A Distributed Coordination Framework for Adaptive Sensor Uncertainty Handling

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Abstract. The evaluation and management of sensor uncertainty is particularly necessary in a noisy multi-sensor context. In this paper, focusing on the potential of distributed coordination among sensor nodes based on the built-in association between wireless sensor networks and multi-agent systems, meanwhile in a rough set technique sense of uncertainty, we show how an adaptive distributed coordination framework for a hierarchy of sensor data uncertainty performs local data fusion to increase the certainty of real-time sensor readings coherently, makes global rational decisions under imprecision and partial truth, and reconciles the conflicts somewhat, thus evolving adaptive and robust sensor uncertainty handling systems. Implementation results for an example sensor field demonstrate the application of our proposed approach.

Keywords: adaptive distributed coordination strategy, rough set theory, multi-agent systems, modeling sensor uncertainty, wireless sensor networks.

1 Introduction

Generally, an explicit definition of uncertainty may refer to the idea of an information gap between what we do know and what we need to know [1]. However, as a suitable mathematical formalization of uncertainty, rough set theory can quantify both what is known and what is unknown. Moreover, from rough set perspective, further research is needed to view the ways in which uncertainties are hierarchical and interconnected. Especially, so far there exists little work on incorporating coordination mechanism into adaptive sensor uncertainty handling, for which the issue of a distributed coordination framework is actually an important and novel research direction.

2 Background Concepts and Motivation

Rough set theory approaches the problem of inexact concepts in the form of a decision system $(U, A \cup \{d\})$. Here U is a non-empty finite set of objects, A is a set of condition attributes, and d is decision element. For any subset R of A , $AS = (U, R)$,

an ordered pair, is the approximation space [2]; $[x]_R$ denotes the equivalence class of R containing x , for $x \in U$. The lower approximation of X is the set $\underline{R}X = \{x | x \in U, [x]_R \subseteq X\}$ and the upper approximation of X is the set $\overline{R}X = \{x | x \in U, [x]_R \cap X \neq \emptyset\}$. The results in $\underline{R}X$ are certain. The boundary region $\overline{R}X - \underline{R}X$ contains those uncertainty results that are possible, but not certain.

Multi-agent systems are fundamentally designed for dealing with and offering architecture for complex distributed applications that require collaborative problem solving, and wireless sensor networks consist of a collection of light-weight sensors connected via wireless links to each other or to a more powerful gateway node [3].

While principles taken from the rough set theory are suitably employed for the mathematical modeling and further handling of sensor uncertainty through the use of its approximation space, the need for cooperative processing of spatially and temporally dense collected data because of limited resources, makes multi-agent system architecture an ideal candidate for analyzing and modeling distributed sensor data, and these ideas are the motivation behind this approach.

3 Modeling of Sensor Uncertainty

Herein, we identify uncertainty as a measure of the level of confidence of a sensed value, or of validity of a conclusion at a higher level. Due to hardware limitations and signal processing inaccuracies, there are always some forms of uncertainty associated with sensor measurement and the processed information. First, some uncertainties can only be inferred as the absence or incompleteness of certain observational data item values because of inaccessibility. And second, uncertainty can be seen as a scaling of the noise level of inconsistent data sets, also in the form of the binary data inconsistency failures during the actual sensor processing. Additionally, a sensor node usually faces uncertainties owing to its limited or outdated partial information about the states of complex problem solving in other nodes. Furthermore, there exists the uncertainty which arises from the issue of granularity effect. All these form a hierarchy of sensor data uncertainty.

4 Adaptive Distributed Sensor Uncertainty Coordination Frame

In order to effectively handle sensor uncertainty, as shown in Figure 1, we may use the term “agent” to mean any sensor node, and there are three kinds of hierarchically dispersed agents embedded on sensors, i.e. sensor agents, cluster agents, and the manager agent, which form a wireless sensor network into a distributed multi-agent sensor system. Furthermore, as coordination is the process of effectively managing interdependencies between activities distributed across agents [4], we propose a hierarchical distributed coordination framework for sensor uncertainty handling, which bridges the potential of adaptive coordination to reduce sensor uncertainty with that of intelligent decision in the form of rule with an appropriate level of certainty.

