論文の内容の要旨

論文題目

Study on Adaptive Contact Force Distribution of Humanoid Robots
- Force Distribution in Toe-Thenar Mechanism and Impedance Distribution between Legs -
（ヒューマノイドロボットの接地力の適応的分配に関する研究
ー爪先・拇趾球間力分配機構と脚間インピーダンス分配制御ー）

氏名　山本　江

Humanoid robots are expected to work in the human life environment. In real environment, there are unknown irregularities on the ground and unknown disturbances. It is required that humanoid robots realize motions with absorbing these unknown disturbances. In previous works, successful results have been shown by *Trajectory Replay approach*, in which the control problem is simplified by separating it into the referential pattern planning and the compensation of modeling error and disturbances. In order to put humanoid robots into practical use, however, there are a lot of problems that should be solved.

Biped locomotion is realized by manipulating a distribution of contact forces on left and right feet. In previous works, this *contact force distribution* is realized by manipulating Zero Moment Point (ZMP), which is the point of application of the total reaction force. There is a physical constraint on the contact force distribution, and this constraint changes as the contact region deforms. In order to achieve a robust biped locomotion, it is important how to synthesize 1) deformation of the contact region and 2) manipulation of the contact force distribution.

One of purposes of this dissertation is to improve a deformation capability of the contact region for mobility enhancement. While the force distribution specifies relative positional relationship of ZMP in the contact region, the contact region determines the manipulable limit of ZMP, in other words, how much COG acceleration is manipulable. Therefore, mobility enhancement is expected by enabling larger contact region to be achieved. Humans have evolved a foot mechanism specialized in biped locomotion. While foot structure of most existing humanoid robots is very simple, human can increase the effective length of the leg by utilizing toe joint. As a result, it is possible to increase a stride length or decrease knee joint velocity compared with walking on the flat sole. In this respect, a novel toe-thenar mechanism is proposed in Chap. 2. Although some researchers added 1 DOF toe joint to humanoid robots, the joint axis tends to become larger because a large radial load imposed on it. Proposed mechanism enables human-like multiple contact and force distribution on the toe and the thenar. Using this mechanism, the robot can support a major part of its weight on the thenar, and the radial load is decreased. Fig. 1 shows the developed toe-thenar mechanism for a miniature humanoid robot.

