A Framework for Search and Retrieval Tasks Using Specialised Cooperating Autonomous Agents

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Abstract
We define a framework for search and retrieval tasks using cooperating autonomous agents. The significance of this work is our experimental demonstration that specialising the functionality of these agents can lead to increased efficiency, flexibility and scalability. In this paper, we describe a model of cooperating autonomous agents with specialisations, as well as the simulation used to demonstrate the model. We frame our demonstration in terms of a search and retrieval task in an unknown environment by simulating multiple specialised autonomous robots. The agents require only the ability for movement, localised sensing and directed communication to perform their task.

INTRODUCTION

There are many domains where it is highly desirable to use mobile autonomous agents to perform various tasks. Prescribing a framework by which agents can achieve such tasks, and a methodology for the design and physical realisation of these robotic systems is therefore also desirable. In the literature several robotic systems have been proposed in theory, a few of which have been physically implemented, however the domains in which such systems operate have been limited and the applications specialised.

We present a model that takes into account the main functionalities required for a search and retrieval task and proposes robotic teams that are composed of specialised agents that represent these functions. The model is significant in that it experimentally validates claims in our work (and in the work of others) that specialised agents with limited communication functionality can provide efficient, flexible and scalable cooperating systems.

BACKGROUND: INTERACTING AGENTS

A common thread through this research is the oversimplification of the problem in simulation and thus a simplified theoretical model. There is a need to show a correspondence or mapping of a solution model to real world situations [11].

Aside from describing (often futuristic) hardware which can accurately carry out the task of sensing the world, the much more dire problem of how to represent such knowledge is paramount to realising a world model [15]. Brooks argues that not only are accurate world models impossible, but not necessary [4]. He claims that agents may act in a competent manner without explicit symbolic representations via direct interaction with the environment.

The major advantage in using multiple agents, similar to using multiple people in human teams, comes from the concept of synergy. Synergy is the concept that the behaviour of a system as a whole is more than just the sum of its parts. By having multiple agents in a given environment operating in parallel there are obvious advantages as to the amount of work which must be done by each to complete a task or tasks at the global level. Moreover for certain tasks cooperation may be necessary as the functionality of a single agent is incapable of performing the required operation alone. Such a system comprising "ant-like" robots is described in [17].

Multiple agents are best suited to tasks which can be partitioned into separate identifiable operations. Examples of such tasks include search and retrieval, construction, surveillance and mapping. Comparisons can be drawn to the field of theories of computation for parallel architectures where "work" needs to be partitioned into modules which can be carried out in parallel.

One of the most important aspects of using multiple agents is that the control strategies at the individual level may be simplified. This is due to the synergistic properties of group behaviour causing emergent intelligence at the global level as proposed in [9]. Mataric shows how simple individual control laws can be designed so as to reduce computational complexity typified in traditional approaches.

Arai and Ota [1] designed a system in simulation in which robots could sense in their local environment and used random movement to resolve spatial competition and avoid oscillations.

Recent research has concentrated on making sure an agent's internal models are as simple as possible and generally adopt a behavioural approach (see, for example, [4], [17] and [10]). By using the concept of simple interactions at the local level producing global emergent intelligence they show that relatively complex tasks can be completed as is similar to biological models.

Emergence is manifested in global states or time-extended patterns that are not explicitly programmed, but result from local interactions between a system's components. Emergent behaviour can be observed in any sufficiently complex system,
for example systems which contain local interactions with temporal and/or spatial consequences. They are typified by systems where there are multiple agents and determining the global behaviour of the system beforehand is not possible. This is generally due to the large number of variables and non determinism.

An example of a foraging type task is presented in [2] that uses homogeneous robots which observe the behavioural state of others and where additional robots may be added dynamically. Their study tested the improvement of multiple robots when using direct communication as opposed to indirect communication alone. A simulation was created where the robots complete a gathering task. Initial runs used only observed behaviour and no direct communication, then this was compared with the direct communication case. Findings showed substantial improvement in the direct communication case, though there was higher complexity introduced to the problem.

