireless network connection, that allows remote operation via radio ethernet, 4) software for dynamic walking trajectory generation, motion planning, and 3D stereo vision. We give an overview of both the hardware and software design components of H6, and discuss some experimental results involving remote operation.

1. Introduction

Recently, research on humanoid-type robots has become increasingly active, and many fundamental issues are under investigation. In particular, techniques for bipedal dynamic walking, soft tactile sensors, motion planning, and 3D vision continue to progress. However, in order to achieve a humanoid robot which can safely operate in a human environment together with human beings, not only the fundamental components themselves, but also the successful integration of these components will be required. At present, almost all humanoid robots that have been developed have been designed for bipedal locomotion experiments. In order to satisfy the functional demands of locomotion as well as high-level behaviors, humanoid robots require good mechanical design, hardware, and software which can support the integration of tactile sensing, visual perception, and motor control.

The child-sized, full-body humanoid "H5" (127cm height, 33kg mass) was previously developed for conducting research on dynamic bipedal locomotion, and techniques for dynamically-stable trajectory generation have been proposed[1, 2, 3]. However, a humanoid robot which can operate safely in a human environment requires fully self-contained on-board processing, sensing systems, power supply, and sophisticated software. The humanoid robot H6 was developed with the aim of satisfying these requirements.

In this paper, the functional requirements, design and implementation,

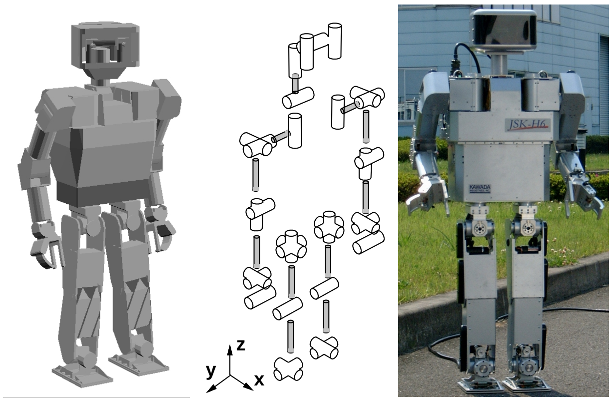

Figure 1. Geometric Model in Euslisp, DOF arrangement, Photo of H6

and remote-operation experiments using the humanoid robot H6 as a research platform for perception-action integration are described.

2. Conceptual Design and Specifications of H6

2.1. Design Criteria

The following criteria were considered in selecting the design for H6:

- Compact and light weight body.
- Modular structure for ease of maintenance and enhancement.
- Fully self-contained, including batteries, CPU, and network connection to a LAN via wireless ethernet.
- Sufficient DOF, range of movement, and maximal joint torque and speed, that enables dynamic walking as well as the ability to stand up should the robot fall down.
- Head-mounted dual cameras capable of looking straight down at the feet, as well as having vergence control motors for 3D vision.
- Smooth body surface, suitable for mounting tactile sensor skin made of pressure sensors and air-chambers.
- On-board high performance PC/AT computer running RT-Linux as the primary system controller.
- Software libraries for dynamically-stable walking trajectory generation, motion planning, 3D vision, and voice recognition and synthesis.

2.2. Specifications

The humanoid robot H6 was designed and developed according to the above requirements. The robot weighs a total of 55.0[kg] (including batteries), and measures $285(l) \times 598(w) \times 1361(h)$ $[mm]$ when standing at rest. H6 has a total of 35 degrees of freedom (DOF): 6 for each leg, 1 for each foot (toe joint), 7 for each arm, 1 for each gripper, 2 for the neck, and 3 for the head-mounted

