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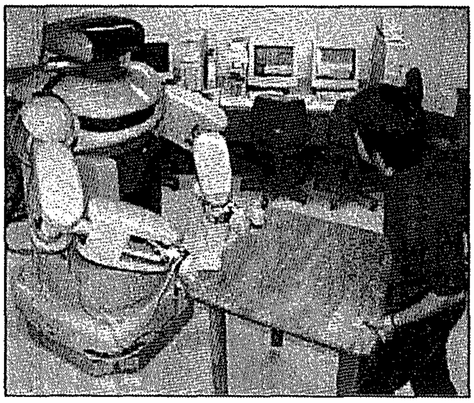
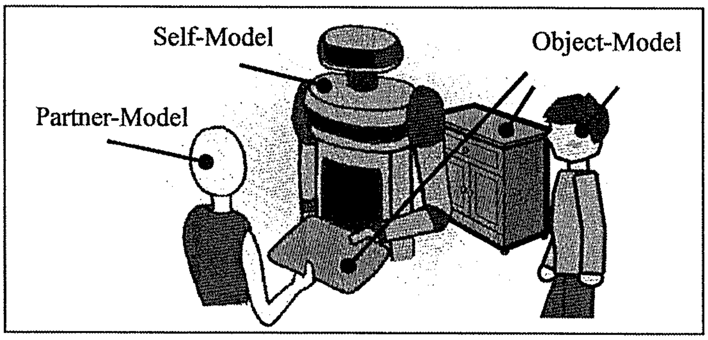
論文内容要旨

Many kinds of robots have been developed to date. Historically, most of them have been applied to some fields as industrial robots. These industrial robots have been isolated from humans, and have performed hard and simple repetitive tasks which humans do not want to do or can not do. However, especially in Japan, the labour force is shrinking and aging because of the falling birthrate and the aging population. To solve such problems that beset Japanese society with robot technologies, robots are making their way from industrial fields to our daily life: home, office, hospital and so on. A new field of robotics is emerging with the development of robot technologies. For this purpose, a lot of robot systems and systems using robot technologies have been developed, even some systems have been available commercially. These robot systems which are currently in practical use have limited applications, and they have difficulty performing the task which have not been prepared. Then, the robot systems which could perform not only prepared tasks but also various tasks in our daily life are needed. Most of the tasks in such daily life are difficult to be automated perfectly, because humans and their living environment has a lot of uncertainty.

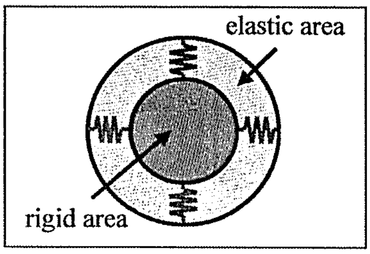


However, these difficulties could be resolved by assuming interactions between robots and humans, and various tasks in our daily life could be executed by human-robot cooperation. Under the assumption that robots are used in real environments with humans, these robot systems should consider how they realize cooperation with a human/humans more safely and effectively, not just carrying out the cooperating tasks. Especially, ensuring safety is essential because these robot systems should perform some tasks in real environments with humans different from industrial applications, so there is a possibility of harming humans when some problems occur in the robots. Furthermore, another problem is that all people who will become the users of these robot systems in their daily life does not have enough knowledge about robots. Considering these problems in human-robot cooperating systems, the robot systems with which humans could cooperate safely and simply are needed to realize our daily life with robots. Most of these human-robot cooperating systems can realize simple and user intuitive control based on the haptic interaction between robots and humans, however, there are a lot of control problems about safety and maneuverability such ass elf-collisions, collisions with obstacles, limitation of the range of the joint movement and so on. One of the dangers in haptic interaction is the self-collision problem, which includes collision of the robot's body with its arms, collision between two arms/legs. When the self-collision occurs, the robot is damaged or loses its balance and fall down, and harms humans around it. Limitation of the range of the joint movement is another danger in haptic interaction between robots and humans. Unfortunately, the possibility of these problems increases when the robot is cooperating with a human/humans, because the motion of the robot is affected by the intentional force/moment applied from a human/humans in a real-time so that resultant movements of the robot cannot be predicted in advance. Moreover, humanoid robots and mobile manipulators, both of which have redundant degrees of freedom, are very useful for realizing a variety of tasks in cooperation with a human/humans, however, these robot systems are likely to have these problems because of their redundancy. Therefore, solving these problems are essential for robots cooperating with a human/humans.

