学位報告

報告番号	※甲　　　第　　　号

主 論 文 の 要 旨

論文題目　Contact Interaction-Based Navigation and Manipulation in Humanoid Robotics
（ヒューマノイド・ロボットのための接触情報に基づくナビゲーションとマニピュレーション）

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論 文 内 容 の 要 旨

The development of humanoid robots, which can coexist and interact with humans and their surroundings and make decisions based on their own judgments, will be a crucial part of commercial success. Recently, research on humanoid robots in areas related to human-robot interaction has rapidly increased especially for applications to human living environments and emergency sites. Environments to be shared with humanoid robots are normally reserved for humans. Therefore, to effectively work and cooperate with humans, humanoid robots must display abilities and skills that are compatible with humans. Indeed, for collaboration with humans, robots must perform tasks in environments with obstacles that will impose on their mechanical-control structure. Hence, robots must incorporate a reliable navigation strategy to effectively recognize the environment in which they are operating to avoid collisions. In this research, we focused on developing systems and strategies for humanoid robots to effectively interact with their surroundings.

In robot systems, navigation is a complex behavior, particularly for biped walking robots. To realize robots in the real-world, a sensor-based navigation function is required because the robot alone cannot autonomously operate based on environment recognition. In navigation tasks so far, the types of sensors that have been used can be categorized into two types: non-contact, including vision and laser range sensors, and contact-based such as force and tactile sensors. In this research, we use six-axis force and optical three-axis tactile sensors. This thesis describes the development of a navigation system and a strategy for a biped humanoid robot using contact interaction. Furthermore, to enhance the robot navigation performance in real environments, we develop object manipulation tasks based on tactile sensing. The main purpose of this research is to develop a navigation system for biped humanoid robots using a contact interaction approach to improve current visual-based navigation in humanoid robotics.

In normal conditions, humanoids usually depend on vision information to operate. However, they cannot just rely on such sensing information because in actual situations, they are likely to experience environments that limit vision information. Furthermore, in real applications of humanoid robots, in addition to the capability to navigate and avoid obstacles, they must also perform tasks that need manipulation skills, such as finding and turning on switches, opening door knob or locks, inserting keys, removing objects, performing light assembly, etc.. These tasks can definitely not be done by environment recognition alone; nor can they be done by using only grasping tasks. Humanoids need skills and good tactile sensing systems to realize contact senses so that object manipulation tasks can be done effectively. Therefore, applying object manipulation in humanoid robot navigation is inevitable and crucial. In this research, we developed a research prototype humanoid robot, *Bonten-Maru II*, a multi-fingered humanoid robot arm, and a robotic finger system as experimental platforms to evaluate the performance of the proposed navigation system and object manipulation. Furthermore, to generate a reliable and smooth trajectory for each joint in the robot's body, we proposed a simplification method of forward and inverse kinematical solutions in conjunction with interpolation formulations.

The proposed navigation system consists of five main tasks: searching, self-localization, correction of locomotion direction, obstacle avoidance, and object manipulation. The tasks were compiled in an algorithm installed in the robot control system. In our proposed navigation strategy, the robot realized a wide locomotion environment by touching and grasping using both arms mounted with force sensors that functioned as end-effectors for force control. Priority was given to right-side direction to navigate robot locomotion in conjunction with strategies to avoid obstacles. We conducted analysis of a biped locomotion strategy and controlled the biped walking speed to improve the navigation system's performance. The strategy was verified in simulation and experiments that applied biped humanoid robot *Bonten-Maru II* during biped walk, side-step, and yawing motions. In speed-up walk analysis, simulation and experimental results proved that walking speed can be improved in stable biped locomotion without reducing the reduction ratio in the robot joint-motor system. Consequently high torque output at the robot's manipulator to conduct tasks in various motions is maintained. In addition, we proposed a collision checking method in conjunction with the motion algorithm in our proposed navigation system. The above analysis results contribute to efforts to create stable and reliable biped walking locomotion while performing tasks in the proposed navigation system. Finally, the proposed algorithm was evaluated in experiments using humanoid robot *Bonten-Maru II* operating in a room with walls and obstacles. The experimental results revealed good robot performance in recognizing the environment conditions and generating suitable locomotion to walk safely towards a target.

For a humanoid robot to perform precision and object manipulation tasks using its dexterous arms, we developed an optical three-axis tactile sensor system mounted on robotic fingers for acquiring normal and shearing forces. It uses an optical waveguide transduction method and applies image processing techniques. Such a sensing principle is expected to provide better sensing accuracy to realize contact phenomena by acquiring the three axial directions of the forces to simultaneously measure normal and shearing forces.

In the future, this tactile sensor system is expected to replace force sensors in all navigation tasks because tactile sensors not only can detect contact sensing but also shearing and slippage sensing, which are important sensing information to dexterously handle robot arms. However, some issues such as the material strength of the tactile sensor elements and a suitable control algorithm to precisely detect and handle various objects in real environments have become the main problems. Therefore in our developmental tactile sensor system, we proposed a new control algorithm of object manipulation tasks based on tactile sensing in a multi-fingered humanoid robot arm toward applications in real humanoid robot. We use a low force control scheme to distinguish object hardness in a robot manipulation task based on tactile sensing.

Initially, to evaluate the performance of the proposed tactile sensor system, we conducted an experiment using one finger mounted with the optical three-axis tactile sensor to touch hard and soft objects as well as spherical objects. Experimental results revealed that the proposed system managed to detect and grip the given objects by defining optimum gripping pressure. Next, we conducted calibration experiments to determine suitable parameters for the object hardness distinction using a low force control scheme, whose parameters defined in the calibration experiments enabled the robot finger system to recognize and classify objects based on their hardness. Then, we finalized the control algorithm using the calibration results. The performance of the proposed control algorithm was evaluated in experiments with real objects using a multi-fingered humanoid robot arm and a humanoid robot *Bonten-Maru II*. Experimental results revealed good performance for the robot fingers in recognizing the hardness of unknown objects and performing simple manipulation tasks. Furthermore, the proposed control algorithm managed to respond to sudden changes of object weight during the object manipulation tasks.

Finally, since the proposed navigation system is evaluated using *Bonten-Maru II*, a humanoid robot, we must analyze robot performance when conducting the required motions in navigation tasks. Therefore, we analyzed the flexibility of the *Bonten-Maru II* design to attain human-like motions by focusing on its structure design, particularly in the joints and the links. Comparisons were also made with the flexibility of humans when performing motions. Verification experiments were conducted in simulations and real-time motions of *Bonten-Maru II* performing difficult human-like motions such as crawling and hopping over low obstacle that revealed good results of *Bonten-Maru II*'s design to attain flexibility for human-like motions.