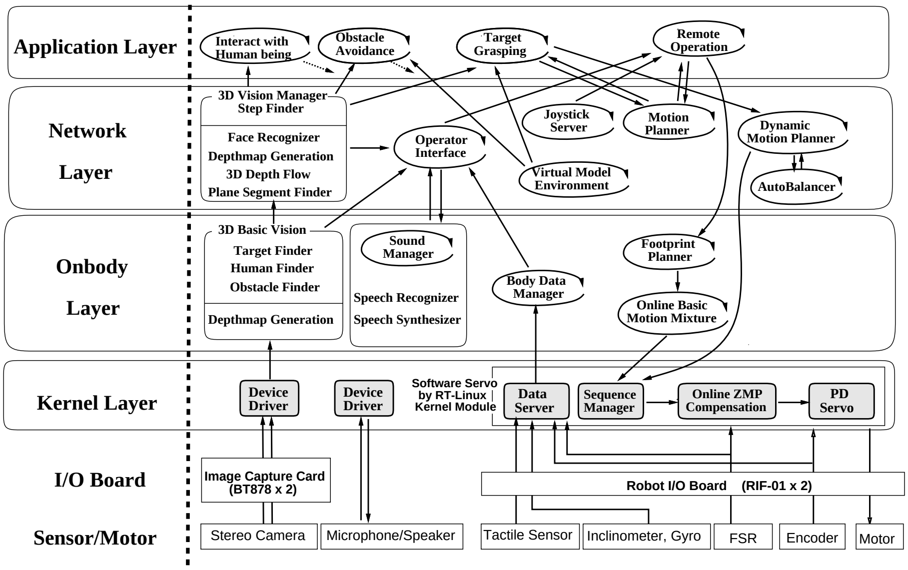

Figure 2. H6 Software Components

cameras (including vergence control). All major joints are driven by DC motors and Harmonic drive gears. An onboard PC/AT computer equipped with dual PentiumIII-750MHz processors running RT-Linux is used for real-time servo and balance compensation, as well as coordinating high-level 3D vision and motion planning component software modules. The system is connected to the network via wireless ethernet. Thus, the robot is fully self-contained (it can be operated without any external cables).

A 24V DC power supply is used for H6, thus two (12V, 5.0A, 2kg) lead-acid batteries are stored inside the torso for both controllers and motors. This configuration can supply power for about 10 to 15 minutes of normal operation on average (5 minutes for continuous walking). When squatting down, the maximum current drawn by the motors is about 29A, with the average current at approximately 4A(96W). The power consumption for the computer is 4.3A(102W) on average.

Twelve force sensing resistor (FSR) sheets are attached to the soles of each foot, so that the total force along the vertical axis and the ZMP position can be measured. An inclinometer and accelerometer are also mounted inside the center of the torso. Data from these sensors are measured using RIF-01 A/D boards.

A tactile skin sensor suit consisting of air chambers with pressure sensors was designed to provide both tactile feedback and shock absorption.

3. Software Design

3.1. Requirements of Humanoid Robots

A humanoid robot research platform should satisfy many aspects of experimental research, from low-level quick/smooth motion control to high-level vision/sensor-based behavior in complex environments. Therefore, a transparent software-layer system is adopted for real-time control and high-level computations. There are two fundamental requirements: 1) efficient software servoing, and 2) high-performance multi-tasking with network capability, such as remote resource utilization, application interface to developers, etc.

In order to simultaneously satisfy the demands of legged locomotion control and high-level perception and behavior processing, RT-Linux[4] is adopted with the servo loop implemented as a kernel module. Since Linux is not a real-time OS originally, RT-Linux has two special mechanisms: one is a scheduler for real-time processes, and the other is a two-level interrupt handler.

3.2. H6 Software Components

There are six software components in H6(Fig.2). i) realtime servo-loop, online ZMP compensation mechanisms for servoing and walking, ii) online footprint planning mechanisms, iii) onbody low-level 3D vision processing, voice processing functions, iv) motion planning and obstacle-avoidance functions, v) a vision, sound, and other sensor data server, in order to achieve network through data processing, vi) high-level 3D vision functions, voice recognition, and other high-level recognition functions are distributed on other network computers.

3.3. Joint Servo Unit

All 28 joints except those in the head are controlled by one RT loop which runs at a 1msec cycle (Motor servo in Fig.2). It is essentially PD control.

3.4. Online ZMP Compensation

For humanoid-type robots, it is difficult to "replay" dynamically-stable walking trajectories correctly in the real world, even if they satisfy the ZMP constraints. Therefore, various local compliance control methods have been proposed [5, 6, 7, 8]. Currently, we have adopted a torso position compliance method to track a given ZMP trajectory. This method attempts to track a given ZMP trajectory by adjusting the horizontal motion of the torso. It consists of two parts: one is a ZMP tracking mechanism, and the other is inverse pendulum control used to maintain dynamic balance (Online ZMP compensation in Fig.2)[9].

