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ScienceDirect
Information Fusion 8 (2007) 56–69
INFORMATION FUSION
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Communication between agents with heterogeneous perceptual capabilities ☆

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Received 28 October 2004; received in revised form 17 May 2005; accepted 17 May 2005
Available online 14 July 2005

Abstract

In real world applications robots and software agents often have to be equipped with higher level cognitive functions that enable them to reason, act and perceive in changing, incompletely known and unpredictable environments. One of the major tasks in such circumstances is to fuse information from various data sources. There are many levels of information fusion, ranging from the fusing of low level sensor signals to the fusing of high level, complex knowledge structures. In a dynamically changing environment even a single agent may have varying abilities to perceive its environment which are dependent on particular conditions. The situation becomes even more complex when different agents have different perceptual capabilities and need to communicate with each other.

In this paper, we propose a framework that provides agents with the ability to fuse both low and high level *approximate* knowledge in the context of dynamically changing environments while taking account of heterogeneous and contextually limited perceptual capabilities.

To model limitations on an agent's perceptual capabilities we introduce the idea of partial tolerance spaces. We assume that each agent has one or more approximate databases where approximate relations are represented using lower and upper approximations on sets. Approximate relations are generalizations of rough sets.

It is shown how sensory and other limitations can be taken into account when constructing and querying approximate databases for each respective agent. Complex relations inherit the approximativeness of primitive relations used in their definitions. Agents then query these databases and receive answers through the filters of their perceptual limitations as represented by (partial) tolerance spaces and approximate queries. The techniques used are all tractable.

Keywords: Rough sets; Database and sensor fusion; Approximate reasoning; Intelligent agents; Cognitive robotics; Software agents

1. Introduction

In real world applications robots and software agents often have to be equipped with higher level cognitive functions that enable them to reason, act and perceive in changing, incompletely known and unpredictable environments. One of the major tasks in such circumstances is to fuse information from various data sources. There are many levels of information fusion, ranging from the fusing of low level sensor signals to the fusing of high level, complex knowledge structures. In a

☆ A short version of this study was presented at the Seventh International Conference on Information Fusion (FUSION 2004) in Stockholm, Sweden [1]. Supported in part by the WITAS UAV project grant under the Wallenberg Foundation, Sweden and an NFFP03 research grant (COMPAS).
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doi:10.1016/j.inffus.2005.05.006

dynamically changing environment even a single agent may have varying abilities to perceive its environment which are dependent on particular conditions. The situation becomes even more complex when different agents have different perceptual capabilities and need to communicate with each other.

Research in more traditional robotics has emphasized low-level sensing, sensor processing and control tasks. One of the open challenges in cognitive robotics is to develop architectures which seamlessly combine low-level sensing and sensor processing with the generation and maintenance of higher level knowledge structures. This implies signal-to-symbol transformations at many levels of abstraction. One particularly difficult issue involves the quantitative to qualitative transformations required to support the use of qualitative knowledge structures in high-level reasoning tasks. To add to the difficulty, sensors, by their very nature, introduce uncertainty and noise in the data. In order to provide an adequate representation of a robotic environment, some of this uncertainty, or lack of knowledge, should be reflected in the higher-level knowledge structures. In other words, some of the high-level knowledge structures should be approximate in nature, having both quantitative and qualitative characteristics.

The perceptual limitations of a robotic agent constrained by the peculiarities of its sensor suite should be taken into account not only when the robotic agent reasons about its external and internal environments, interpreting its own measurements made in different conditions, but also when one or more robotic agents communicate with each other by asking questions concerning each others' knowledge about the world or themselves. In this case, two robotic agents communicating with each other can only ever ask queries of an approximative nature and receive answers of an approximative nature as seen through their respective filters of perceptual limitation.

In this paper, we propose a technique that can provide agents with the ability to ask *approximate* questions to each other in the context of heterogeneous perceptual capabilities and approximate knowledge derived through uncertain sensor data. Even though they may have concepts in common, their ability to perceive individuals as having specific properties or relations can be distinct. The concern then is how this affects the questions that can be asked and the replies that can be generated by agents with perception functions limited to varying degrees. In particular, we address the following problems related to information fusion:

- given various information sources[1] with heterogeneous perceptual capabilities, what facts based on those sources can be accepted by an agent to be certain, what facts are unknown and what surely do not hold?
- given agents equipped with (approximate) knowledge, what knowledge common to a group of agents should be accepted as certain, unknown or surely not holding?

The methodology developed in the current paper allows one to deal with both problems in a uniform fashion.

In order to set the proper context as to how this work is specifically related to data or information fusion, it should be emphasized that in the past several years, attempts have been made to broaden the traditional definition of data fusion as state estimation via aggregation of multiple sensor streams. There is a perceived need to broaden the definition to include the many additional processes used in all aspects of data and information fusion identified in large scale distributed systems. In this case, the nodes in such systems may not only include sensors in the traditional sense, but also complex systems where data and information are fused at many different levels of abstraction to meet the diverse situation assessment needs associated with different applications. It is at this level of abstraction the techniques in this paper should be understood.

One of the more successful proposals for providing a framework and model for this broadened notion of data fusion is the JDL data fusion model [2] and its revisions [3,4]. In [3] for example, data fusion is defined as "the process of combining data or information to estimate or predict entity states" and the data fusion problem "becomes that of achieving a consistent, comprehensive estimate and prediction of some relevant portion of the world state".

We are interested in nodes in such complex systems which store relevant portions of the world state where world state information is approximate in nature and mechanisms for asking questions about nodes is in place as part of the higher-level information fusion process. In this case, some of these nodes may be viewed as containing tolerance agents which manage approximate information in a node and may communicate across nodes about such information and assist in further fusions of information content in the larger system.

In order to provide the proper level of detail for the framework considered here, the following set of abstractions is used in the article. Each agent will have access to the following functionalities and representations:

- an abstraction called a (partial) tolerance space which is used to represent similarity of data points for basic domains in addition to complex data domains;
- a set of sensors and a sensor model for each sensor. The sensor models take into account the contextual

[1] For example, those provided by actual or virtual sensors.