Proceedings of the 2002 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
EPFL, Lausanne, Switzerland • October 2002

The Design and Control of the Flexible Spine of a Fully Tendon-Driven Humanoid “Kenta”

Ikuo Mizuuchi, Ryosuke Tajima, Tomoaki Yoshikai, Daisuke Sato,
Koichi Nagashima, Masayuki Inaba, Yasuo Kuniyoshi, and Hirochika Inoue

Department of Mechano-Informatics, University of Tokyo, Japan
{*ikuo,rosk,yoshikai,dsk,naga,inaba,kuniyosh,inoue*}*@jsk.t.u-tokyo.ac.jp*

Abstract

We are trying to realize a humanoid which has flexibility. If humanoids have flexible structure, safety and variety of the posture will be achieved. We especially focus on the role of human's spine and muscle-driven system. By having a flexible spine, a humanoid will have safety and many degrees of freedom to realize the variety of the postures. By driving joints by tension-controllable tendons, flexibility of the joints will be able to be controlled. We developed a whole-body tendon-driven flexible-spine humanoid named “Kenta”. This paper describes the design and control of Kenta's, focusing on the design of the spine. The spine consists of ten joints, vertebrae and rubber disks, ribs, and forty muscles equipped with tension sensors. The design refers to the structure of human's spine. This paper also proposes kinds of control methods of the spine. One uses a geometric virtual robot model, and another is based on direct teaching. Using these methods, some whole-body motions are presented.

1 Introduction

Almost all humanoids ever built [1, 2, 3, 4] have rigid bodies, and their motions often seem restricted because of the rigidity. The flexibility will be one of the keys to the next stage of humanoid research. From the point of view, we developed a whole-body tendon-driven humanoid, who has a ten-jointed flexible spine. The name of the humanoid is “Kenta”[5](*Figure 1*). The flexible spine will be needed to achieve human-like motions, and also to realize the sufficient and efficient DOFs for practical purposes. Using the tension-sensored tendons of the whole body, the joints and the spine can be both adaptive (flexible) and stiff. The variability of the flexibility of the spine enables the spine to play also a role of the support of the upper body. The aim of this research is to develop a humanoid which has a variable flexible structure like human's spine, and to show the way of this field.

Figure 1: *Kenta: a whole-body tendon-driven flexible-spine humanoid*

2 Flexible-Spine Humanoid with Tendons

2.1 Flexibility of humanoids

Humanoids are expected to work in the human's field, but we often feel that their motions seem unnatural or restricted because of the rigid body. Almost all of the human-form robots ever developed were so rigid that there was a danger for human to be hurt. If a humanoid intentionally has some flexible structure, the possibility of avoiding the danger increases. We especially focus on the flexible spine structure and tendon(muscle)-driven system. Flexible spine brings safety and the expansion of degrees of freedom. By driving joints by tendons in conjunc-