3.5. Walk Trajectory Generation

For walking, it is difficult to generate controls for every DOF interactively. We have proposed an offline dynamically-stable trajectory generation method for humanoid robots[9]. From a given input motion and the desired ZMP trajectory, the algorithm generates a dynamically-stable trajectory using the relationship between the robot's center of gravity and the ZMP. A simplified robot model is introduced that represents the relationship between its center of gravity and ZMP. It can then be shown that a horizontal shift of the torso can satisfy the given desired ZMP trajectory.

Let the z axis be the vertical axis, and the x and y axes be the other components of that sagittal and lateral plane respectively. First, we introduce a model of humanoid-type robot by representing the motion and rotation of the center of gravity (COG). Let the total mass of the robot be m_{total}, the position of the center of gravity be $\boldsymbol{r}_{cog} = (r_{cog_x}, r_{cog_y}, r_{cog_z})$, and the total reaction force that the robot feels be $\boldsymbol{f} = (f_x, f_y, f_z)$. The ZMP $\boldsymbol{p}_{cog} = (p_{cog_x}, p_{cog_y})$ around the point $\boldsymbol{p} = (p_x, p_y, h)$ on the horizontal place $z = h$ is defined as the point where the total moment around point $\boldsymbol{p}$ is $\boldsymbol{T} = (0, 0, Tz)$. Then following differential equation is obtained.

$$\boldsymbol{p}^{err}_{cog}(t) = \boldsymbol{r}^{err}_{cog}(t) - \frac{m_{total} r_{cog_z}(t) \ddot{\boldsymbol{r}}^{err}_{cog}(t)}{f^o_z(t)} \tag{1}$$

Here, $\boldsymbol{p}^{err}_{cog}$ is the error between the ideal ZMP $\boldsymbol{p}^*_{cog}$ and the current measured ZMP $\boldsymbol{p}_{cog}$, and $\boldsymbol{r}^{err}_{cog}$ is the error between the ideal center of gravity trajectory $\boldsymbol{r}^*_{cog}$ and the current measured trajectory $\boldsymbol{r}_{cog}$.

Finally, an iterative numerical method is adopted to eliminate approximation errors arising from the simplified model.

3.6. Online Mixture and Connection of Pre-designed Motions

In order to implement interactive and adaptive behaviors, an online walking pattern generation function is developed. Enhancing "Dynamically Stable Mixture of Pre-designed Motions[2]", an appropriate body position, posture and velocity can be generated by mixing pre-calculated candidate motions online (Footprint planner in Fig.2). The step cycle time is fixed, and arbitrary footprint positions on the plane can be achieved.

Utilizing the properties of the ZMP, a dynamically-stable mixture of pre-designed motion is carried out to generate a desired walking motion. This mixture consists of three stages: 1) offline typical stepping pattern generation, which calculates 21 pre-designed basis motions using the previously-described offline trajectory generation method for translational motions, 2) mixing the pre-designed basis patterns independently along the X&Y axes, and then mixing the resulting patterns, 3) connecting subsequent stepping motions by selecting patterns in which the torso velocities at the boundaries are smooth enough.

The 2^{nd} and 3^{rd} stages of this mixture method incur a relatively low computational cost, so that desired walking patterns can be generated in real-time. The user need only to designate the direction and speed of the motion using a pointing device. Fig.3(Top row) shows a joystick control experiment using the humanoid H6.

3.7. Autobalancer

The "AutoBalancer" software reactively generates dynamically-stable motions of a standing humanoid robot on-line, given an input motion ([10, 3]). The system consists of two parts: 1) a planner for considering state transitions defined by the nature of the contacts between the legs and the ground, and 2) a dynamic balance compensator which maintains balance by formulating and solving a second order nonlinear constrained optimization problem. The latter can compensate for the centroid position and the tri-axial moments of any standing motion, using all joints of body in real-time. The complexity of AutoBalancer is $O((p+c)^3)$, where p is the number of DOFs and c is the number of constraint equations (Autobalancer in Fig.2).

3.8. 3D Vision Processing

Real-time 3D Vision functions are fundamentally important for a robot that behaves in the real world. Recently, several real-time 3D depth map generation systems have been proposed in the computer vision literature (e.g. [11, 12]) and some commercial products are also currently available (e.g. [13]). However, these solutions typically require special hardware. Since an onboard real-time system is needed for mobile robotics (or other camera moving) applications, it is difficult to build such a system given the extra hardware requirements.

