University of Pretoria etd – Rodić, D (2005)

Chapter 10: Conclusion

This chapter presents a brief summary of the contributions and findings of this thesis, as well as some discussion on future research. The contribution and findings related to the new proposed INDABA framework are discussed in section 10.1. Section 10.2 discusses the main contribution of this thesis, i.e. the novel coordination approach through task allocation, based on social networks. Section 10.3 discusses a number of future directions for future research, following from this thesis.

10.1 INDABA

The first part of this thesis investigated agent architectures and multi-agent architectures, with the emphasis on a particular type of agent, namely robots.

Chapter 3 provided an overview of three major robot architectures. Each of the architectures, namely reactive, symbolic and hybrid, were first discussed in general terms, followed up by a more detailed discussion of an example of each architecture.

An overview of two major multi-robot team architectures was presented in chapter 4. Again, each architecture was first discussed in general terms, followed by a more detailed discussion of a particular example of each architecture.

Based on the findings of the study of agent architectures, as presented in chapters 3 and 4, a new architecture was proposed for the development of cooperative multi-robot teams. The new architecture, INDABA, was introduced in chapter 5. INDABA is a conceptual framework and guideline for the agents' implementation, rather than a fully developed and prescriptive framework. This allows the architecture to be applied to a variety of robotic platforms. Although INDABA is not prescriptive with respect to technologies, particular implementations and coordination mechanisms, INDABA is prescriptive in the adopted layering approach.

Most of the current robot architectures used hybrid robot architectures that consist of three layers. INDABA consists of four layers, with the fourth layer added to facilitate ease of implementation of coordination mechanisms.

The INDABA framework was used to develop an abstract robot simulator and simulated robot environment. The abstract robot simulator was discussed in chapter 7 and the simulated robot environment was introduced in chapter 8. In both examples, the INDABA framework was flexible enough to cater for different levels of abstractions used by the simulators, as well as to cater for different coordination mechanisms.

A full implementation of all four-layers of the INDABA framework in a physical environment with robots was described in chapter 9.

INDABA has proved to be a suitable architecture for implementing embedded agents, namely robots, either in simulated or in physical environments. The addition of the fourth layer, the interaction layer, facilitated the implementation of a coordination mechanism, for example the auctioning mechanism and the social networks based mechanisms.

10.2 The Social Networks Based Approach

The main contribution of this thesis is the development of a flexible, biology inspired approach to coordination through the use of social networks.

Various existing coordination approaches to multi-robot team task allocation were overviewed in chapter 6. Social networks and related concepts were also introduced in chapter 6. A novel coordination mechanism for multi-robot teams, based on social networks, was also presented in chapter 6. This new, social networks based coordination mechanism was tested in the experiments in the following chapters.

The social networks based approach was presented in great detail and a comparison with a natural system was made to illustrate its biological and societal origins.

The social networks based approach was first tested using the abstract robot simulator. The abstract robot simulator provided for simulations with a relatively large number of agents (a population of fifty agents was created) over a relatively large number of simulated tasks executions (ranging from 50 to 700). Probabilistic team selection was considered and rejected in favour of straightforward ranking selection, as it did not perform as well as the straightforward ranking selection.

The social networks based approach consistently performed better than a pure market based approach in conditions of uncertainty about task details. Furthermore, the new approach exhibited excellent learning capacity.

The social networks based approach exhibited an intriguing similarity between the overall behaviour of the multi-robot society and biological systems. Cliques emerged, as well as natural specialisation of agents toward particular tasks. The importance of kinship and trust were confirmed, even in artificial agent societies. Furthermore, the social networks approach has proven that concepts such as kinship and trust, traditionally related to higher mammalian societies, can be used for coordination of artificial societies of agents.

Results from a simulated robot environment, using the same social networks based approach to coordination, followed up the results from the simulations done in the abstract robot simulator. The results were similar to the results from the simulations done in the abstract robot simulator. The social networks based approach was yet again confirmed to be valid.

10.3 Directions for the Future Research

A number of aspects have been identified that merit further research. These are summarised next.

10.3.1 Use of Multiple Alternative Coordination Methods in INDABA

Coordination through task allocation is not the only coordination method and the consequence of other coordination methods such as negotiation [140] and cooperation should also be explored. A possible direction for further research is to implement various coordination methods in the interaction layer of INDABA, and to build a mechanism that will choose the most appropriate one for the current task and for the society of agents. This possibility can be seen as a negotiation protocol between agents. In other words, based on agents' capabilities, a consensus is reached on which coordination mechanism to use.

10.3.2 Flexible Information Exchange in Multi-robot Teams

For the purpose of this thesis, the information that is exchanged between the robots in a multi-robot team was predefined and its format was hard-coded (such as information about position of food and environment). Ideally, robots should be able to discover new concepts, and share these concepts and knowledge about the concepts with other team members. For example, new environment attributes could be detected that were not pre-defined. For this purpose, future applications should consider use of more flexible mechanisms, based for example on KQML [66][99] and XML [186] for information and knowledge exchange.

10.3.3 Investigation of Applicability of Additional Social Relationships to Multi-robot Systems

In this thesis, only two social relationships, kinship and trust, were used for the implementation of the social networks based approach to coordination. In the real-world, more social relationships exist among human society. For example, by living in a specific area, working in a particular environment etc. One social relationship that easily comes to mind as a potential candidate for application in multi-robot teams is that of friendship. Friendship could be implemented around the concept of reciprocal altruism [203]. The mechanism for maintenance of social relationship can also benefit from further research by investigating a partial goal completion reward system, as opposed to the currently implemented "all or nothing" approach.

10.3.4 Social Networks as a Rule-Extraction Mechanism

The learning capacity of the social network based approach opens interesting possibilities that can be explored in future work. In the INDABA deliberator layer, all robot and environment attributes are defined in almost symbolic terms. Using such definitions, it should be relatively possible to express selection rules in a symbolic form, for example in the form of production rules. Based on the best performing scout attributes (refer to section 7.5.2), it would be simple to extract a rule for scout selection, e.g.

IF SPEED_FAST **AND** DETECTION_ADVANCED **AND** POWER_BATTERY **THEN SCOUT.**

Future research will develop a mechanism to extract such symbolic rules from social networks.

10.3.5 Investigation into a More Formal Kinship Rating Mechanism

The current implementation of kinship rating is fairly crude and heuristic. A different, more formal mechanism for determining the strength of kinship relationship should be investigated. A possible direction for research is to expand on work that proposes encoding of robot building blocks in a formal way, for example, using a graph grammar as in [147]. To illustrate the point, the research done for this thesis found that the sensitivity of the used robot platform to sensor positioning was somewhat of a surprise. Kinship rating, as currently implemented, takes into account only the existence of a sensor, not sensor positioning. The sensor positioning influences sensor readings and the kinship relationship should take this into account.