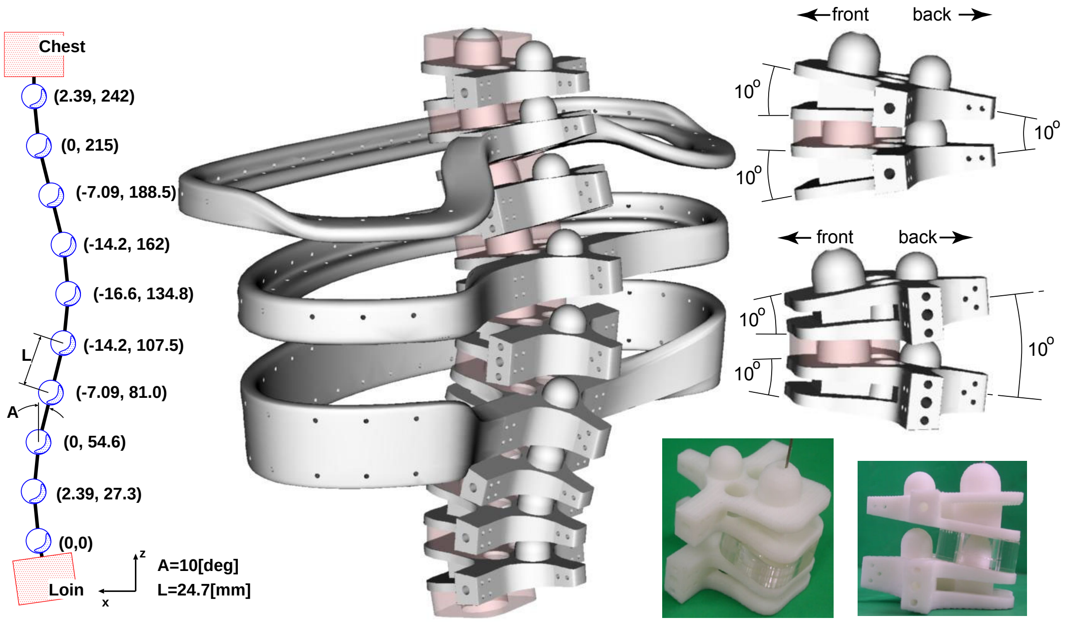


Figure 2: *Left: the link arrangement of the spine, Middle: CAD design of spine, Right: two kinds of inclination of vertebrae (an elastic part is between each adjacent vertebrae.)*

tion with tension sensors, the joints have the possibility of changing the stiffness.

The researches on flexible robots[6] or multi-joint-structure robots[7, 8] have not been applied to the torso of humanoids. On the other hand, even though there have been some researches on embedding a movable mechanism in the torso (trunk) of human-form robot[9], these robots' torso can rotate around only one concentrated axis. The difference between a hip-joint and a spine is that the latter has more degrees of freedom. A spine has much more possible postures than a hip. By using the spine, the robot can move more efficiently. For example, when a flexible-spine humanoid is raising the upper body from the floor, it can move each joint one by one from the neck joint to the hip joint. This procedure lessens the maximum torque or maximum force during the motion compared with using only hip or crotch joint. Furthermore, the motions of flexible-spine humanoids could be nearer to natural (human-like) ones.

2.2 Variable flexibility

The variability of flexibility is very important. On a certain occasion the spine or joints are needed to be soft, and on another occasion they have to support the structure against the gravity. There have been a research on a joint with mechanical adjustable elasticity and viscosity[10]. The adjustable flexibility of a structure is somewhat different from the adjustable flexibility of a joint. In the case of flexible joint, the ability to absorb shock is often diminished by the large mass of the descendant links, compared with flexible structure. Flexible spine is a flexible structure.

2.3 Control of the flexible-spine

There has been a research on a flexible-spine human-form robot[11]. In the work, a flexible spine of five joints are controlled by eight muscles (tendons) equipped with tension sensors. The determination of muscles' lengths was done by geometric calculations, in which the interference between muscles and/or bodies was not considered. If there is a conflict of the lengths of some muscles, the stretching muscles are controlled using tension sensors in order for the tensions not to exceed a limit. With many conflicts, control by this method may fail. In the robot described in this paper have far more muscles and the failure of control often occurs. This paper describes how to solve the problem of such case.

3 Design of Flexible-Spine Humanoid Kenta

3.1 Design of the flexible spine

Follow the advantages of human's spine. The design of the spine structure of Kenta follows the basic policy as below: based on the investigation of the structure and characteristics of human's spine, we try to follow the design and function as much as possible.

Basic design of the spine. *Figure 2* shows the structure of Kenta's spine. The spine consists of 10 ball-and-socket joints. Each joint has three degrees of freedom. The parts which joints consist of can be compared to the vertebrae of human's spine. Between each adjacent vertebrae, there is an "interspinal disk" made of elastic silicone rubber, and there are also "ligaments" made of tension spring between the adjacent vertebrae. The height of the disk is slightly larger than the gap size between the adjacent vertebrae. Therefore, the rubber is put pressure in advance (pre-compression). The distance between the points where each ligament (spring) is attached is slightly longer than the natural length of the spring; therefore the spring is put tension in advance (pre-tension). When spine's posture differs from the neutral posture, the balance of disks' pressures and the balance of ligaments' tensions are lost and some force to return to the neutral posture is generated. This restoring force helps the actuators against gravity.

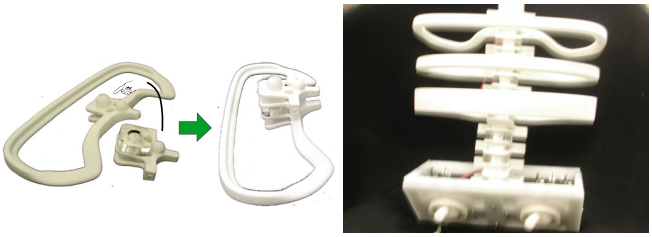
The ten-jointed spine is driven by 40 muscles, each of which has a tension sensor. The more muscles, the more variety the spine's posture has. The number of actuators was a decision in the design.