In order to solve this problem, we proposed a real-time depth map generation system using only standard PC hardware and a simple image capture card [14]. Four key issues were considered in order to achieve real-time performance and to obtain accurate range data: 1) use of a recursive (normalized) correlation technique, 2) cache optimization, 3) an online consistency checking method, 4) utilizing the MMX/SSE(R) multimedia instruction set.

So far we have developed real-time 3D vision functions that include: 1) depth map generation[14], 2) 3D depth flow generation[15], and 3) a plane segment finder[16]. Th real-time depthmap generation system, along with an application for finding and tracking human targets can run on the onboard PC. Other high-level vision functions such as the plane segment finder, face recognition software, and so on, consume much more computational resources. Thus, they are run on other processors distributed over the network.

3.9. Dynamically-stable Motion Planning

Since humanoid robot has many DOFs, it is difficult to calculate a full-body trajectory, such as reaching towards a target object, without colliding with itself or an obstacle in the environment.

We have developed an approach to path planning for humanoid robots that computes dynamically-stable, collision-free trajectories from full-body posture goals. Given a geometric model of the environment and a statically-stable desired posture, we search the configuration space of the robot for a collision-free path that simultaneously satisfies dynamic balance constraints [17].

Our approach is to adapt a variation of the randomized planner described in [18] to compute full-body motions for humanoid robots that are both dynamically-stable and collision-free. This planner (RRT-Connect) and its variants utilize Rapidly-exploring Random Trees (RRTs) [19] to connect two search trees, one from the initial configuration and the other from the goal. These methods have been shown to be efficient in practice and converge towards a uniform exploration of the search space.

3.10. Sound Processing

Since a humanoid robot has many motors, a significant amount of sound is generated during its operation. Therefore, voice recognition software should be able to filter internal noises. We adopted voice recognition software developed by Dr.Hayamizu at ETL. This software has the advantage that it can run on the onboard processor (it runs on Linux), and a programmer can very easily manage its dictionary. Leveraging this advantage, task-based dictionaries which contain only a limited set of words specific to a given task are prepared, which makes the recognition function robust in terms of noise. The speech synthesis is done using commercial software (Fujitsu), which also runs on Linux. Fig.3 2^{nd} row shows a voice-command based walking experiment.

4. Remote Operation of a Humanoid Robot

The software components described in the previous section are still rather primitive considering the kinds of sophisticated autonomous behaviors likely to be expected of future humanoid-type robots. Thus, a graphical user interface for network remote operation with limited autonomy was adopted. It requires low-level autonomy for stability and task execution, but can accept high-level commands. Currently the Humanoid Robotics Project(HRP:MITI Japan) contains a sub-project for network-based, remote tele-operation of a humanoid robot [20]. However, instead of developing low-level autonomy, it is strongly dependent on virtual reality technology and hardware, and the availability and training of a human operator to carefully control the robot.

Increasingly sophisticated low-level autonomy will be required to enable higher-level autonomous behavior research on humanoid-type robots. Therefore, not only tele-operated applications will benefit, but also this autonomy will be useful for building other direct applications which require high-level autonomous behavior and adaptability to environments with uncertainty.

4.1. Network Operation Interface for Humanoid Robot

There exists three major requirements for a network-operated humanoid robot interface: 1) control interface, 2) environment interface, and 3) interaction interface.

The first requirement is the interface for controlling the joints of the robot body. Due to the number of DOFs, it is tedious and nearly impossible to control a robot by adjusting each joint position manually. Even using a master-slave control interface, it is very difficult to control the robot so as to maintain dynamic stability. Thus, we have designed a “virtual-puppet” graphical interface that combines the Autobalancer, and walking controls. An operator can issue high-level commands to the humanoid robot, such as to manipulate a particular object, or walk in a desired direction.

The second requirement is an interface for recognizing the environment. A remotely-operated robot working in a real environment typically has cameras with a relatively narrow field of view, thus it is difficult to obtain an overall 3D picture of the environment surroundings. Using a graphic display, the internal robot environment model, state display, and 3D vision results can be visualized and compared to local internal models. With this interface, an operator can simply designate a target object to grasp or a direction to walk with relative ease.

The third requirement consists of an interface between human beings who are a) working in the same environment as the remotely-controlled humanoid robot, and b) the user in front of the remote operation interface. Voice recognitionspeech and human findingface recognition functions are denoted. An operator can communicate with other human beings in the robot's environment without having to spend a lot of effort to do so. Thus, he or she can better concentrate on the robot's given task at hand.