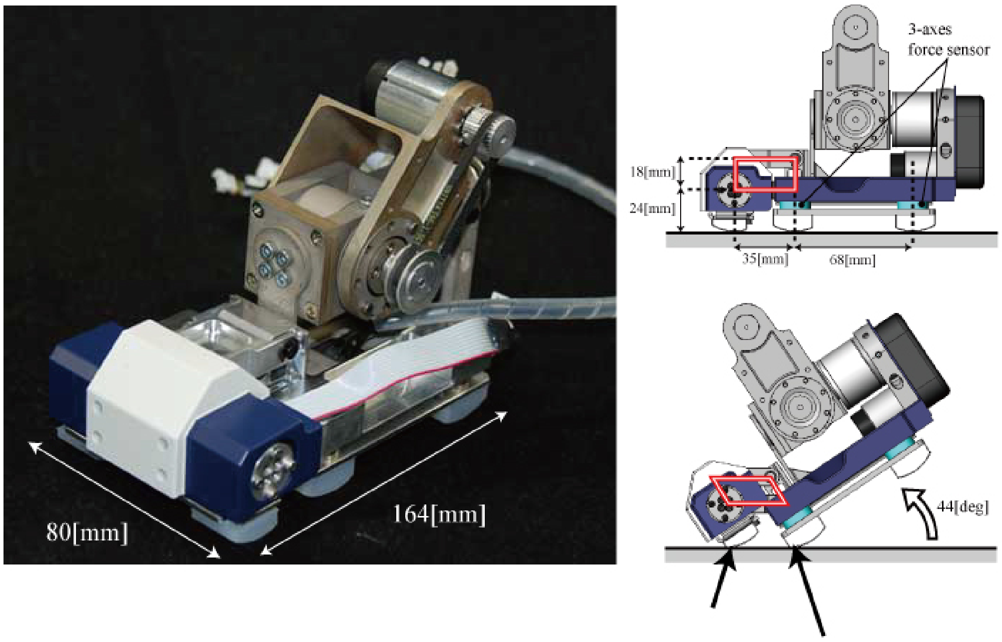

Fig. 1 Toe-Thenar mechanism with parallel four-bar linkage

In Chap. 3, we present a contact force distribution planning for a motion with toe contact phase. In biped locomotion planning, it is required to consider the discontinuous change of the contact region and the physical constraint depending on it. In particular, the change of contact region becomes more complex when the robot utilize toe contact phase.   Extending the Boundary Condition Relaxation method, force distribution and COG pattern while the contact region changes from the sole to the toe is planned simultaneously. Fig. 2 shows snapshots of a walking motion including toe support phase which is planned with proposed method. Fig. 3 shows planned COG, ZMP and the change of the contact region, and ZMP is planned with the physical constraint satisfied. The left side of Fig. 4 shows loci of the knee and toe joint angles, and the right side shows loci of the knee joint angle velocities. Compared with the normal waking motion with the same stride length, the maximum joint velocities was deduced by about 40[%].

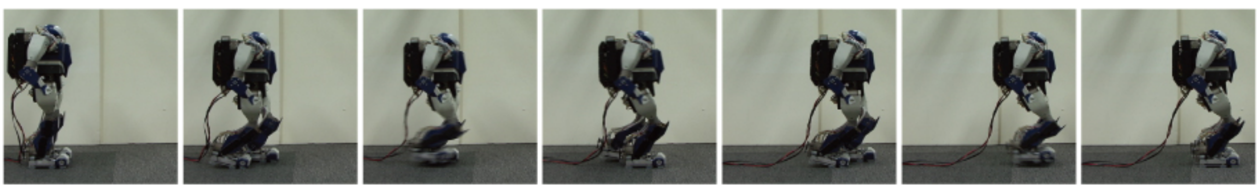

Fig. 2 Snapshots of the walking motion including toe support phase

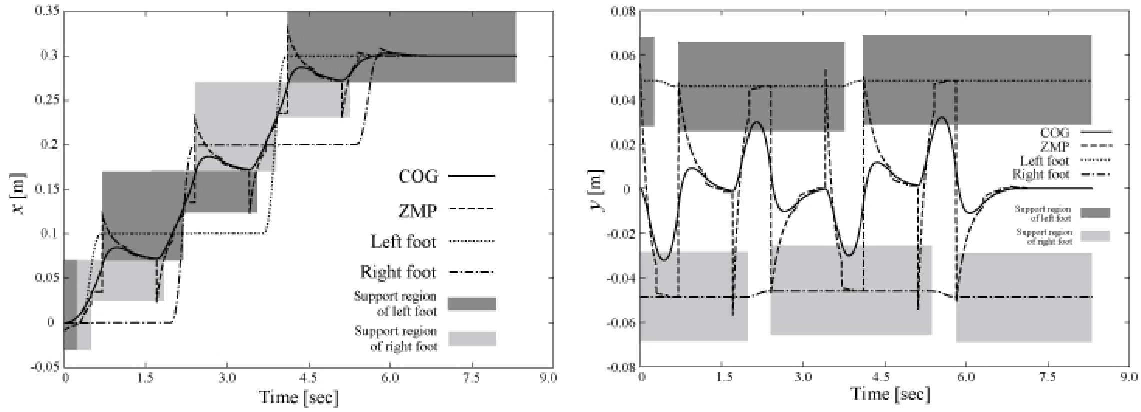

Fig. 3 Planned COG and ZMP for walking motion including toe support phase

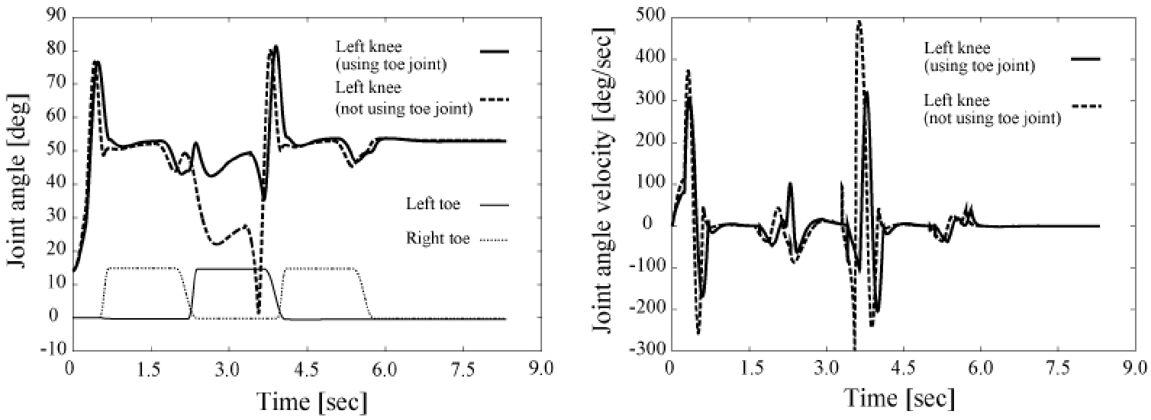

Fig. 4 Loci of the knee and toe joint angles, and the knee joint angle velocities