The 'S'-curve of the spine. The parts of vertebrae have two kinds of inclination of ten degrees. The right side of *Figure 2* shows the two kinds of inclination of vertebrae. By the combination of the two kinds of inclination, the posture of the spine is in a curve of 'S' character, shown in the left figure of *Figure 2*. (The center figure is in a right-back view.)

Vertebrae. Each vertebra has two spherical projections on the top surface and two spherical dents on the bottom surface. One spherical projection of lower vertebra matches one spherical dent of upper vertebra, and this structure organizes a ball-and-socket joint. A silicone-rubber disk is inserted in the gap. Another projection and dent is a mechanical limit of the joint, in order for the joint not to over-bend. Human's spine has the same function though the structure is different.

Each vertebra has the other three projections, which are not spherical. The projections are backward, leftward, and rightward (*Figure 2*), and these are for attaching ligaments.

Ribs. Kenta's spine has three ribs. Kenta does not have the internal organs to be protected by ribs. By putting the ends of muscles on the ribs, the positions of the muscles are parted from the center of rotation of the joints. By parted from the center of rotation, the contribution of the muscles to the modification of the spine's posture will be larger.



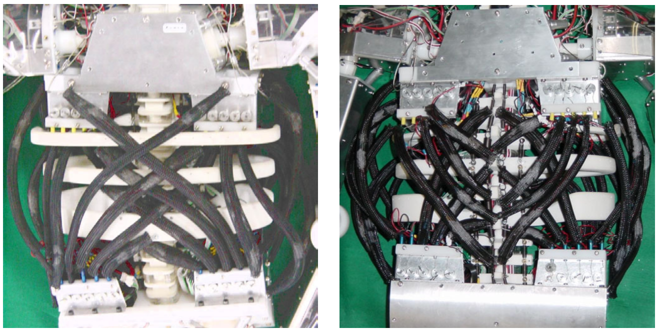


Figure 3: *The arrangement of muscles of the spine (left picture:front, right picture:back)*

Actuators. There are 40 motors to move the spine; twenty in the shoulder-block, and the other twenty in the hip-block. In the shoulder block, ten are in the right block, and the other ten are in the left block; in the hip block, ten in right and the other ten in left. The motors placed in inner side have power rather than speed, and the ones in outer side have speed rather than power. This is by the differences of gear ratios.

Figure 3 shows the arrangement of muscles. At the front side, muscles are placed traversing the front surface, while at the back side, all muscles are fixed to the spinous processes (back protuberances) of the vertebrae. At the right and left sides, muscles traverse the surfaces.

3.2 The other parts of the body

In legs and arms, all joints except knees and elbows are ball-and-socket joints, each of which is driven by four tendons, equipped with tension sensors. Each of knees and elbows has one degree of freedom and is driven by two tendons with tension sensors.

The structure of neck is like a small-scale version of the spine. The neck has five ball-and-socket joints like spine's vertebrae. It is driven by six muscles. The posture of the structure is decided by the balance of muscle's tension, rubber-disks' force, and the external forces containing gravity.

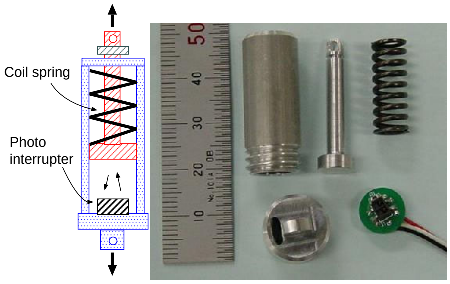


Figure 4: *Tension sensor unit*

3.3 Sensors

Muscle-length sensors. The lengths of muscles are calculated using the rotary encoders of motors. One thing to be noticed is that the relation between the encoder and the muscle-length is not linear since using pulley.

Muscle-tension sensors. Every muscle of Kenta has a tension-sensor. *Figure 4* shows the tension-sensor unit attached to the muscles. When the tension of the muscle changes, the length of the coil spring in the cylinder changes. By measuring the distance between the piston head and the cylinder's bottom, the tension is detected. The measurement of the distance is done by a photo interrupter which uses infrared LED and infrared photo transistor.

