

Cooperative Information Fusion in a Network Robot System

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Abstract—The vision of network robot systems involves robots embedded in smart environments, with which they can collaborate and communicate. In such systems, robots have access to many different sources and types of information, which need to be coordinated and combined effectively. In this work, we propose a framework which addresses the problem of combining heterogeneous information in a network robot system. The approach is inspired by work on conceptual spaces and perceptual anchoring, and is implemented using tools from fuzzy logic.

I. INTRODUCTION

When dealing with network robot systems, as opposed to standalone robotic systems, one of the main new aspects is the unprecedented richness of information available. In these systems, agents do not need to rely solely on their own perception to obtain information about objects: they can also receive information from the objects themselves, or from other agents with knowledge about objects in the environment. Moreover, various types of information are often available; for example, an agent might have access to multiple sources of perceptual and non-perceptual information. While this richness of information opens a new landscape of opportunities, it also adds a number of fundamental challenges – namely, those of *communicating, coordinating and fusing* these items of information.

A number of approaches to highly distributed robotic systems exist, under different names, including: network robot systems [1], intelligent spaces [2], sensor-actuator networks [3], ubiquitous robotics [4], and PEIS-Ecologies [5]. Most of the approaches have much in common, and all of them need to address the challenges mentioned above. In the rest of this paper we will refer to these systems as PEIS-Ecologies, since this work was carried out from within this context.

We propose a framework for fusing different types of information obtained from various sources. If done correctly, information fusion can yield improved knowledge about the state of the world. Redundant information can be used to reduce uncertainty and imprecision, while complementary information can be used to resolve ambiguities and incompleteness. The work is inspired by work on *perceptual anchoring* [6],

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[7], [8] and *conceptual spaces* [9], and as such it is well suited for dealing with both perceptual and non-perceptual (often symbolic) information. The framework uses geometric spaces, called *anchoring spaces*, to represent, compare and combine information. The instance of the framework described here uses tools from fuzzy logic to represent, match, and fuse various items of information. The main contribution of the framework is that it allows the many different types of information which are present in robotic systems to be efficiently represented, matched and fused using a single conceptual space representation. More details on the framework, as well as a discussion on related work, can be found in [10].

II. INFORMATION FUSION IN A PEIS-ECOLOGY

In a PEIS-Ecology [5], all agents which are members of the ecology are abstracted by the *uniform notion* of a PEIS (Physically Embedded Intelligent System), which is any device incorporating some computational and communication resources, and possibly able to interact with the environment via sensors and/or actuators. A PEIS can be as simple as a toaster or as complex as a humanoid robot. Our general framework for fusion within a PEIS-Ecology can thus be summarized as follows. Consider a set $P = \{p_1, \dots, p_n\}$ of PEIS. For each PEIS p_i in P , we define:

- An *anchoring space* S_i . This is a multi-dimensional metric space. Dimensions correspond to qualities of interest in the application domain; i.e., groups of dimensions are related to an object’s interesting properties.
- A set $X_i = \{x_i^1, \dots, x_i^k\}$ of *information sources* for each PEIS p_i . For a typical PEIS, a local symbol system (e.g. a knowledge base, or a task planner), and a number of sensing modalities could all act as information sources.
- For each source x_i^j , we define a *grounding function* g_i^j which maps information from the given source into the anchoring space S_i . For example a source containing symbolic information might have a grounding function which maps predicate symbols to regions in S_i . Alternatively, a grounding function might map percepts from a perceptual system to areas or points in S_i .
- A *shared anchoring space* S , which is the space into which shared information, obtained from various PEIS, is mapped. This shared space provides a common reference frame, which is needed in order for communicated

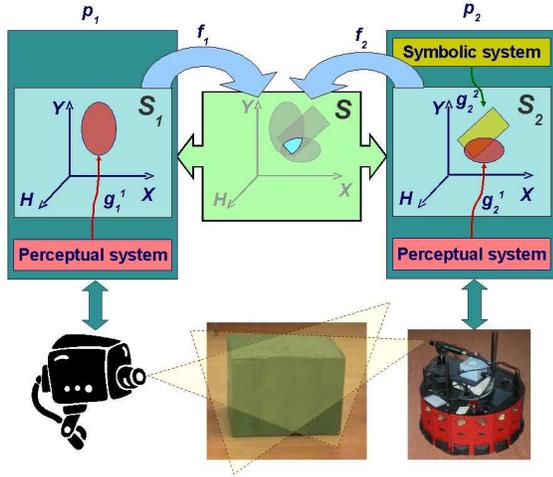


Fig. 1. A simple PEIS-Ecology containing two PEIS.

information to be compared, matched, and fused.

