Whole-body Cooperative Balanced Motion Generation for Reaching.

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This paper addresses a constructing method of a system that realizes whole body reaching motion of humanoids. Humanoids have many redundant DOFs for reaching, and even the base can be moved by making the robot step. Therefore there are infinite final posture solutions for a final goal position of reaching, and there are also infinite solutions for reaching trajectories that realize a final reaching posture. It is, however, difficult to find an appropriate solution because of the constraint of dynamic balance, and relatively narrow movable range for each joint. We prepared basic postures heuristically, and a final reaching posture is generated by modifying one of them. Heuristics, such as, the fact that kneeling down is suitable for reaching near the ground, can be implemented easily by using this method. Methods that compose the reaching system, that is, basic posture selection, modification of posture for generating final reaching posture, balance compensation, footstep planning to realize desired feet position, and generation and execution of whole body motion to final reaching posture are described. Reaching to manually set positions, and picking up a bat at various postures using visual information are shown as experiments to show the performance of the system.

Keywords: Humanoid; Reaching; Manipulation; Dynamical Balance.

1. Introduction

Humanoids are expected to be used in environments where humans live and work. Fetching objects is considered to be a basic and important ability of such humanoids. In order to realize the fetching ability, technologies of locomotion, reaching, and grasping are especially required. Active research has been performed on dynamically stable biped walking, and walking that follows online commands (ex. [1,2,3,4,5,6,7]). Some research on path planning for biped robots has also been performed [8,9,10]. However, reaching and grasping objects by humanoids are not so actively studied relative to walking.

We focus on the reaching motion in this paper. Picking up an object from a floor, picking up an object from the shelf at high position, as well as, picking up an object from a table are required for humanoids working in human environments. Therefore we consider the reaching of humanoids as reaching motion using whole body joints cooperatively. The difference of this type of reaching relative to the reaching of industrial manipulation are as follows:

- Dynamic balance in order to avoid falling has to be taken into account, as the base is not fixed.
- Collision between links occurs more easily.
- Motion range of each joint angle are usually smaller than usual robotic arms.
- Much more redundancy can be utilized than usual arms.
- Position of the base can be moved actively.

There will be infinite solutions for the final reaching posture, due to te fact humanoids can move around. The number of reaching trajectories will also be infinite. In this work, we decided to construct a system that can find one adequate solution in realtime. The system adopted heuristics in order to limit the solution and make the motion looks natural.

2. Approach

In this section the approach to construct the reaching system is described and some related works are mentioned.

Our goal for this work is to construct a system that make the robot hand move to a position and posture specified in a global coordinate system. We decided to realize the reaching motion in two stages. Decision of final reaching posture is the first stage, generation and execution of trajectory to the final posture is the second stage.

The main topic of this paper is how to generate a final reaching posture that is dynamically balanced and natural. (We thought that the natural looking postures consume less energy at joints compensating for the gravitational force.) This is a problem of inverse kinematics with dynamic constraints. As mentioned in the previous section, there are infinite solutions to realize one specified hand position

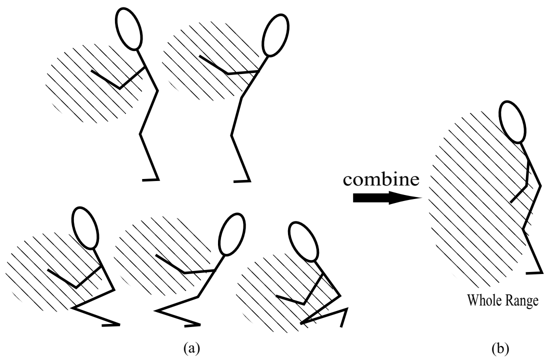

Fig. 1. Concept of generating reaching motion using basic postures. (a) Workspace by each basic posture, (b) Combined workspace.

and posture. However, it is not so easy to find a solution, because of the narrow movable range of each joint and dynamic constraints. Therefore, we constructed a reaching system with some heuristics to find a solution that appears to have a natural posture.

The concept of our approach is as follows: a) some typical basic postures are prepared, b) desired reaching posture is generated by mainly modifying the posture of arms from one of the prepared basic postures (Fig. 1). Reaching with different supporting conditions, such as, standing and kneeling, can be realized by preparing basic postures that have different supporting conditions. The workspace realized by one basic posture is not adequately large, but we can sufficiently increase the space by preparing a number of basic potures and combining their workspace. Then the final reaching postures with different supporting conditions are automatically generated according to the desired hand position. Because the robot can move horizontally by walking, the workspace is designed to have a wide range along vertical direction. Preparing basic postures can be considered as giving a knowledge of desirable reaching postures according to the reaching positions, such as, it is better to kneel down when reaching an object on the floor.

There are some works that realize required hand motion by using whole body joints. Inoue et al. proposed a method that changes body posture and makes steps in order to keep manipulability at hands[11]. Sian et al. implemented a "switching command based tele-operation system" which realizes desired motion of a specific point of the robot's body according to an operator's input by generating a stable whole body motions[12].