The second purpose is to compensate the error of the force distribution. The unknown irregularities on the ground cause an error from the planned contact force distribution. We propose a compensation method by adjusting leg impedance depending on each leg function in Chap. 4. Although the impedance control is efficient to compensate the effect of the ground irregularities, the desired characteristics of support and swing leg are different: the support leg is desired to be rigid to support the robot weight whereas the swing leg is desired to be flexible to absorb the touchdown impact and the error due to the irregularities. In proposed compensation method, the leg impedance is adjusted with the force distribution ratio. Fig. 5 shows snapshots of a walking experiment on the ground with 3[mm] height plastic plate. Applying the proposed impedance control with leg impedance adjustment, the robot carried out the total four steps walking without falling or body oscillation.

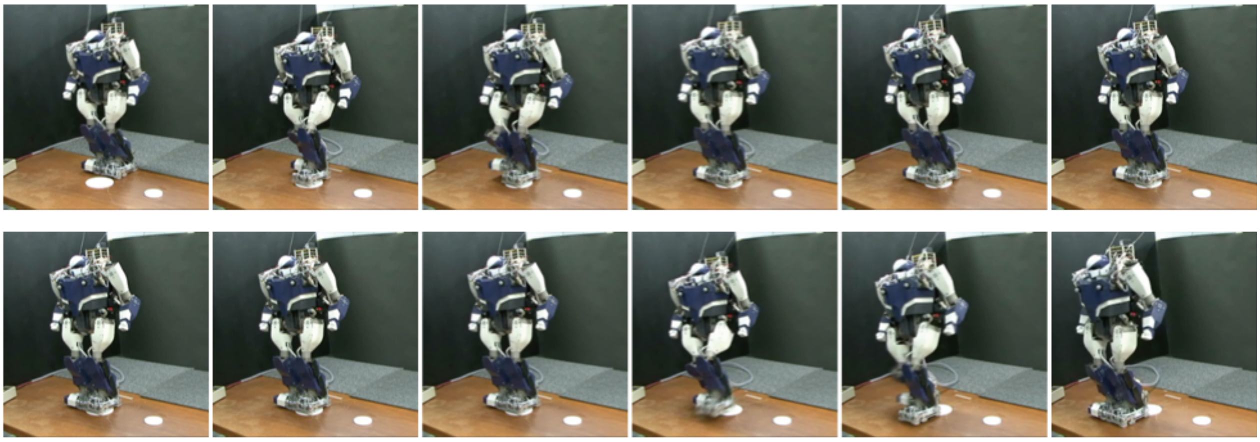

Fig. 5 Snapshots of walking experiment on the ground with a plastic plate. Applying impedance control, the robot carried out the total four steps walking motion.

The third purpose is to absorb a disturbance by controlling the force distribution. It is required of the control of the force distribution to consider the physical constraint specified by the contact region. In Chap. 5, we specify state values without violating the physical constraint based on the maximal CPI (Constraint Positively Invariant) set assuming COG-ZMP inverted pendulum model. Furthermore, we apply the switching control of constrained systems and improve convergence speed of COG. We simulated initial responses with three different feedback gains. Fig. 6 shows the simulation results of each feedback gains (namely, without the switching control). Feedback gains were designed such that the gain becomes higher as its index becomes larger. When the feedback gain 2 or 3 were applied, the constraint of ZMP, which is indicated in the gray region in the figure, was violated. Simulation result applying the switching control is shown in Fig. 7. The feedback gains were switched at 0.75[sec] and 0.84[sec], and the convergence time is reduced from 2.4[sec] to 1.1[sec], by about 54[%].