Mataric [9] showed that the control laws of agents can be reduced in complexity via the usage of multiple agents (using the concept of emergent intelligence). The model is heavily based on social systems that have been extensively studied in biology. Much is known about the efficiency, if not the mechanisms by which insect colonies such as ants achieve complex behaviour at the group level [8]. This is in the absence of centralised control or planning, and communication is in a very limited form.

It is becoming clear that purely reactive methods such as [5] which uses localised information to place context in situation knowledge, and [16] on producing local plans in unknown environments, are not suited to many applications. Nor are purely deliberative methods such as [7] and [19] who describe agent interactions using classical symbolic models and reasoning assumptions.

Systems such as [12] attempt to use both local and global knowledge in the completion of tasks. Parker argues that by modelling sub-sets of the local and global environment greater flexibility is realised. Dependent on the application domain it may be extremely beneficial to ground global knowledge by using locally sensed information.

**METHODOLOGY**

In our model, we divide the functionalities of the agents into three distinct areas: supervision of the tasks, location of objects, and moving the objects. The agents communicate by passing messages, which use the semantics of a rendezvous, as this is a representative abstraction of a communication task. This uses the concept of synchronisation in communication, such that both the sender and receiver can take part in a dialogue. We assume an error free communication service is provided by a lower level communication protocol [13].

In order for agents to carry out such search and retrieval tasks in a physical environment they must be able to effectively move about that environment. In our model, spatial competition is resolved using directed communication and a concept similar to "modest cooperation" [14] with other agents in the environment. When another robot is sensed within an agent's local environment, directed communication occurs to the sensed agent if it is impeding the progress of the given robot. A communication call designated as challenge is issued to the other robot, as a means of resolving conflict for that particular spatial resource.

The concept of reactive navigation involves the ability to sense obstacles in the immediate environment, and adjust course trajectory accordingly to compensate. The goal acts as a general guidance heuristic for the navigational task. By using the heuristic of moving in a straight line towards the goal and adjusting where obstacles hinder the agent, a "best-first" type search is emulated, in which the agent will attempt to follow the best path first.

The foraging behaviour is the most important behaviour and is the cornerstone of the search and retrieve framework. It is taken from several biological models and causes the agent to describe an essentially random movement about its environment.¹

The foraging behaviour is implemented as a random movement through an environment. It is similar to the model proposed by [6] where the agent tends to be repelled from obstacles within the environment by effectively "bouncing" off of them. On average, there is an even distribution of an agent visiting points within the environment.

The simulation engine is designed to be adapted as a controlling module for a physical system. The ability to adopt a phased approach for moving from a theoretical to physical system allows an easier implementation of the physical system and also provides feedback as to the effectiveness of such a system at intermediate stages. One intermediate phase might be to use physical robotic systems equipped with the main sensors. The actual robots are centrally controlled by the simulation engine. Due to the modular fashion in which the code has been designed and the fact that Ada provides a lower level interface to hardware, modules can be replaced by those which access physical hardware.

We simulate a search and gather task, which is defined as collecting some object from one point in the environment and depositing that object at some other specified point. Since the environment is not known beforehand the required objects are first found and then placed in the desired new position. It is assumed that the identifier has the ability to accurately detect any element in the set of goal objects. The agents, as modeled in the simulation, are all assumed to have the same size and move at the same velocity. Perfect communication and accurate local sensing is also assumed.

The most representative way of studying the system behaviour is in the presence of only one supervisor (or at the individual robotic team level), noting the scalability of adding additional robotic teams for larger environments. The first tests were therefore made by varying the number of goals and

¹ One interesting example of a natural system which uses random movement to search for objects in its environment is contained in [3].
identifiers, with no obstacles in the environment. The identifier is the most non-deterministic agent, since it describes a foraging pattern about its environment, whereas in a zero obstacle environment a worker should move, retrieve and place an object in approximately the same time. Several models were defined, varying the number of goals, the number of identifiers, or the number of obstacles. The objects to be collected were scattered about the environment in a random, dispersed way.