The followings are previous research methods for whole body motion. "Auto-balancer" is a method that realizes dynamically stable motion by modifying the angles of input motion[13]. Although this method itself is not for realizing the desired trajectory of end points, Kuffner et al. presented dynamically stable whole body motion planning by using the auto-balancer technique[14]. Yamane et al. realized

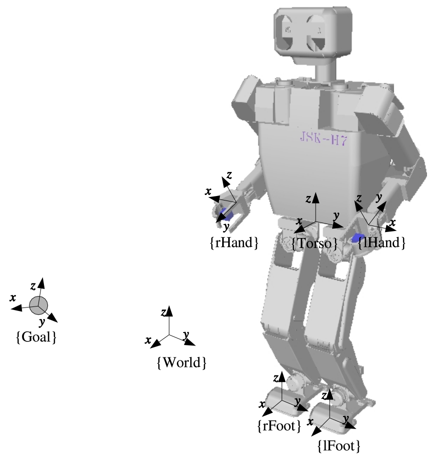

Fig. 2. Definition of coordinate system. {World} is fixed to the ground.

"Pin-and-Drag Interface" for modifying the posture of human figure[15]. This method allows one to move an arbitrary link of human figure relative to other arbitrary links. Those two method are possible candidates to improve the whole body motion trajectory generation described in section 3.9.

3. Whole Body Reaching Motion Generation System

3.1. *Overview of the System*

Fig. 2 illustrates the definition of coordinates of the reaching system. The orientation of these coordinates are represented by roll, pitch, and yaw angles. The goal is to move either $\{lHand\}$, or $\{rHand\}$ to $\{Goal\}$.

Fig. 3 shows the overview of the system. It consists of 2 stages: search for the final reaching posture, and reaching motion generation and execution. The former is the trial–and–error loop of changing basic postures to fit to a final posture, and the latter is the transition to the desired posture.

One of the basic postures is selected according to the current posture of the robot with rules (a). Then if the desired hand position is far, and walking is required, desired feet positions are decided (b). If walking is not required, the positional relationship between feet of selected basic posture is modified to be the same as the current robot posture (c). This stage is added in order to omit unnecessary stepping. Then the posture is modified to realize the reaching (d). If the reaching is successful, the balance constraint is satisfied by changing the feet position, and final reaching posture is obtained (e). If it fails in some stage, then the next candidate is selected from basic postures (a), and the same procedure is repeated. A walking pattern is generated and executed first, if it is required (f). Then the posture is changed to the final reaching posture (g). Details of each part will be described in

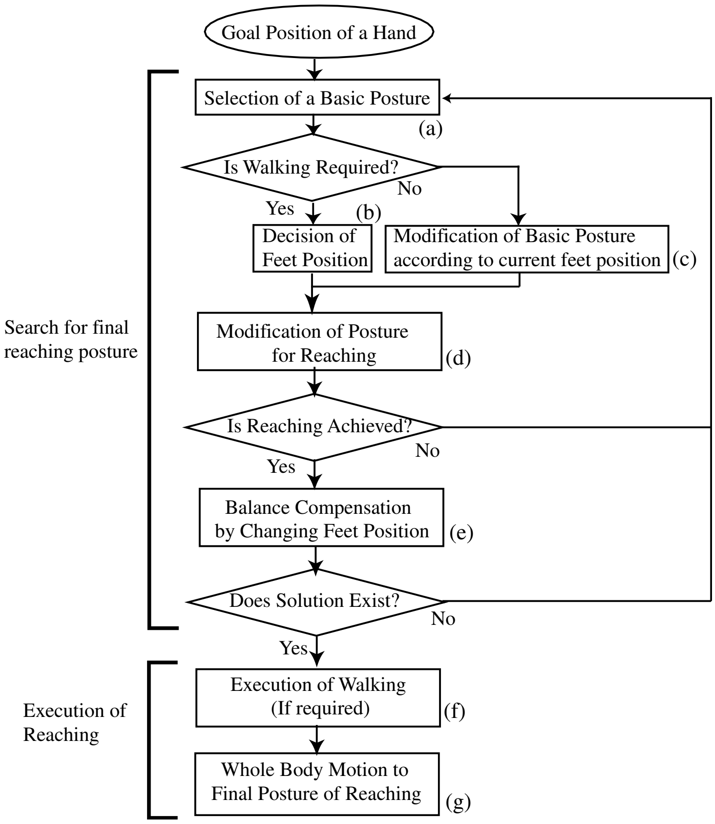

Fig. 3. Outline of whole–body–reaching system.

the following subsections.

3.2. *Representation of Goal Position*

The goal is given as the position (x, y, z) and the orientation $(roll, pitch, yaw)$ of hand in the torso coordinate system. This can be expressed by transformation matrix:

$$^{Torso}_{Goal}T = \begin{bmatrix} c_\alpha c_\beta & c_\alpha s_\beta s_\gamma - s_\alpha c_\gamma & c_\alpha s_\beta c_\gamma + s_\alpha s_\gamma & x \\ s_\alpha c_\beta & s_\alpha s_\beta s_\gamma + c_\alpha c_\gamma & s_\alpha s_\beta c_\gamma - c_\alpha s_\gamma & y \\ -s_\beta & c_\beta s_\gamma & c_\beta c_\gamma & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where $c \equiv$ cos, $s \equiv$ sin and α, β, γ are roll, pitch, yaw respectively.

Describing the goal position in $Torso$ frame is suitable when the information from cameras on the robot, or remote control input is used to decide the goal position.