Fig. 1. Distributed multi-agent wireless sensor networks

Firstly, on the layer of local data fusion, the principle issue is to manage and minimize the measured sensor agent uncertainties through suitable fusion algorithms. On the one hand, redundant data fusion can increase the accuracy and certainty of sensed data in the case of sensor failure. On the other hand, complementary data fusion allows features to be sensed coherently through fusing the different types of data from more than one source sensors to synthesize meaningful information.

Secondly, on the layer of attribute reduction and decision rule, the major topics consist in the fact that one must not only be aware of sensor uncertainty, but also discover hidden concise relationships that agree with uncertain sensor situations. At the cluster agents, by employing the notion of reduction in a rough set sense, which is the minimal set of condition attributes that eliminates pairwise dependencies and makes the same decisions as the whole set, those redundant condition attributes along with their associated uncertainties may be removed, then the reduction of the number of attributes and further the discovery of deterministic decision rules are achieved, thus providing an appropriate model for the distributed multi-agent sensor system.

Thirdly, on the layer of global conflict resolution at the manager agent, problem of conflict resolution is of most importance due to exclusive interpretations of the same thing or conflicting sets of rules from different source sensors. In rough set approach, inconsistency is represented by the concepts of lower and upper approximation, and confliction relation is expressed by the notion of boundary region, which may be of minimal level of uncertainty by forcing a finer granulation of the partitioning. Moreover, through the use of explicit rule priorities, we can reconcile the consistency degrees about the inferences under uncertainty as far as possible.

5 Case Study: Example Implementation Results

In this section we illustrate the above presented ideas by a distributed multi-sensor paradigm for real-time forest fire detection. Herein, the sensor data can be represented as a decision table, which is constitutive of condition attributes $\{temperature, relative\ humidity, rainfall, smoke, wind\ speed\}$ and decision attribute $\{fire\ level\}$.

Here we discuss some primary kinds of hierarchical sensor uncertainty at the cluster agents and the manager agent. A schedule of these uncertainties and the corresponding example implementation results are listed in Table 1 and Table 2, respectively. While raw uncertainty sensor data from distributed sensor agents and cluster agents have been converted into the minimal efficient sets of certain condition attribute data and deterministic decision rules at the manager agent, these demonstrate the efficiency of the adaptive distributed sensor uncertainty coordinate framework.

Table 1. A schedule of hierarchical sensor uncertainties

Sensor uncertainty class	Site	Handling method
failure uncertainty	cluster agents	redundant data fusion
incompleteness uncertainty	cluster agents	complementary data fusion
inconsistency data item uncertainty	cluster agents	prior data fusion
condition attribute uncertainty	cluster agents, manager agent	the notion of reduction
hidden relationship uncertainty	cluster agents, manager agent	the notion of reduction
conflicting rule uncertainty	manager agent	conflict resolution

Table 2. Summary of kinds of uncertainty handling in distributed multi-agent sensor system

Agent class	Node num	Failure uncertainty		Incompleteness uncertainty		Inconsistency data item uncertainty		Condition attribute uncertainty		Hidden relationship uncertainty	Conflicting rule uncertainty	
		total	disposal	total	disposal	total	disposal	total	reduction		total	disposal
cluster1	40	4	4	12	12	4	4	5	2	3	0	0
cluster2	50	6	6	20	20	8	6	5	2	3	0	0
cluster3	36	4	4	10	10	2	2	5	2	3	0	0
cluster4	52	8	8	24	24	6	4	5	2	3	0	0
manager	178	0	0	0	0	0	0	5	2	3	2	2

6 Conclusions

Considering there is some room for a mixture of approaches for the sensor uncertainty problem based on rough set theory and multi-agent system, we have proposed and demonstrated an adaptive distributed coordination frame reflecting the handling of multiple levels of sensor uncertainty, along with emphasis on how to make a complex multi-agent sensor system self-repairing and behave deterministically to some extent.

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