Distributed Autonomous Control Architecture for Intelligent Mobile Robot Systems

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INTRODUCTION

In the past decades, robots are becoming commonplace in unstructured and dynamic environments, ranging from homes to public and disastrous sites. Intelligent robots, such as humanoid robots, are typically designed to have capability of manipulating objects enough to achieve complicated and variable task goals as well as to have the locomotion capability, while adapting its behavior to particular environment conditions (Elkady et al., 2011; Hammer et al., 2010). Current behavior-based robot architectures so far mainly concerns navigation tasks performed by mobile robots (Arkin, 1987; Brooks, 1987; Connell, 1992), and are not fit for intelligent robots because the task executing environment is not well structured (Gat, 1992; Noreils, et al. 1995). Advanced intelligent mobile robots have to deal with a number of subtasks in real time in order to perform complex tasks with a broad variety of objects autonomously in dynamic and much less structured environments. (Konolige et al., 1997). It is necessary to attain the autonomous synchronization of the various subsystems involved in the navigation and task operation system, because intelligent subsystems have the inherent capability to act asynchronously and concurrently or collaborate with each other.

The use of a single processor system in a multitasking kernel with real-time features establishes a common system resource that is shared among all software modules or behaviors, but raises the possibility for mutual interference with negative effects in terms of timeliness with slower and longer modules blocking faster reactive ones, reducing the robot's reactive capabilities. Controllers with the multiprocessor in parallel can realize real-time performance effectively, dividing the complex task into the several simple subtasks which every processor does respectively and coordinating the processors. Generally, distributed control systems consist of several decision making and executive subsystem controllers, and available information is processed by the subsystem controllers, which communicate and negotiate to come to a common decision using a communication channel, and then the decision is executed by them to fulfill a global goal. From the view of communication networks, two approaches are distinguished for multiprocessor based control system design, namely, centralized and decentralized approaches. In the centralized approach, control of each executive subsystem controller (processor or agent) is based on global information achieved by a central controller. A decision is made in the central mechanism for the system goal and transmitted to executive subsystem controllers. Whereas, in the decentralized approach, each subsystem controller makes decision based on its local information achieved through its own sensors and from the neighbor subsystem controllers. Decentralized control is useful when the global information is not available, because there is no central mechanism to coordinate the overall robot behavior. In contrast to the centralized approach, decentralized control architectures reveal their main advantages when it becomes necessary to maintain the system, to integrate components, and to enhance the system, through system-inherent redundancy without any error model, cooperation of subsystems, addition of new system components, and so on (Camargo et al., 1991). Practically, the main problem of decentralized architectures is coordination between the subsystem controllers to make sure that the system will fulfill an overall or global goal, due to the independent task execution by the subsystem controllers.

In this article, distributed autonomous control architecture is designed as modular and hierarchical software systems to make it easier to realize complex

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system functions using a composition of more simple task-oriented modules. The distributed control architecture supports task specification, where robot actions are expressed by means of an event-driven state-based net model (Frankowiak et al., 2009; Montano, 2000). In this context, the distributed architecture takes an approach where multiple modules concurrently share control of the robot by sending messages to be combined for or against various alternatives in the command space, without regard for the level of planning involved. Petri nets are used for the handling of concurrency in single robot systems as well as cooperative multiple robot systems. The article, focused on the system architecture and distributed control system implementation, presents a novel type of modular hardware and software architecture for intelligent mobile robots. A behavior-based methodology for distributed autonomous control is implemented on the distributed control architecture using discrete event net models as a formal approach for an example mobile robot task.

BACKGROUND

As the first research on non-centralized or distributed autonomous control system, the author was involved with a project on constructing a grouping robot (Mori, 1975). From the viewpoint of control, the system structure was designed as a non-centralized system; the robots are homogenous since the capabilities of individual robots are identical. There exists no computer on each robot or outside of the robots. Each robot body is two-wheeled with one rear caster. It has one lamp that emits infrared rays, and three infrared eyes; the central eye for following another colleague robot, and two outside eyes for avoiding other robots and obstacles within the specified distance to the right or left. The central eye is composed of three small fields of eye for the following action. The robot has the following three action modes: random, following, and avoidance. When a robot detects a colleague robot within a specified distance for following of the central eye, it follows the colleague, such that it detects the colleague in the center field of the central eye. If there are two or more colleague robots within the distance for following in the central eye, it selects the nearest colleague. When the colleague enters within the distance for avoidance of the central eye, it stops following and waits some time. Then, if the colleague is within the distance for following, it continues to follow the colleague, and if the colleague is still within the distance for avoidance, it avoids the colleague. Each robot moves in a random way when it detects no robot or obstacle. When it detects an electro-magnetic barrier using two sensors on the front side of the body, it avoids the barrier to the right or left as the highest priority level. If it detects another colleague robot within the distance for avoidance in the outside eyes during the following action, it avoids the colleague at the second highest priority. If it detects one colleague in each of the outside eyes, it moves straight. Under the above rules, the robots exhibited flocking behavior as a result. In the too wide or narrow environments, any grouping behavior cannot be produced well. The leader robot is not fixed, and a robot that happens to be at the head leads the other robots. Each robot moves rather freely in a group. The system is coordinated somehow vaguely. It was shown that small differences of individual capabilities such as response, timing, field width of eye, are amplified in the behavior of the system, and they greatly influence the probability of the corresponding robot being a leader or follower. According to the shape and size of the environment barrier and the number of the robots in the environment, the grouping behavior of the system greatly changes. The above features reveal that, motivated by innate behavior of each robot, a seemingly intelligent behavior arises out of their interactions as emergent cooperation. These suggest that cooperation can arise as a result of the local interactions of a large number of homogeneous robots, although it can be explicitly designed into the system.

Following the development of grouping mobile robots, based on the concept of non-centralized system, advanced distributed autonomous robot controllers were built as a multi-agent robot system (Yasuda, 1999). An intelligent agent, as a control or goal-directed behavior module, is capable of conducting autonomous actions in an environment in order to satisfy its design objective with some degree of autonomous flexibility by being reactive and proactive. In the multi-agent system, several agents communicate and interact in order to solve a complex navigation problem. So, it can be considered as a society of agents from whose coexistence and cooperation emerges the functionality of the robot. Elementary agents are responsible for reflexive or reactive abilities by acting together cooperatively. Some high-level agents are responsible

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