Motor-current sensors. In the motor-driver circuit, there is a 0.5[Ω] resister connected in series in the motor-power line. By measuring the drop of the voltage through the resister, the motor-current can be detected.

Vision sensors. Two CCD color cameras are installed in the eye-balls. Using the two cameras, it can calculate the depth by stereoscope. The depth map, 3D optical flow, color labeling, plane segment finder[12], etc. are implemented.

3D-accelerometers and gyroscope. There are eight 3-axis-accelerometers; in the hip, five vertebrae, the chest, and the head. They help to detect the information about the posture of the spine, and the information on Kenta's inclination, by detecting the direction of gravity.

Tactile sensor. Kenta has 62 tactile sensor unit (FSR: force sensing register). By using them, Kenta can obtain information of contact to the environments. These sensors can be also used for direct teaching of posture. By touching the tactile sensors directly, human can teach postures and motions.

3.4 The communication system

Kenta has 96 motors and over 350 sensors (7 kinds); a multiple input/output system. 43 microprocessors are onboard distributedly. These are connected through the onbody networks. Four hubs (gateways) of the networks collect the sensor information from distributed processors connected to several local sensors and send them to a remote host computer[13]. The hubs also receive the actuator information from the remote host and distribute them to the dispersed processors connected to several local motor drivers, which drive the actuators. Each microprocessor except hubs controls the local actuators.

The lowest layer in the remote host computer works as a hardware abstraction layer. This layer communicates with the hubs of the onbody networks. It is also a TCP/IP socket server, and when a request for connection from an upper layer software, it opens a connection and starts to send/receive sensor/actuator information to/from the upper layer.

4 Whole-Body Motions

How to generate whole-body motions using the complex structure like Kenta's spine or human's body is an important and difficult problem. This paper shows some simple solutions.

4.1 Virtual robot model and muscle-control modes

One method to manage the body is using a geometric virtual robot model in conjunction with some control modes of muscles[11]. The model can approximate the lengths of muscles of any posture of the body. The approximation is done as follows. Each muscle has information of the positions of the both ends. When some joints move, the both positions move following to the movement of the attached link. When the lengths of the muscles are asked, the model answers the lengths by calculating the straight-line distances between each two positions of all muscles according to the current posture of Kenta.

Depending on the posture, the error range of the muscles' lengths calculated as above could be a certain extent. When there are some interferences between the muscles and bodies, or between the muscles, then the motors have to generate large torques. To avoid such case, muscles can be controlled in other control-mode using the tension-sensors' information. By using the information of tension sensors, muscle's tension can be limited.

In *Figure 5*, Kenta is tracking a color object by coordination of eye-balls, neck, and spine. Vision processing of object-tracking is done in a remote host

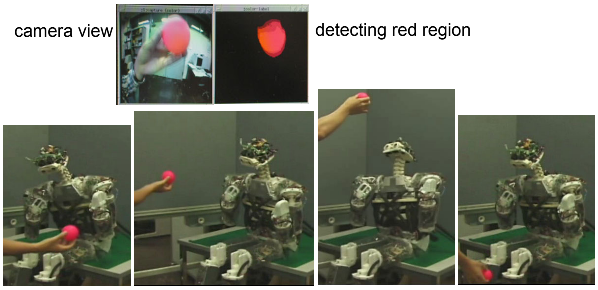


Figure 5: *Tracking an object by whole-body*

computer. There are three independent control-loops of object-tracking; the eye-balls are moving so as to see the object in the center of the view, and the neck and the spine are also moving in the same manner. These three control-loops are independent and by the combination of the three loops, the tracking motion using eye-balls, neck, and spine is realized. The parameters of the control-loops are tuned by human.

The model is used to calculate the relations between the joint-angles and the muscle-lengths. For example, in the control-loop by the spine, the required changes of the postures of the spine-joints are calculated from visual information, and then the required changes of the length of muscles are calculated using the geometric virtual robot model.

4.2 Direct teaching

A simple and strong way to make whole-body motions of a complex structure is direct teaching. By controlling all muscles in the tension-control mode, each tension of them is kept in a constant value. When we directly change the posture of the robot ((T1) and (T2) in *Figure 6*) in this condition, the lengths of all the muscles are modified to keep the tension. By recording the lengths while directly teaching, we can obtain the possible combinations of the lengths. At the stage of playing back, the muscles are controlled in the length-control mode, so as to reproduce the posture or the motion.