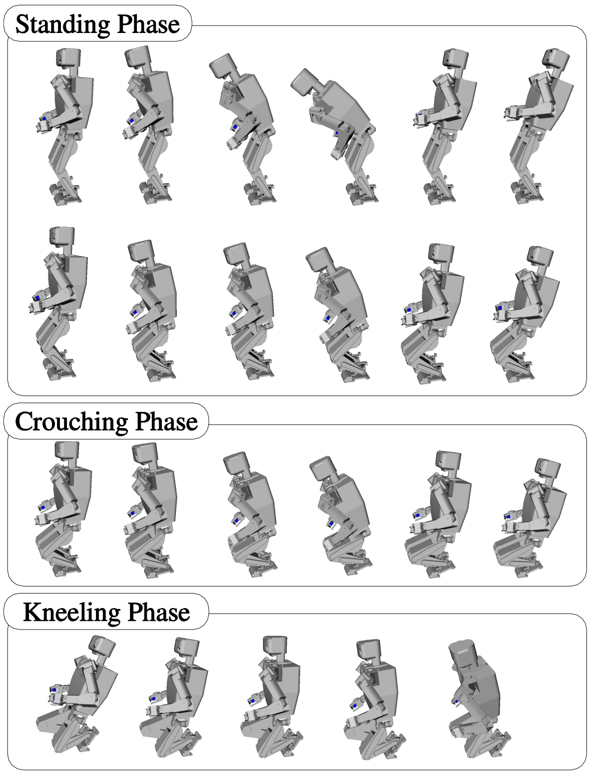

Fig. 4. Basic postures for H7. These are the basic postures for left–hand reaching. Those of right hand is symmetric to them. The priority sequence goes from left to right and top to bottom in each phase.

${}^{Torso}_{Goal}T$ has to be updated if the torso is moved in the later process. Let the previous and updated torso position be $\{Torso_{old}\}$, $\{Torso_{new}\}$ respectively, then

$$ {}^{Torso_{new}}_{Goal}T = ({}^{Torso_{old}}_{Goal}T^{-1} \, {}^{Torso_{old}}_{Torso_{new}}T)^{-1} \tag{2} $$

3.3. *Selection of a Basic Posture*

This stage is for selecting suitable posture from a prepared set of basic postures. Fig. 4 shows the basic postures we prepared for Humanoid JSK-H7. The "phase" is determined by which links are supporting the body; "standing" means that the robot is supported by both toe and heel links, "crouching" by toe links, and "kneeling" by toe and knee links. As static balance of the final reaching posture is guaranteed in the later stage, the basic postures are not always constructed to be well balanced, but are prepared to make the later balance compensation easier. The difference between standing and crouching phase is the use of the toe (H7 is standing on its toe in crouching phase).

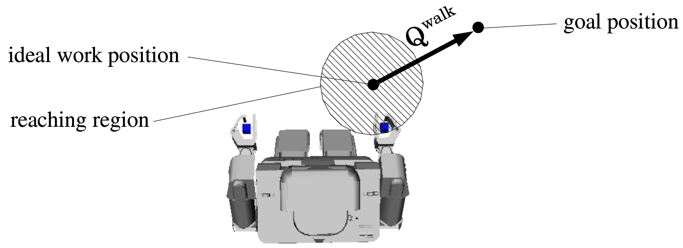

Fig. 5. Modification of the feet position. Reaching region for the right hand is shown. If the goal position is not included in this region, position of feet is changed. Robot will walk in execution stage as a result.

Basic postures are classified into groups by the phase of the posture. A current posture always belongs to one of them. If it is after the walking or the first reaching after starting the system, current posture belongs to "standing'. Otherwise, current phase is that of adopted basic posture in last reaching. Selecting priority is decided by the following two principles.

First Principle The group of basic postures to which the current posture belongs is the first ones to be selected.

Second Principle Postures of nearer to the upright is selected earlier. Three phases are selected in the following order, "standing", "crouching", and "kneeling". Postures whose torso links are nearer to upright are selected rarlier in the same phase.

If solution is not found in the following process, a basic posture of the next priority will be selected and the same process is carried out. If all of the basic postures are consumed, the system gives up reaching.

3.4. *Decision of Feet Position*

The next stage is to check the distance from the goal position and modify feet position if it is not within the reaching region (Fig. 5). The reaching region is a cylindrical region in front of the robot. Its size is conservatively defined since the shape of reaching region changes according to the orientation of $\{Goal\}$. The "ideal work position", which is the center of reaching region, depends on the basic posture.

If the goal position is not in the reaching region, new feet position is decided so that the torso moves Q^{walk}. Here,

$$Q^{walk} = {}^{Torso}P^{goal} - {}^{Torso}P^{ideal} \tag{3}$$

and goal position of the hand in torso coordinate system is updated as,

$$ {}^{Torso}_{Goal}T = \begin{bmatrix} c_\alpha c_\beta & c_\alpha s_\beta s_\gamma - s_\alpha c_\gamma & c_\alpha s_\beta c_\gamma + s_\alpha s_\gamma & x - Q_x^{walk} \\ s_\alpha c_\beta & s_\alpha s_\beta s_\gamma + c_\alpha c_\gamma & s_\alpha s_\beta c_\gamma - c_\alpha s_\gamma & y - Q_y^{walk} \\ -s_\beta & c_\beta s_\gamma & c_\beta c_\gamma & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

where ${}^{Torso}p^{goal}$ and ${}^{Torso}p^{ideal}$ are the positions of "goal position" and "ideal work position" in Fig. 5 respectively. The robot will walk in execution stage if the feet position is modified in this stage.

3.5. *Modification of Basic Posture according to Current Feet Position.*

Assuming that the goal position of the hand is within reaching region, the robot still has to make a step if the positional relationship of the two feet for the adopted basic posture does not coincide with the current configuration. Therefore if the goal position of the hand is inside the reaching position, then the basic posture is modified once in this stage, so that the positional relationship between the two feet becomes the same as the current posture. The feet position may be changed in the later stage in order to guarantee the balance.