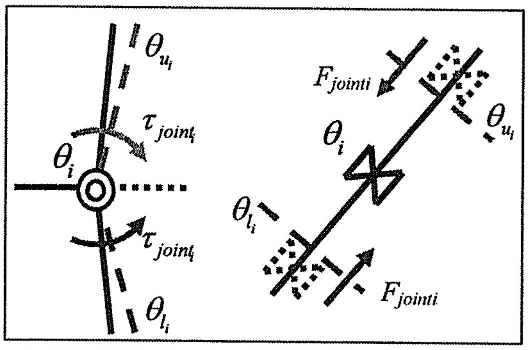
We pay attention to the problem of the robot handling a single object cooperating with a human in real environments in this dissertation, and we describe how to construct a unified methodology which could deal with many control problems existing in human-robot cooperating systems such as self-collision, collisions with obstacles, limitation of the range of the joint movement throughout this dissertation. Many control algorithms have been proposed to date for solving control problems existing in human-robot cooperating systems, however, there is no research that could deal with many control problems with a unified approach during human-robot cooperation. To construct such methodology, we could realize safe and highly maneuverable human-robot cooperation as well as human-human cooperation. For this purpose, we propose a concept of "Body Models" which represents the structures and their motions of robots, objects in the environment and the partner for the cooperation (humans), from the point of view of constructing a unified methodology by providing the models of the information about the structures/motions of its body, objects in the surrounding environment and the partner of the cooperation (a human) to the robot as well as humans. There would be a lot of modeling methods to construct the "Body Models", and we have to select a modeling method which meets the problem to be solved.



In this dissertation, we address a self-collision problem as the examples of the problems during human-robot cooperation first, and we explain "RoBE (Representation of Body by Elastic elements)", one of the modeling methods to construct body models. The self-collision problem is one of the dangers in



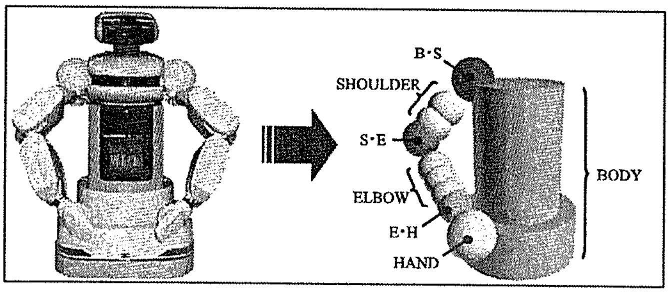
haptic interaction as mentioned above, however, there are few research about this problem and almost no of them could deal with the self-collision problem during human-robot cooperation. The self-collision avoidance control algorithm proposed in this dissertation enable robot systems which cooperate with a human/humans to avoid self-collisions in a real-time. Furthermore, we consider task constraints and environmental constraints during the self-collision avoidance motion, and propose two priority functions for generating the self-collision avoidance motion which could deal with these constraints. We also design the proposed control algorithm could be applied to any human-robot cooperating systems. Then, we focus on the range of the joint movement of the robots. By



considering the range of the joint movement on the self-collision avoidance motion generation method, the robot could also avoid the limitation of the range of the joint movement caused by the kinematic constraints while cooperating with a human, as well as self-collisions. Additionally, by setting the range of movement of robot's mobile base according to the position of obstacles, the task condition and so on, we could generate the cooperating motion which could deal with environmental/task constraints.

All of proposed control algorithms, we could construct a unified methodology based on force/moment information which could deal with self-collisions, collisions with obstacles, limitation of the range of the joint movement and environmental/task constraints while the robot is cooperating with a human/humans based on the intentional force/moment applied from a human/humans. Some computer simulations are done for illustrating the validity of these proposed control algorithms. Furthermore, some of these control algorithms are experimentally implemented in the human-friendly robot referred to as "Mobile Robot Helper (MR Helper)", and the experimental results illustrate the validity of these proposed control algorithms.

