Chapter 16
Design and Implementation of Distributed Autonomous Coordinators for Cooperative Multi-Robot Systems

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ABSTRACT

The paper presents a systematic method of the design of cooperative task planning and execution for complex robotic systems using multiple robots. Because individual robots can autonomously execute their dedicated tasks, in cooperative multi-robot systems, robotic activities should be designed as discrete event driven asynchronous, concurrent processes. Further, since robotic activities are hierarchically defined, control requirements should be specified in a proper and consistent manner on different levels of control abstraction. In this paper, Petri nets are adopted as a specification tool for task planning and execution by multiple robots. Based on place/transition Petri nets, control conditions for inter-robot cooperation with synchronized interaction are represented, and control rules to achieve distributed autonomous coordinated activities with synchronous and asynchronous communication are proposed. An implementation of net based control software on hierarchical and distributed architecture is presented for an example multi-robot cell, where the higher-level controller executes a global net model of task plan representing cooperative behaviors performed by the robots, and the parallel activities of the individual robots are synchronized through the transmission of requests and the reception of status between the associated lower-level local controllers.

INTRODUCTION

The rapid and broad progress of robot technologies makes operation control for robotic systems more large-scale and complicated one, in which some robots or subsystems operate concurrently and synchronously based on sensing information by external sensors and/or inter-robot communications as

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cooperative multi-robot systems (Yasuda et al., 1991). Multiple robots have the possibility to perform robotic tasks requiring large-scale and complex sensing and actuation activities, which a single robot cannot carry out, by cooperating in some way. Further, in many cases there are advantages to using multiple robots, such as robustness and less complexity. However, to perform complex robotic tasks efficiently, such as cooperative fixing and mating of separate parts by two or more robots, in addition to motion control of individual robots, new distributed control scheme for cooperative intelligent multi-robot tasks should be developed (Hörmann, et al., 1991). The first scientifically conceptualized non-centralized system was proposed for artificial biomimetic self-reproducing processes in 1971 and applied to develop self-coordinating robots with non-centralized neural networks and grouping robots or agents without centralized control mechanism (Yasuda, 1971). Our system may have been the first to apply the non-centralized system concept seriously to automation systems, and also one of the first mobile robots specifically designed for distributed autonomous group intelligence. Following the concept of non-hierarchical control, to realize cooperative intelligent multi-robot systems where synchronization between associated robots is the most crucial, the following schemes have been proposed: 1) emergence of some unforeseen behavior based on global-local interaction, 2) cooperation based on ad hoc master-slave or leader-follower relationships, 3) ideal cooperation through mutual coordination extending synchronous communication with no time delay such as cooperative motion of human both arms or hands. One of the ad hoc master-slave control schemes, generates interlocking coordination where each robot adjusts its action selection based on the evolution of the ongoing interaction, specifying a conditional sequence of actions and goals or joint plan involving the temporary master and slaves. The cooperative interaction consists of a series of actions including communication acts such that a robot causes a change in the environment that triggers the precondition of the next action of a sequence. In multi-robot systems the robots independently plan and execute their own tasks, negotiating the time uncertainty on the tasks based on message sending and receiving.

Among the existing modeling formalisms, Petri nets provide a powerful framework to model and analyze robotic systems, characterized by their ability to naturally represent the causality and the concurrence and synchronization of activities, the presence of conflicts, resource sharing, mutual exclusion, etc. (Hasegawa, 1996), which are inherent characteristics of multi-robot systems. Since one can directly convert Petri net definitions into control code for real-time control of robotic systems after correct Petri net models are constructed, the systematic modeling of robotic systems becomes very important (Caccia, et al., 2005). An example robotic control system is naturally decomposed into two sublevels: the flow control of parts through the buffers and the distributed coordination of robot operations. The former can be viewed as system control based on producer/consumer processes. The distributed coordination system receives a rather static schedule from the upper level, may ask for rescheduling, and sends global activity commands to the robots, provided with dynamic information about particular states of robots in a system. The distributed coordinators behave concurrently with links to both upper and lower levels, coordinating cooperation and competition relations among associated robots. In this paper, based on the hierarchical and distributed structure of the robotic system, a structural design methodology through a top-down and bottom-up relationship between abstract specification and practical implementation of a behavior-based architecture is described (Yasuda, 2015). In particular, multi-robot cooperative task planning and execution is presented to perform the distributed autonomous control of cooperative interactions and reactive behaviors without supervisors so that robots can synchronize activities and avoid harmful conflicts.