3.6. *Modification of Basic Posture for Reaching*

JSK-H7 has arms with 6 DOFs for each, and legs with 7 DOFs for each (including 1-DOF toe joint). On the other hand the goal position of the hand is expressed with 6 DOFs. There is some redundant DOFs if the reaching motion is considered as a problem of solving inverse kinematics that realizes desired hand position with two feet which are fixed to the ground. The number of the redundant DOFs changes according to the phase actually. For example, when the robot is in standing phase, heels of both feet are fixed to the ground and the angles of toe joints can not be changed, then the number of redundant DOFs is 6.

If the angles of the leg joints are changed from the basic posture, position and posture of the torso are changed. This causes a relatively large movement of the center of mass from basic posture. Therefore, we try to achieve desired hand position only by changing angles of arm joints first, then if it fails, angles of leg joints are modified. The detail of the procedure is as follows:

(1) Calculate forward kinematics of the arm with angles of basic posture and create transformation matrix ${}^{Torso}_{Hand}T$.
(2) Create n temporary goal positions by equal interior division of parameters between ${}^{Torso}_{Hand}T(x_h, y_h, z_h, \alpha_h, \beta_h, \gamma_h)$ and ${}^{Torso}_{Goal}T(x_g, y_g, z_g, \alpha_g, \beta_g, \gamma_g)$:

$$ {}^{Torso}_{TmpGoal_i}T\left(\frac{(x_g - x_h)}{n}i + x_h, \frac{(y_g - y_h)}{n}i + y_h, \cdots, \frac{(\gamma_g - \gamma_h)}{n}i + \gamma_h\right), \quad (5) $$

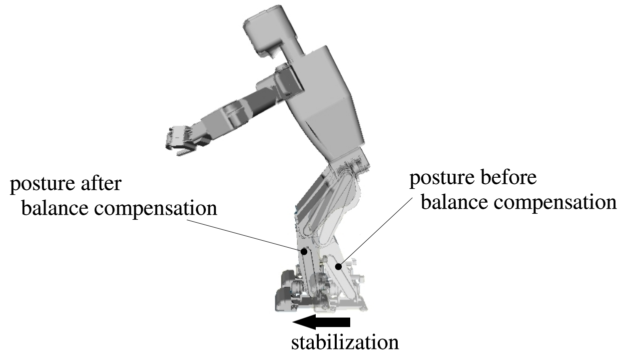

Fig. 6. Change of posture for balance compensation. Feet are shifted forward to make the posture stable in this case. Torso link is fixed to global frame so as not to change the position of hand frame in the global coordinates.

where α, β, γ are roll, pitch, yaw respectively. Considering the efficiency of calculation, $n = 10$ is chosen.

(3) Solve inverse kinematics of the arm to move the hand position to $\{TmpGoal_i\}$ where i starts from 1. If the solution is found, update $\{Hand\}$ and increase i by 1 and repeat this step. Otherwise, go to 4. Inverse of Jacobian is utilized for solving the inverse kinematics.

(4) Change the torso position to compensate the insufficient movement of hands. The angles of legs are changed according to the movement of the torso. Required movement of torso is

$$T_{move} = {}^{Torso}_{TmpGoal_i}T\,{}^{Torso}_{Hand}T^{-1} \tag{6}$$

Therefore, the required position of foot $\{Foot_{new}\}$ is

$${}^{Torso}_{Foot_{new}}T = \left({}^{Torso}_{Foot_{old}}T^{-1} T_{move}\right)^{-1} \tag{7}$$

Equating this transformation matrix and leg inverse kinematics, joint angles of legs are obtained. If solution is found, update $\{Foot\}$ and return to 3. Otherwise, end this procedure with the result “no solution”.

(5) End the process if $\{Hand\}$ reaches the $\{Goal\}$ (i.e. $i = n$).

In this procedure, all joints are used for reaching and the balance is ignored.

When the phase is “crouching”, there is redundancy at the legs. The redundancy is used to keep the angle of toe joint as small as possible. And when the phase is “kneeling”, we decided not to change the posture of legs, as the postures are very near to joint angle limitation for many joints of the legs.

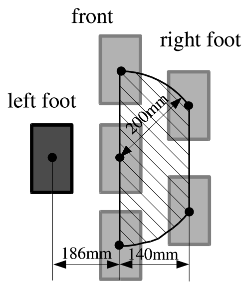

Fig. 7. Single step region of H7. Region of right step is described in this figure. Left step region is symmetric to this. The center of the right foot is restricted to hatched area.

3.7. *Balance Compensation by Changing Feet Position*

The role of this process is to make the posture statically–stable (Fig. 6). Torso link should not be changed relative to $\{World\}$ so as not to change the reached hand position. The principle of this process is "move the foot in such a way that the center of mass comes to the middle of centers of two feet". H7 has heuristic limitation of single step range as shown in Fig. 7. The solution posture must have their feet to exist within this range in order to realize the configuration by normal stepping motion.

