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論文内容要旨

Cooperating Multiple Behavior-Based Robots for Object Manipulation
（対象物の操作作業を目的とした複数行動要素型ロボットの協調に関する研究）

This report addresses a multiple robot system, BeRoSH (Be*havior-based Multiple* Ro*bot* S*ystem with* H*ost for Object Manipulation*), incorporating a behavior-based dynamic cooperation strategy for multiple robots.

Chapter 1 : Introduction

Using robots to help or replace human beings when performing some useful task has always been an important driving force in the development of robotic systems. The object manipulating task is popular one in robotics research, perhaps because it can have various interpretations without losing the most basic nature －*to act on the real world*－. This chapter describes an introduction on the object manipulation task and the cooperative work by multiple mobile robots. In this part, the purpose, the motivation and the results preview of the study are also addressed.

Chapter 2 :Multiple Robot System

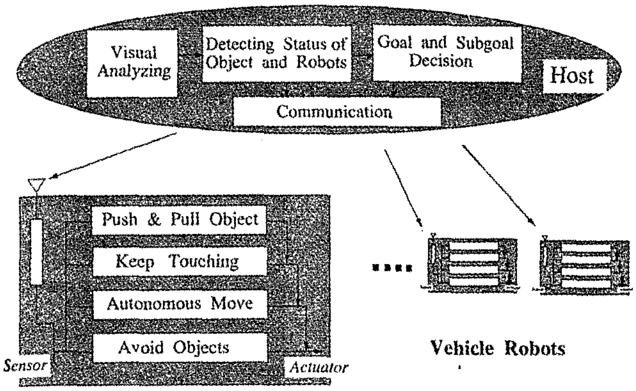

Fig.1 : The System Consists of a Host and Behavior-Based Vehicle Robots

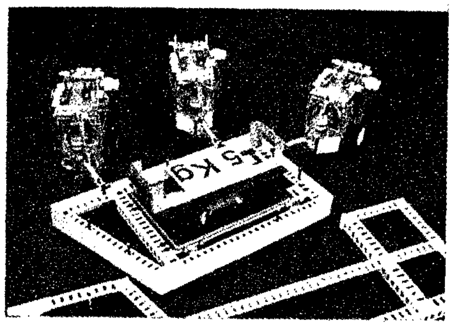

Fig.2 : A Vehicle robot team in manipulation.

The second chapter describes a scheme of a multiple robot system, BeRoSH, which maintains a host as its leader, and incorporates homogeneous behavior-based robots which have limited ability for performing a cooperative task. The host in BeRoSH acts as a leader and organizer which coordinates the robots' behavior, generates goals for the robots, and offers some global information to each robot to modify its own data. The host does not perform any calculation of target object dynamics or force distribution for dynamic cooperation. System BeRoSH is not a centralized system, because the dynamic cooperation for its manipulation task is realized by each robot's cooperative behavior and the organization of these behaviors. In this chapter, two experimental testbeds used in the multi-robot cooperation study: a simulated robots system and a real robots system, are also introduced.

Chapter 3 : Cooperation Strategy in Manipulation

This chapter describes the behavior-based dynamic cooperation strategy for achieving an object manipulation task. The cooperation strategy in system BeRoSH is realized in two steps: designing the distributed robots' cooperative behavioral attributes according to their abilities, and organizing these abilities. The idealogy of this cooperation strategy is that each individual robot, which has some definite behavioral attributes, is used as the subject for cooperation. It is different from those system in which some physical parameters related to robot control are used as key subjects for cooperation. The policy for designing each robots behavioral attributes is based on the following two items:

(1) let every robot agent have the nature that it is active in its *ability direction*

(2) let every robot agent have the nature that it is passive in its non-*ability direction*

The active nature of each robot and the correct organization of robots enables all robots to work on on performing the cooperative task. The passive nature in the non-*ability direction* of each robot prevents conflicts from occurring among robots. In organizing robots' abilities, the concept of Form Closure is introduced to the host as the basic planning strategy for organization. Through the behavior design, this cooperation strategy allows the dynamic cooperation control to be distributed equally among the robots. Therefore, the cooperation strategy has a very good adaptability to cope with redundancy in the number of robots which perform the task. Also, it has a good potential to realize a middle to large scale system for achieving some cooperative tasks.

Chapter 4 : Behavior-Based Vehicle Robot

To realize the autonomous moving and cooperative manipulating action of each robot, the robot's behavioral attributes is designed using an extended subsumption architecture. All behaviors are designed as several behavior layers in a wholly parallel, simple architecture. From the view point in which the robot's behavior is a Finite-State Automaton, when designing such as system, the phase of each behavior-based robot, which includes some states and corresponding transitions caused by some situation such as motivation to achieve a task, shows a dramatic change. This change occurs in the appearance of some phases which indicate whether the robot is in a cooperative state or not, rather than by the addition of some phases for new motivation. By discussing the state changing of a behavior-based robot in cooperative manipulation, it can be shown clearly that the phase "*in Cooperative State—non-Motivated to a Cooperative Task*" plays an important role in a behavior-based cooperation strategy.