5. Conclusion

The paper describes the humanoid robot "H6", which was designed to serve as a platform for experimental research on the development of advanced humanoid-type robots. The key features of the design of H6 include: 1) complete, 35-DOF human-shaped body with joints having sufficient torque to support full-body motion, 2) high-performance PC/AT compatible on-board computer running RT-Linux, a real-time OS that facilitates simultaneous low-level and high-level control, 3) fully self-contained on-board power supply and wireless network connection, that allows remote operation via radio ethernet, 4) software for dynamic walking trajectory generation, motion planning, and 3D stereo vision. We hope that H6 can become a common test-bed for experimental research aimed at developing humanoid-type robots with higher levels of both performance and autonomy.

Acknowledgements

This research has been supported by Grant-in-Aid for Research for the Future Program of the Japan Society for the Promotion of Science, "Research on Micro and Soft-Mechanics Integration for Bio-mimetic Machines (JSPS-RFTF96P00801)" project.

References

[1] K. Nagasaka, M. Inaba, and H. Inoue. Walking Pattern Generation for a Humanoid Robot based on Optimal Gradient Method. In *Proc. of 1999 IEEE Int. Conf. on Systems, Man, and Cybernetics No. VI*, 1999.

[2] K. Nishiwaki, K. Nagasaka, M. Inaba, and H. Inoue. Generation of reactive stepping motion for a humanoid by dynamically stable mixture of pre-designed motions. In *Proc. of 1999 IEEE Int. Conf. on Systems, Man, and Cybernetics No. VI*, pp. 702–707, 1999.

[3] S. KAGAMI, F. KANEHIRO, Y. TAMIYA, M. INABA, and H. INOUE. Autobalancer: An online dynamic balance compensation scheme for humanoid robots. In *Proc. of Fourth Intl. Workshop on Algorithmic Foundations on Robotics (WAFR'00)*, pp. SA–79–SA–89, 2000.

[4] V. Yodaiken and M.Barabanov. *RT-Linux*. http://www.rtlinux.org.

[5] Ken'ichirou NAGASAKA, Masayuki INABA, and Hirochika INOUE. Stabilization of Dynamic Walk on a Humanoid Using Torso Position Compliance Control. In *Proceedings of 17th Annual Conference on Robotics Society of Japan*, pp. 1193–1194, 1999.

[6] Honda Co. Ltd. *Walking Control System for Legged Robot.* Japan Patent Office (A) 5-305583, 1993.

[7] Honda Co. Ltd. *Walking Control System for Legged Robot.* Japan Patent Office (A) 5-200682, 1993.

[8] Honda Co. Ltd. *Walking Pattern Generation System for Legged Robot.* Japan Patent Office (A) 10-86080, 1998.

[9] S. KAGAMI, K. NISHIWAKI, T. KITAGAWA, T. SUGIHARA, M. INABA, and H. INOUE. A fast generation method of a dynamically stable humanoid robot trajectory with enhanced zmp constraint. In *Proc. of IEEE International Conference on Humanoid Robotics (Humanoid2000)*, 2000.

[10] Y. Tamiya, M. Inaba, and Hirochika Inoue. Realtime balance compensation for dynamic motion of full-body humanoid standing on one leg. *Journal of the Robotics Society of Japan*, Vol. 17, No. 2, pp. 268–274, 1999.

[11] K. Konolige. Small Vision Systems: Hardware and Implementation. In Y. Shirai and S. Hirose, editors, *Robotics Research: The Eighth International Symposium*, pp. 203–212. Springer, 1997.

[12] T. Kanade, A. Yoshida, K. Oda, H. Kano, and M. Tanaka. A Stereo Machine for Video-rate Dense Depth Mapping and Its New Applications. In *Proc. of the 1996 International Conference on Computer Vision and Pattern Recognition*, pp. 196–202, Jun 1996.

[13] Point Grey Research Inc. *Triclops Stereo Vision System.* http://www.ptgrey.com.

[14] S. KAGAMI, K. OKADA, M. INABA, and H. INOUE. Design and implementation of onbody real-time depthmap generation system. In *Proc. of International Conference on Robotics and Automation (ICRA'00)*, pp. 1441–1446, 2000.

[15] S. Kagami, K. Okada, M. Inaba, and H. Inoue. Real-time 3d optical flow generation system. In *Proc. of International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI'99)*, pp. 237–242, 1999.