Fig. 8 shows a detailed explanation of this process. At the first decision, if the center of mass is inside the supporting area with specified margin, this process ends successfully. Otherwise, the process continues until either foot can reach its ideal position determined by the policy above. The next foot position candidate is the closest point to the "ideal position" within the "step region", and on the line that connects the "ideal position" and "initial position". Here, the inverse kinematics of the leg is used to move the position of the foot. Balance compensation fails if any joint angle comes to the limit. The last branch before the end of compensation is to reduce the effect of the movement of the center of mass caused by the displacement of leg links by repeating the procedure. Required motion in this process is represented as Q^{left} and Q^{right} for left feet and right feet.

3.8. *Planning and Execution of Walking*

The process described above is for obtaining a final posture of reaching. This subsection and the next subsection deal with the planning and execution of the trajectory for moving to the final posture. This execution stage is divided into 2 parts, that is, the walking part and the whole body reaching part without changing position of feet (Fig. 9). The walking part is not executed when the desired position of feet is identical to current position.

Walking motion that follows desired footprints with commanded upper body posture can be realized by the online walking control system described in [16]. Foot-

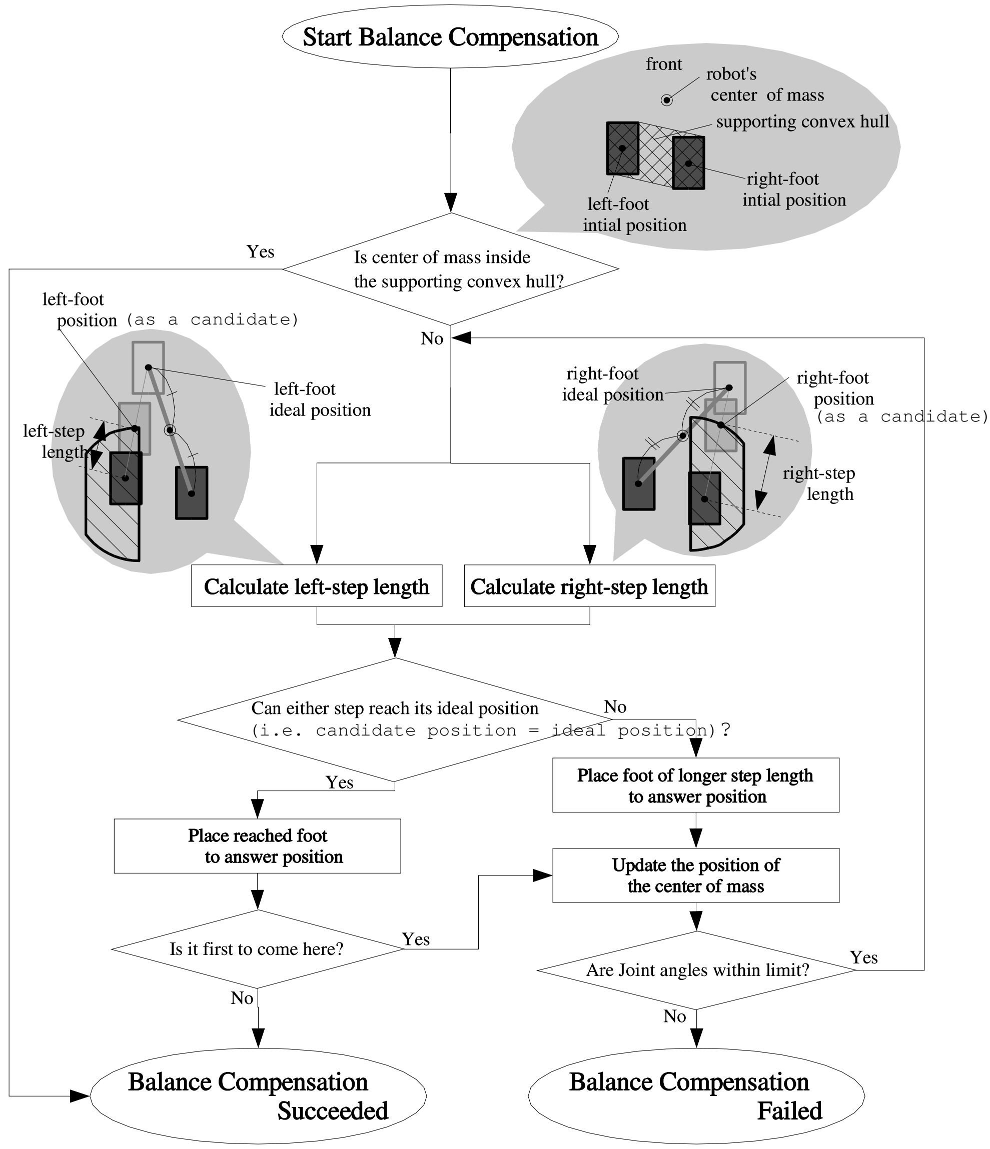

Fig. 8. Flowchart of balance compensation.

prints are planned as shown in Fig. 10. Required movement of each foot is given by $Q^{walk} + Q^{left}$, $Q^{walk} + Q^{right}$. Each footprint is placed as close as possible to its "goal position" within the step region, and on the line between the "goal position" and "initial position". Dynamically–stable walking motion is created from these footprints by Walking Pattern Generator and executed with sensor feedback modification.

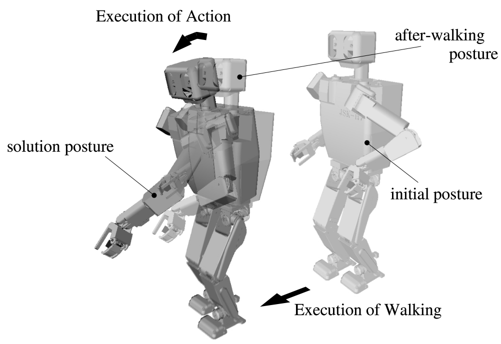

Fig. 9. Executing sequence of reaching. Motion to the solution posture is executed in two stages: walking and the whole body motion after that. After walking, the position of feet are not changed.