Chapter 5 : System Construction and Cooperation

Some basic simulation and experimental results on achieving object transportation task and a simple object assembly task are presented in the first part of this chapter. These results have verified the ideas: the basic dynamic cooperation strategy, the behavior design of each robot, and the system construction of BeRoSH, which are described in the previous chapters.

Also an advanced dynamic cooperative strategy which cooperates the robots team to perform complicated manipulation tasks, has been presented. These complex tasks are those one which must consider the problem resulting from disturbances that prevent the task from being achieved, such as an object transportation task with unknown obstacles in the environment. In the advanced dynamic cooperative strategy, a new behavior, which works on checking the task performing status on each robot's ability direction, is implemented into each vehicle robot's controller. This new behavior gives the system a nature that, the system will remove elements

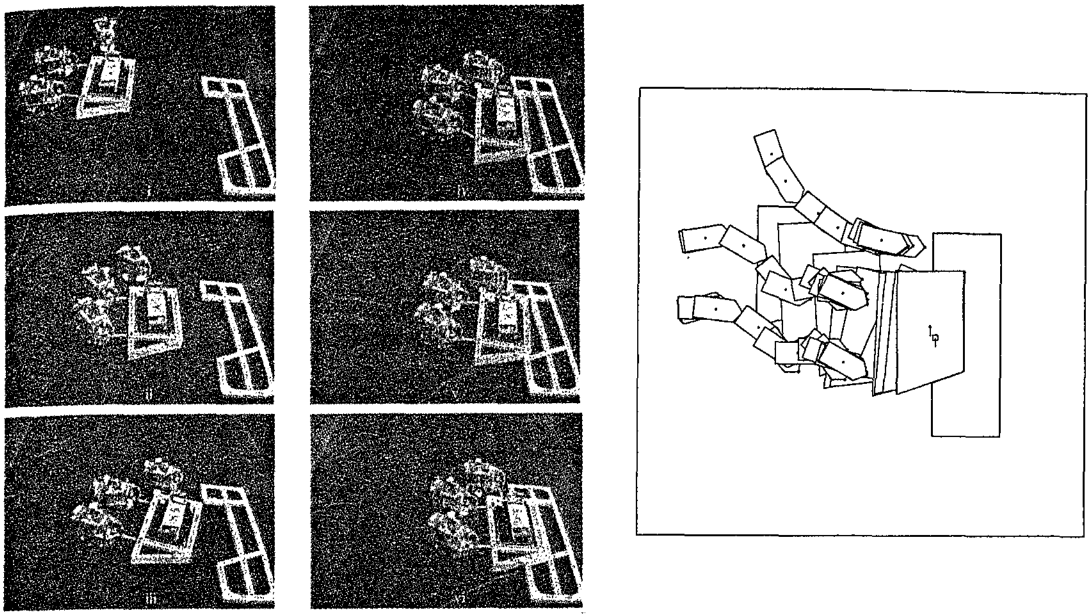

Fig.3 : Experiment Result : Three robots transport an object to the target position and assemble it into another fixed part.

which have resulted in the deadlock on task achieving when a deadlock occurs. The new strategy give us a clear image of how the system style is based on a bottom-up approach.