Figure 6 shows a motion using some directly taught postures. In (T1) and (T2), two postures are being taught by a man touching directly. (P1), (P2) and (P3) shows three postures played back. (P2) and (P3) correspond with (T1) and (T2) respectively. By the combination of the postures directly taught, some motions are realized.

4.3 The posture database

To help the directly teaching, we propose the 'posture database'. *Figure 7* shows the concept of the

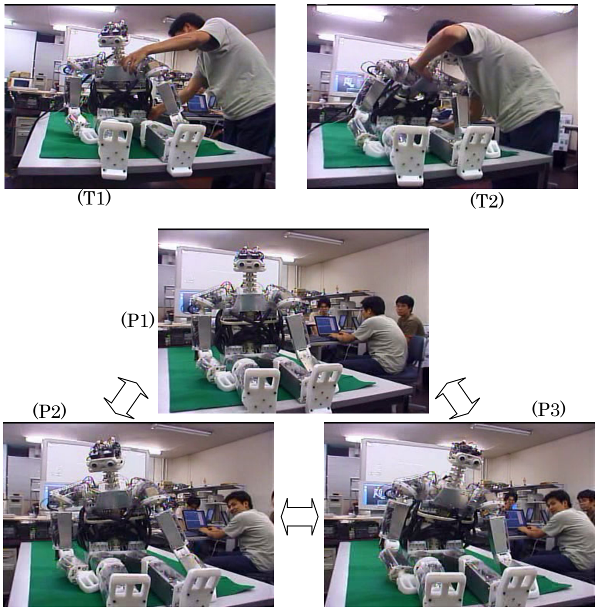


Figure 6: *Teaching postures and playing back them*

posture database. This database is automatically created when the robot moves. An element in the database includes the information of the muscles' lengths and 3D-accelerometers. The elements are segmented by the sensor information. When the distance between an instant data and every element of the database is larger than a threshold, a new element created by the data will be added to the database. In *Figure 7*, pose1 to pose9 are automatically generated in some motion. Pose10 and pose11 are created in the other motion of A to B. The elements of the database are guaranteed to be combinations of the muscle-lengths without the interference. The amount of data which should be recorded can be lessen compared with recording the postures at all moments. And we can use the postures of the database to develop motions.

Figure 8 shows a whole-body motion including spine-motion, which is generated by direct-teaching and using the posture-database and posture-history. The realized motion is a merged motion of separately taught spine-motion and legs-motion.

5 Summary and Conclusions

The design of a fullbody tendon-driven flexible-spine humanoid Kenta is presented. The flexible spine consists of vertebrae, ribs, disks, ligaments, and forty muscles with tension sensors. The structure of the spine is inspired from the human's spine. Some sim-

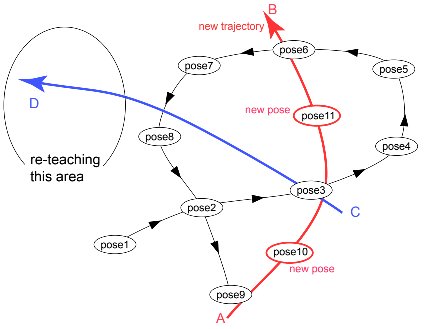


Figure 7: *The concept of posture database*

ple methods for generating whole-body motions are also presented. One is based on the combination of the geometric virtual robot model and several control modes of muscles. Using the method, Kenta's object-tracking motion by eye-balls, neck, and spine is realized. Using another method based on direct teaching, some whole-body motions are also shown.

There are still many problems needed to be solved. Kenta is a prototype of the flexible-spine humanoid. Even the design and control methods could be more sophisticated. We believe this work will be a foothold towards next stage of humanoid research.

Acknowledgments

This research has been supported by "Research for the Future" Program of the Japan Society for the Promotion of Science: Micro-Mechatronics and Soft-Mechanics (JSPS-RFTF96P00801).

References

[1] I. Kato, S. Ohteru, H. Kobayashi, K. Shirai and A. Uchiyama: "Information-Power Machine with Senses and Limbs(WABOT 1)", First CISM - IFToMM Symposium on Theory and Practice of Robots and Manipulators, Vol. 1, Springer-Verlag, pp. 11–24 (1974).