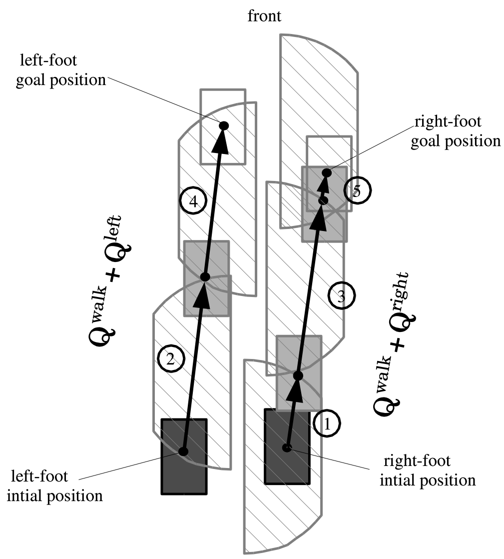

Fig. 10. Planning of footprints.

3.9. *Whole Body Motion to Final Posture of Reaching*

The last process is the motion from after–walking posture to the final reaching posture (Fig. 9). If the phase of initial posture and that of goal posture are different, the shape of supporting convex hull changes during the whole body motion. Therefore whole body motion of this kind requires careful design so that the projection of the center of mass to the ground keeps inside the convex hull of supporting region through out the motion. We prepared intermediate postures. Projection of

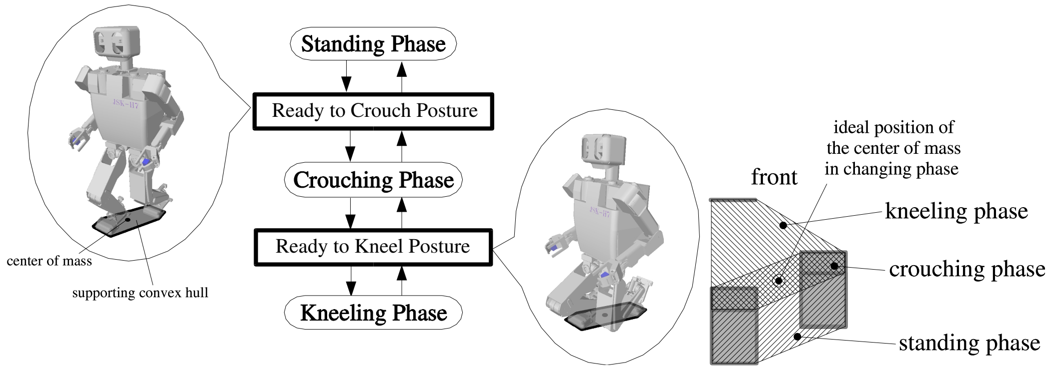

Fig. 11. Motion between posture phases.

the center of mass of an intermediate posture is inside the overlapping area of the supporting convex hulls of two phases (Fig. 11). Whole body motions that include change of phase are designed to pass through the intermediate postures. "Ready to crouch" posture is prepared for the transition between standing phase and crouching phase and "Ready to kneel" posture is for the transition between crouching phase and kneeling phase. The motion between standing phase and kneeling phase is realized by using the crouching phase as an intermediate phase that connects the standing phase and the kneeling phase.

Motions in the same phase is created by cubic–spline interpolation between initial and final postures in joint angle space. In order to make the dynamic effect to the balance negligible, the motion time is decided to be slow enough. Actual time for a motion is calculated by the following equation:

$$t_{motion} = a\sqrt{\sum_{k=1}^{n} w_k(\theta_k^{initial} - \theta_k^{final})^2} \tag{8}$$

where a and w_k are heuristically decided parameters to make the motion slow enough. $\theta_k^{initial}$ are the joint angles of initial posture, θ_k^{final} are the joint angles of final posture, and $n(= 30)$ is the number of DOFs. Higher weights (w_k) are assigned to the lower joints. This is because the movement of lower joint accompanies that of larger mass.

Projection of the center of mass to the ground during the motion is not considered explicitly. As the projection is inside the convex hull of supporting points at the initial and end postures with some margin (margin for current implementation is 50[mm]), dynamic balance for during whole motion is achieved practically.

Collision between links occurs easily during the whole body motion. Self collision detector that can calculate the distance between links rapidly [17] is employed. This method conservatively approximates the shape of each link as convex polyhedra for fast calculation. As the links are represented as convex polyhedra, distance between adjacent links cannot be measured by this method. For those pairs of

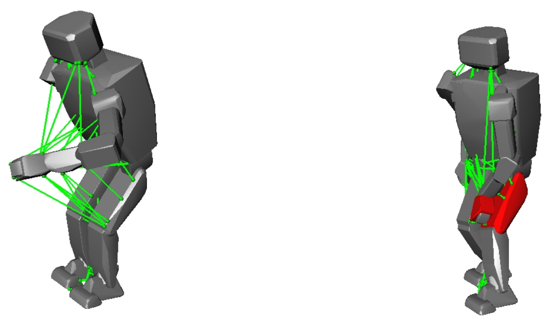

Fig. 12. Self collision detection. Each link is approximated as convex hull. Lines show the distance between links that are checked.