[16] S. Kagami, K. Okada, M. Inaba, and H. Inoue. Plane segment finder. In *5th Robotics Symposia*, pp. 381–386, 2000.

[17] J. J. Kuffner, S. KAGAMI, M. INABA, and H. INOUE. Dynamically-stable motion planning for humanoid robots. In *Proc. of IEEE International Conference on Humanoid Robotics (Humanoid2000)*, 2000.

[18] J.J. Kuffner and S.M. LaValle. RRT-Connect: An efficient approach to single-query path planning. In *Proc. IEEE Int'l Conf. on Robotics and Automation (ICRA'2000)*, San Francisco, CA, April 2000.

[19] Steven M. LaValle and Jr James J. Kuffner. Rapidly-exploring random trees: Progress and prospects. In *Proc. of Fourth Intl. Workshop on Algorithmic Foundations on Robotics (WAFR'00)*, 2000.

[20] H. Inoue and S. Tachi and K. Tanie and K. Yokoi and S. Hirai and H. Hirukawa and K. Hirai and S. Nakayama and K. Sawada and T. Nishiyama and O. Miki and T. Itoko and H. Inaba and M. Sudo. HRP: Humanoid Robotics Project of MITI. In *Proc. of IEEE International Conference on Humanoid Robotics (Humanoid2000)*, 2000.

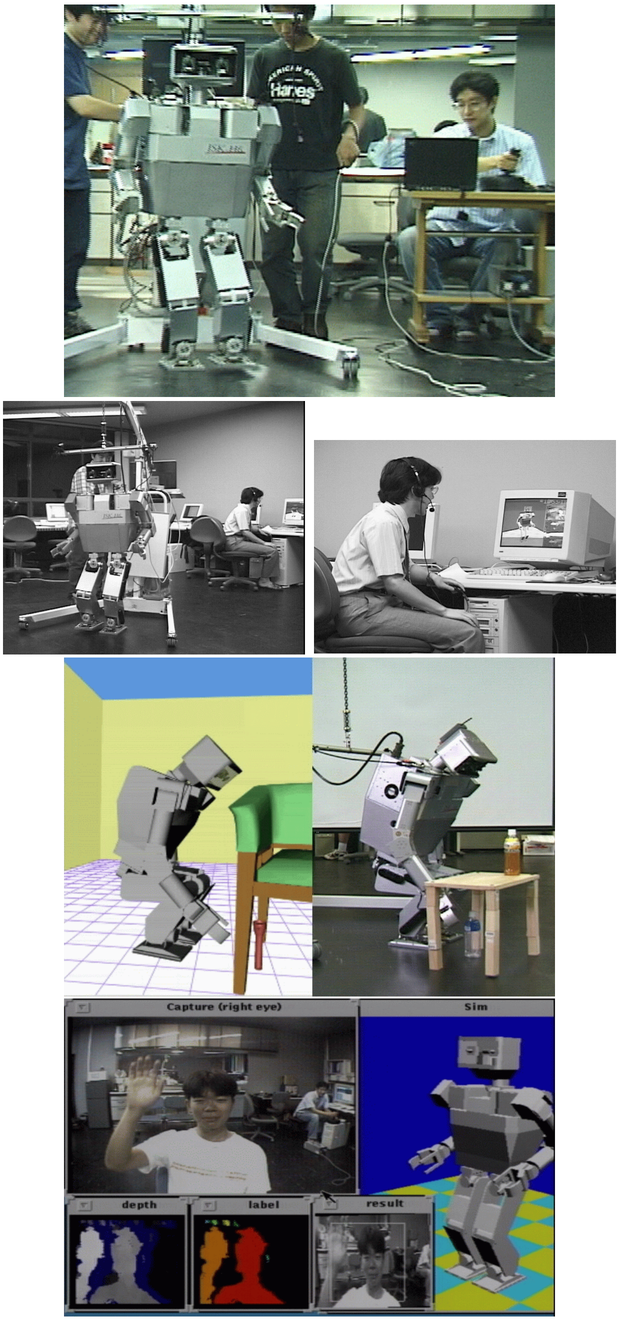

Figure 3. H6 Experiments : Top row: H6 Controlled by joystick (man on the right has joystick), 2nd row: Voice control, 3rd row: Dynamically-stable motion planning, 4th row: 3D vision system which finds and tracks human beings.