By increasing the number of identifiers, the convergence time of the system decreases asymptotically towards an optimal convergence time. Figure 1 shows results in units of simulation time, not real-world time. This is a significant result in that it is observed that substantial efficiency gain may be made regardless of environment by increasing the number of identifier robots. Due to the asymptotic nature of this there will be a “break even” point at which the addition of more identifiers would not be attractive in terms of resource and efficiency costs.

When varying the number of workers and identifiers, an approximately linear relationship between convergence improvement and the number of workers was evident. Note that this test was made with a static number of goals. By varying the number of goals, performance improvement may decrease - possibly even to the extent that convergence time will increase due to needless communication overhead and increased spatial competition. This is most evident in the case where the number of workers exceeds the number of goals, thus there exists idle workers. In general for larger environments with more goals, an increased number of workers will increase convergence time linearly.

Tests were performed with obstacles in the environment, using four identifiers, four workers and four goals. Note that the relationship to convergence time seems to be approximately linear, although there are some discrepancies which are attributable to the random foraging behaviour. It is intuitive that agents should be able to easily navigate around sparsely scattered obstacles, but the more obstacles there are in the environment, the better the chances of the robot needing to divert from its intended path.

Densely placed obstacles have the effect of either guiding or blocking the agent’s path. Logically, obstacles are a constraint within an environment, and therefore constrain the available solution spaces and ease at which such spaces may be navigated. It may be argued that the initial criteria are satisfied, in that the system will converge to a goal state if such a state exists.

CONCLUSIONS

The benefits of agent specialisations in search and retrieval tasks are seen in that greater efficiency through synergy and parallelism of activities occurs, as well as a simplification of hardware at the individual agent level. Dependent on the application and the environments that such agents are required to work in, the hardware costs (such as monetary, mass [11] or spatial) will vary. This in turn can add to greater efficiency via a better utilisation of resources, in that different robotic compositions (number of agents in each specialisation) can be used relative to costs.

The basis of the model is the ability for the system to recover in the face of limited agent failure. This is most prevalent in the specialisations of identifier and worker. As long as one agent does not fail the system can still operate, albeit in a less efficient manner. As such the framework caters for the concept of robustness.

The model can cope with unknown environments in that sensing is required only within the localised environment, and spatial resolution also occurs at the local level. Similarly, dynamic environments are catered for since obstacles and paths are not explicitly modeled (reducing agent complexity), and the framework is tolerant if the limited amount of modeling performed fails (eg, a goal object not being where an identifier reported).

The system has been shown to be scalable since efficiency improves relative to the addition of different specialised robotic agents. Communication bottlenecks and bandwidth problems are also solved in that as agent numbers dramatically increase they may be partitioned into physical “teams” each with a controlling supervisor.

The system is flexible in that the framework is presented at the abstract level of functionality and behaviours rather than actual hardware design. This allows the framework to be incorporated into different applications using different types of hardware, as long as the hardware can be made to exhibit the required behaviours of the framework. Results show that relative efficiency is achieved, but notes that actual effectiveness is by far the most important measure.
The model provides an effective and relatively efficient means of designing multiple specialised robotic agents to carry out general search and retrieval tasks within unknown and dynamic real world environments. It is designed to be cost effective and applicable to a wide range of applications, and allows a simplification of hardware at the individual agent level due to having only localised sensing requirements and specific hardware functionalities.

FUTURE DIRECTIONS

A formal description of the methodology employed in terms of a provable model would be beneficial in that the effectiveness of the framework could then be quantifiably recorded and optimisations made in a controlled fashion. This formal description is now being undertaken.

A much more ambitious project would be to create a formal methodology for defining theoretical robotic models, demonstrably proving such models, defining these models in terms of a descriptive language and then showing a transformation from such a language into hardware. All of the benefits seen in this project would then be realised in a much more provable, controllable and general manner. A definition of such a methodology awaits the completion of some of the work in this project, and the time and hands to do the definition.

REFERENCES