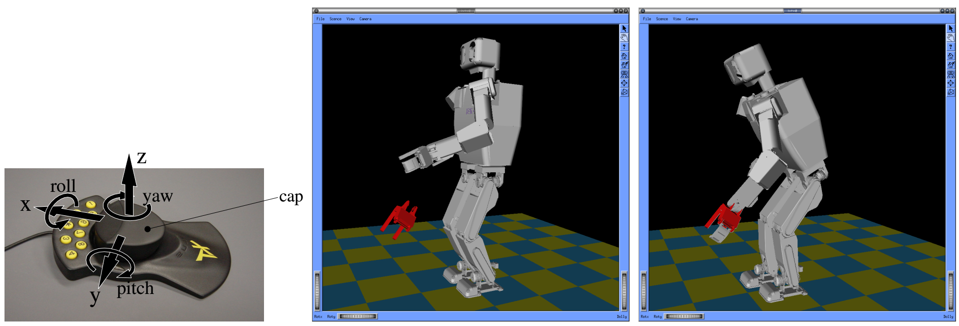

Fig. 13. Interface for giving reaching position manually. Magellan, 6 DOF mouse (left). The hand can be moved with 6D mouse in the 3D model viewer(middle). With execution command, the robot moves its hand to the commanded position (right).

links, inspecting joint angle limitation guarantees collision free motion.

4. Experiments

Two experimental systems are constructed using the presented whole body reaching system.

First one uses 6-D mouse and 3D model viewer for generating the desired hand position. The operator moves the position and posture of hand links in the 3D model viewer by the 6D mouse, and sets the desired hand position. Then the reaching motion can be executed in either the 3D viewer or the real robot (Fig. 13). This system is constructed to execute various reaching motion and confirm the performance on the 3D viewer and on the real robot. Fig. 14 shows some of final reaching postures that are realized by this interface.

For the second system, stereo vision system is employed to generate the desired

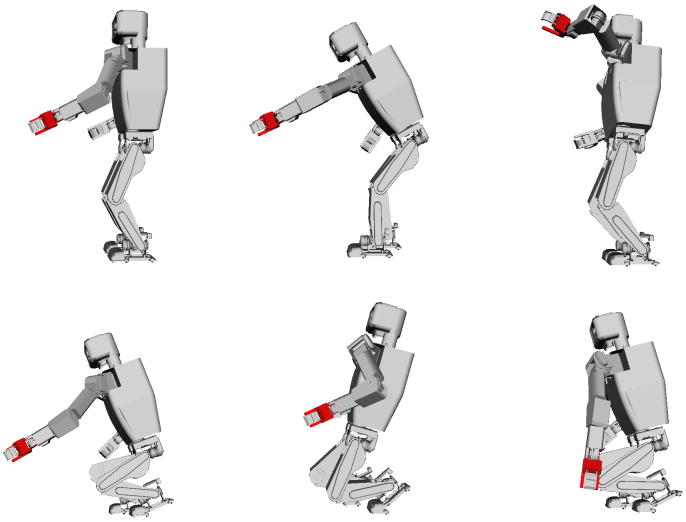

Fig. 14. Commanding various reaching position.

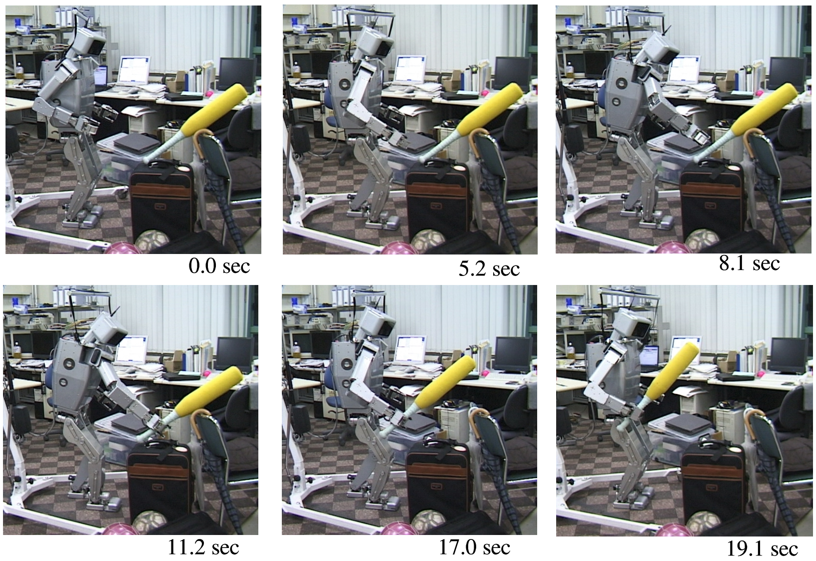

Fig. 15. Picking up a bat using a basic posture in the standing phase.

hand position. A toy bat is selected as the target of reaching, considering the easiness of grasping and recognition by vision. Color stereo cameras on the head is utilized. The region of the bat in the image is extracted by color information. The bat has a yellow body with a light blue grip. A three-dimensional position of the center of each

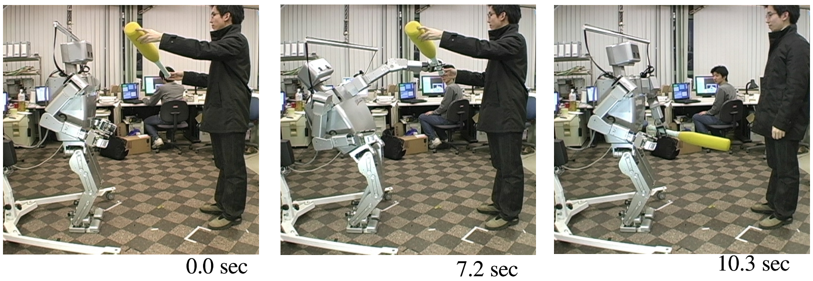

Fig. 16. Reaching for a bat in higher position using a basic posture in the standing phase. The person is holding the bat at fixed position.