[2] K. Hirai, M. Hirose, Y. Haikawa and T. Takenaka: "The Development of Honda Humanoid Robot", Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 1321–1326 (1998).

[3] J. Yamaguchi, E. Soga, S. Inoue and A. Takanishi: "Development of a Bipedal Humanoid Robot – Control Method of Whole Body Cooperative Dynamic Biped Walking –", Proceedings of the 1999 IEEE International Conference on Robotics and Automation, pp. 368–374 (1999).

[4] K. Nishiwaki, T. Sugihara, S. Kagami, F. Kanehiro, M. Inaba and H. Inoue: "Design and Development of Research Platform for Perception-Action Integration in Humanoid Robot : H6", Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'00), Vol. 3, pp. 1559–1564 (2000).

[5] M. Inaba, I. Mizuuchi, R. Tajima, T. Yoshikai, K. Nagashima and H. Inoue: "Building Spined Muscle-Tendon Humanoid", Proceedings of 10th International Symposium of Robotics Research (2001).

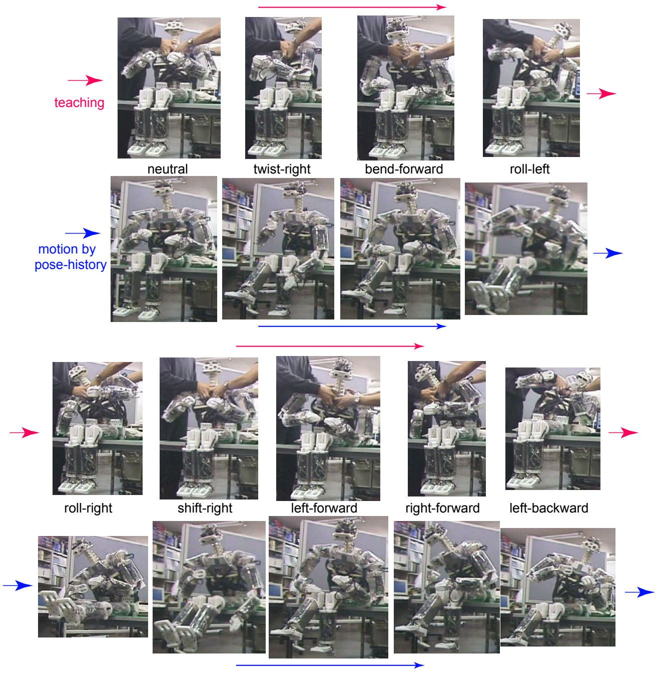


Figure 8: *A motion using pose history*

[6] T. Yoshikawa and K. Hosoda: "Modeling of Flexible Manipulators Using Virtual Rigid Links and Passive Joints", The International Journal of Robotics Research, **15**, 3, pp. 290–299 (1996).

[7] S. Hirose, T. Kado and Y. Umetani: "Tensor Actuated Elastic Manipulator", Proceedings of the Sixth World Congress on Theory of Machines and Mechanisms, Vol. 2, pp. 978–981 (1983).

[8] M. Hannan and I. Walker: "Analysis and Initial Experiments for a Novel Elephant's Trunk Robot", Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'00), pp. 330–337 (2000).

[9] J. Yamaguchi, S. Inoue, D. Nishino and A. Takanishi: "Development of a bipedal humanoid robot having antagonistic driven joints and three dof trunk", Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol. 1, pp. 96–101 (1998).

[10] T. Morita and S. Sugano: "Development and Evaluation of Seven-D.O.F. MIA Arm", Proceedings of the 1997 IEEE International Conference on Robotics and Automation, Vol. 1, pp. 462–467 (1997).

[11] I. Mizuuchi, M. Inaba and H. Inoue: "A Flexible Spine Human-Form Robot — Development and Control of the Posture of the Spine —", Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2099–2104 (2001).

[12] K. Okada, S. Kagami, M. Inaba and H. Inoue: "Plane segment finder: Algorithm, implementation and applications", Proceedings of the 2001 IEEE International Conference on Robotics & Automation, Seoul, Korea, pp. 2120–2125 (2001).

[13] M. Inaba, S. Kagami, F. Kanehiro, Y. Hoshino and H. Inoue: "A platform for robotics research based on the remote-brained robot approach", The International Journal of Robotics Research, **19**, 10, pp. 933–954 (2000).