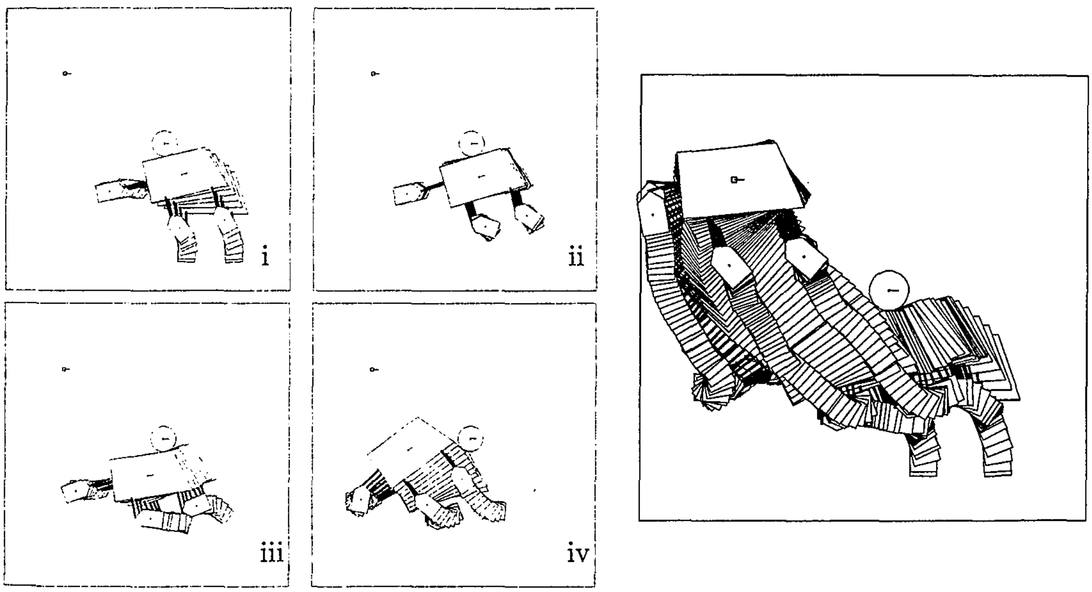

Fig.4 : Simulation Result : Even though there is an unknown obstacle, an object is transported to the target by three robots with the ability of checking task performing situation.

Also the relationship between system style and ability level of each individual robot, the flexibility, and the robustness of system BeRoSH have been discussed in this chapter. An additional policy on organizing all robots' behaviors is introduced to give the whole system a uniform manipulation ability, while the organization of all robots' behaviors satisfies the basic policy *Form Closure*. This makes multiple robot team work more effectively in an object transportation task.

Chapter 6 : Communication Style

This chapter discusses the communication style in BeRoSH. In this part, I also describe how each robot is locally autonomous in an extended environment including the host.

Chapter 7 : Related Research Work on Object Manipulation

This chapter reviews the current state of related work in cooperation of multiple robots on performing box pushing demonstration and object transportation task, and related work in object manipulation using robot arms and fingers.

Chapter 8 : Summary and Conclusions

This chapter summarizes the main contribution of this report and describes areas of future work.

審 査 結 果 の 要 旨

ロボットが複雑な環境でさまざまな作業を行うことは一般に困難とされている。この問題を解決するため，ある程度の能力しか持たない複数台のロボットを有機的に組織化することによって作業を行うという方法は一つの有力な手段となる可能性がある。そしてこの場合，複数のロボットが協調して作業を行うことが必要である。しかしながら，従来の複数ロボットの協調作業の研究は多アーム，多指での研究に中心を置くため，モデルベーストの集中型システムが多く，分散性能をもつ自律ロボットで構成した協調作業システムに関する研究はほとんど行われていない。

本論文は，ロボットの行動要素を協調の主体とする複数ロボットシステムの協調作業を検討するために，複数ロボットシステムの構成，対象物の操作作業を目的とした行動要素型動的協調戦略，及びロボットの行動要素の設計と特性解析に関する研究の成果をまとめたもので，全編8章からなる。

第1章は序論である。

第2章は動的協調作業を目的とした複数ロボットシステムの基本構成としてホストと複数局所自律型ロボットを有するシステムの基本的な構築思想を確立している。さらに，この思想に基づき構成したシミュレーションシステムと実機によるロボット実験システムを示している。

第3章は複数行動要素型ロボットの有機的組織化の基本思想及びロボットの動的協調を実現するため，基本的な協調行動要素およびこれらの行動要素の組織手法を確立し，ロボットの行動要素を協調の主体とした動的協調戦略を提案している。この協調戦略は複数ロボットによる協調作業の本質を忠実に反映するため，簡略かつ高性能の複数協調ロボットシステムの構築が可能となっている。

第4章は移動ロボットの行動要素の基本設計思想としてサブサンプション・アーキテクチャを拡張し，ホストの意図に従いかつ局所自律性をもつロボットの行動要素を実現している。また，ロボットの行動特性を状態遷移の相の観点から考察し，動的協調の実現への協調的な行動要素の相互作用の役割を明確している。

第5章は，動的協調的な行動要素を用いた複数移動ロボットで対象物の移動と組み立て作業を行うシミュレーションおよび実験結果を示し，協調戦略の妥当性を検証している。さらに，複数ロボットシステムの性能及びシステムのスタイルについて論じるとともに，行動要素の追加によりシステムは未知外乱が存在する複雑環境にも対応可能であるという特性改善の効果をもつことを示している。これは，本論で提案したシステム及び協調戦略の優位性を示すものである。

第6章は，複数ロボットシステムの通信スタイルを示すとともに，情報伝達の観点からホストと個々のロボットの依存関係を論じ，ロボットの局所自律特性を示している。

第7章は既往の関連研究の概観である。

第8章は結論である。

以上要するに本論文は，協調操作作業を目的とした行動要素型ロボットシステムを構成し，行動要素を協調の主体とした行動要素型動的協調戦略を提案したものであって，ロボット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。