In chapter 2, we first introduced the concept of "Body Models" which represent the information about structures of robots' body, objects in the environment and the partner of the cooperation (humans) and their motions in this dissertation, to construct a unified methodology realizing natural, smooth and safe human-robot cooperation as well as cooperation among humans. Then we defined three types of "Body Models" to represent the information of structures and motions which have relations with human-robot cooperation; "Self-Model", "Object-Model" and "Partner-Model", and we explained how to deal with the control problems during human-robot cooperation by using these models. Furthermore, we explained "RoBE (Representation of Body by Elastic elements)", one of the modeling methods to construct body models. Constructing the models by using



RoBE, we could deal with the problems of self-collisions and collisions with obstacles with a unified approach. Then we explained how to solve these control problems as the examples of solving some problems during the human-robot cooperation by using the body models constructed by using RoBE.

In chapter 3, the proposed self-collision avoidance control method based on the self-model constructed by using RoBE was implemented in a human-robot cooperating system, referred to as MR Helper. Then we proposed some self-collision avoidance motions for MR Helper, and experiments using MR Helper were done to illustrate the validity of the proposed self-collision avoidance control method.

In chapter 4, we proposed two priority functions for robots to realize the several kinds of tasks in an environment based on the force/moment applied by a human to consider task constraints and environmental constraints during the self-collision avoidance motion. Furthermore, we designed the proposed control algorithm could be applied to any robot systems which used for human-robot cooperation. The pro-posed self-collision avoidance motion was implemented planar 3-DOF manipulator and PA-10, and computer simulations and experiments were for illustrating the validity of the proposed motion control. The experiment using MR Helper was also done for illustrating the validity of the proposed motion control in real human-robot cooperating systems. In addition, computer simulations were done for demonstrating that the robot could also avoid colliding obstacles as well as the self-collision with the proposed method.

In chapter 5, we considered the range of the joint movement on our self-collision avoidance motion generation method based on the self-model which represent the information of the robot's joints and their movements, and proposed how to generate the virtual joint forces/torques to consider the range of the joint movement of the robot. Then, the cooperating motion generation method which could consider the range of the joint movement was proposed. To illustrate the validity of the proposed method, some computer simulations and experiments using MR Helper were done.

論文審査結果の要旨

社会の高齢化にともない，生活空間内で人と共存・協調する人間協調型ロボットの開発が望まれている。人から隔離され，予め計画された動作しかしない産業用ロボットとは異なり，人と共存する人間協調型ロボットにおいては，その運動を，人や環境とのインターラクションを考慮して実時間で制御する必要がある。そこで，本研究は，人間協調型ロボットの制御において，人と協調するロボットそれ自身や，ロボットと環境との衝突を考慮して，ロボットの運動を実時間で制御する手法を提案したもので，全編6章よりなる。

第1章は序論であり，本研究の背景と目的を述べている。

第2章では，人や環境とのインターラクションを考慮したロボットの制御を目的とし，そのモデル化のために，セルフモデル，オブジェクトモデル，パートナモデルからなるボディモデルを提案するとともに，弾性要素を用いてロボットを表現し，セルフモデルを構築する RoBE(Representation of Body by Elastic Elements)を提案している。これは，人が一般的な環境においてロボットと協調運動を行うために有効かつ重要な成果である。

第3章では，RoBE を用いて人間協調型双腕移動ロボット MR Helper をモデル化し，人と協調作業を行っている際の，ロボットの自己衝突回避問題に適用し，その有効性を示している。これは，RoBE によって，人と協調するロボットの自己衝突回避が実時間で可能となることを示したもので，重要な知見である。

第4章では，RoBE によって表現された一般的なロボットの自己衝突問題を，作業拘束や環境拘束を実現する優先度関数を導入することで定式化する方法を提案するとともに，人から操作力が加わるロボットの自己衝突問題に適用し，その有効性を示している。一般的なロボットにおいて自己衝突回避を実現する協調運動制御手法は，人間協調型ロボットにおいて必要不可欠かつ非常に重要な成果である。

第5章は，前章までの自己衝突問題を，マニピュレータ関節や移動ベースの可動範囲，作業状態，環境からの拘束を考慮できるように拡張し，シミュレーションと実験によってその有効性を示したもので，人間協調型ロボットの実用化に向けた重要な成果である。

第6章は結論である。

以上要するに本論文は，人間協調型ロボットの制御において，ロボットそれ自身や，ロボットと環境との衝突を考慮したロボットの実時間制御に有効なモデリング手法 RoBE と，それを用いた実時間制御手法を提案したもので，バイオロボティクスおよび機械工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。