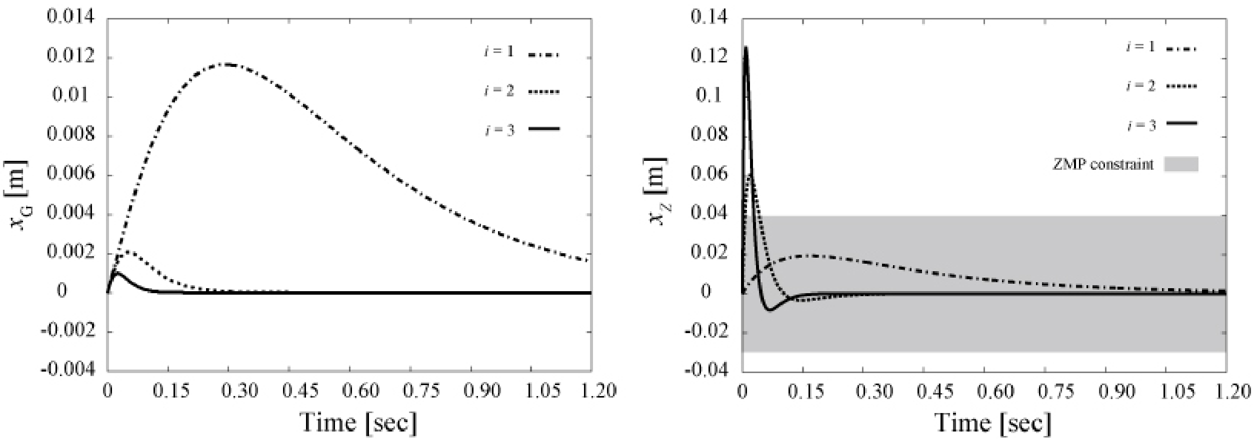

Fig. 6 Initial response of the system. The left and right are response of COG and ZMP, respectively.

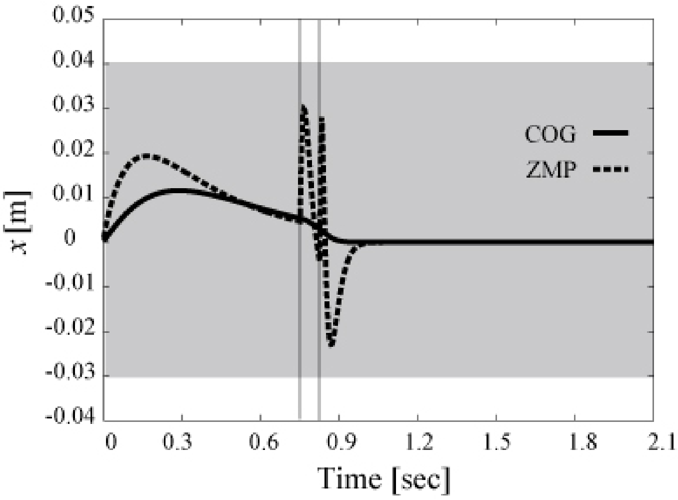

Fig. 7 Initial response of the system when switching control applied. At 0.75[sec] and 0.84[sec], controller switched the compensator.

Originally, the calculation of the maximal CPI set requires iteration of the linear programming. In biped locomotion, however, it is necessary to recalculate the maximal CPI set in real-time when the contact region changes after stepping. In Chap. 6, we present the recalculation method of the maximal CPI set. Furthermore, when a disturbance imposes on the robot, stepping motions to avoid falling are generated by detecting the stepping necessity based on the maximal CPI set. Fig. 8 shows snapshots of an experiment when the disturbance was imposed on the robot from back to front. The stepping necessity was detected and the robot stepped forward and COG was regulated to the center point of both feet after stepping.

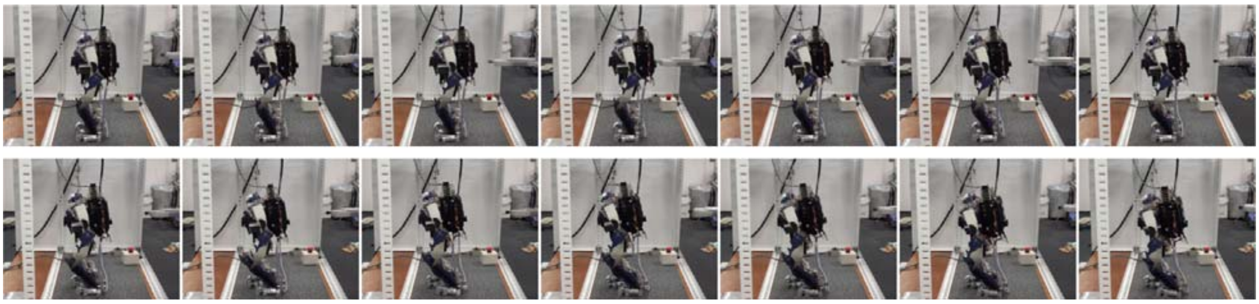

Fig. 8 Snapshots when the disturbance was imposed on the robot from back to front. The stepping necessity was detected and the robot stepped forward.