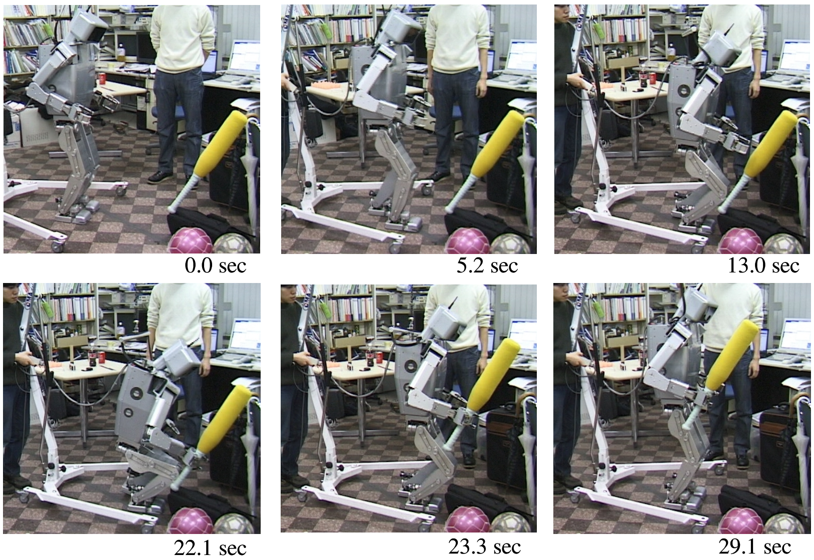

Fig. 17. Picking up a bat using a basic posture in the crouching phase.

color region is obtained by correlation calculation of two images. Desired reaching position and posture of the hand is decided from position and posture of the bat. As cylindrical shape is assumed for the bat, one DOF of reaching posture whose axis is along the axis of the bat can not be decided from the posture of the bat. Y-axis of $\{Goal\}$ is placed in the plane which contains gripping point, intersection of shoulder joints, and tip of the bat. Then the posture of the hand is decided uniquely.

Fig. 15, 16, 17, 18 show the scenes of experiments of picking a bat using visual information. In these experiments, the robot try to grasp by closing the gripper after the reaching motion. Whether the bat is successfully grasped or not is recognized by the pressure sensors (FSR: force sensing resister) inside the hand. If the grasping succeeded, the robot moves to the upright standing posture, and if failed, the robot start the reaching sequence again from the current posture. Calculation time for finding final reaching posture was approximately 30 [msec] at maximum. (The maximum calculation time mainly depends on the number of prepared basic postures.)

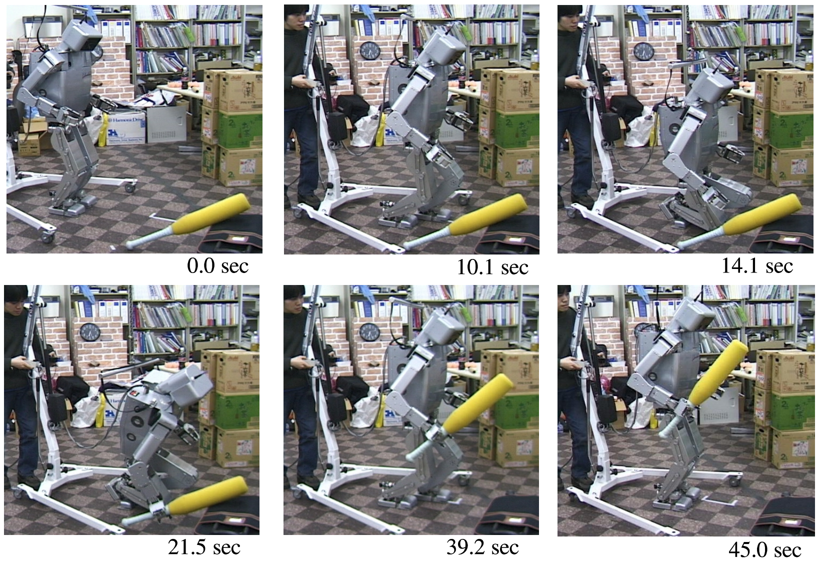

Fig. 18. Picking up a bat using a basic posture in the kneeling phase.

5. Conclusion

We realized a whole body reaching motion generation system that can also generate crouching motion and kneeling motion according to the goal position. The system uses prepared basic postures to generate the final reaching posture. We could implement heuristics, such as, kneeling down for lower reaching, by designing basic postures.

We didn't consider obstacles around the robot for this work. The method of generating final posture can be extended to deal with obstacles by inspecting if there is any collision at the posture and trying next candidate if needed. For reaching motion generation, dynamically stable whole body motion planning mentioned in section 2 as a related work is one good candidate to improve the system.

Integrating sensor feedback especially using vision information for accurate reaching into the execution phase will be our next research topic. Implementing sensor feedback balance control for whole body motion is also an important topic.

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