- For each PEIS p_i , a function $f_i : S_i \rightarrow S$ which maps information from S_i to S . The functions f_i will sometimes involve cylindrical extensions and non-linear transformations, since the dimensionality and coordinate systems of S and S_i might differ.

A. A simple example

Imagine a simple PEIS-Ecology like the one illustrated in Figure 1, which consists of two PEIS: an autonomous robot called Pippi, endowed with a symbolic system (e.g., a task planner) and a perceptual system (e.g., a vision system); and a camera which also has a perceptual system, but no symbolic system. Both PEIS are observing the same object, a green box.

For simplicity, we assume that both PEIS have individual anchoring spaces which have the same dimensions (e.g. X, Y, and Hue) as the shared anchoring space (which is shown above the box in the figure). This means that each PEIS can directly map information obtained from their information sources into the shared space. If a PEIS makes observations in local robot coordinates, a coordinate transformation to global coordinates might be needed in order to map information into the coordinate system used in the shared anchoring space. Note that in practice, position and color information would be maintained separately, to reduce computational complexity.

Before the information in the shared space can be fused, one must determine which items of information refer to the same objects. This data-association is non-trivial, and is part of the *anchoring* problem [6]. For this work, it suffices to note that comparing and matching information can be done conveniently inside conceptual spaces.

Once it is known which items of information refer to a given object (in this case, the green box), the information in the shared space can be fused, resulting in an improved estimate of the box's position and hue. The fusion process will be discussed in more detail in the next section.

III. A FUZZY LOGIC IMPLEMENTATION

We have implemented the framework described previously using techniques from fuzzy logic [11]. Information in the individual and shared **anchor spaces** is represented by n -dimensional fuzzy sets. Simply put, a fuzzy set A over the n -dimensional space S is characterized by a membership function

$$\mu_A : S \rightarrow [0, 1]$$

which gives the degree of membership $\mu_A(s)$ of each point s in S to the fuzzy set A . This means that the grounding function g_i^j maps information from the information source x_i^j to a fuzzy set over the individual anchor space S_i .

Each fuzzy set A is implemented as an n -dimensional array of floats, where the value in each element s corresponds to the value of $\mu_A(s)$. For example, color information can be represented using a 3D space, with dimensions for hue, saturation, and lightness, while 2D position information can be represented using a grid of (x, y) values. If necessary, some dimensions can be approximated to reduce complexity.

In the implementation used in this work, the dimensionality and units of the shared space S are the same as those used in the individual spaces S_i . This implies that for each PEIS p_i , the mapping function f_i which maps information from the individual anchor space S_i to the shared anchor space S is the identity function. This choice does not limit the generality of the framework; it merely simplifies the implementation, by affecting how and when certain computations are made.

The shared space could be implemented in a centralized or distributed way. In this work, the shared space is distributed: each PEIS has a local copy of S , in which it performs matching and fusion operations.

Information **fusion** is implemented using fuzzy intersection. If μ_1 and μ_2 are two fuzzy sets on the same space S , representing two distinct items of information, then the result of fusing these two items is represented by the fuzzy set μ given, for any $s \in S$, by

$$\mu(s) = \mu_1(s) \otimes \mu_2(s),$$

where \otimes is a triangular norm, or T-norm [11]. The most common T-norms used in fuzzy logic are the minimum and product operators; in the experiments reported below, we use the product. Figure 2 shows an example of two 1-dimensional fuzzy sets being fused using the product T-norm. Information **matching** is also implemented using the mechanisms of fuzzy logic. Various definitions for fusion and matching might be used, and several alternatives exist in the fuzzy logic literature.

IV. AN ILLUSTRATIVE EXPERIMENT

The purpose of this experiment is to demonstrate how information of different types (in this case symbolic and perceptual), and from different sources, can be fused using a common representation space. This yields two main benefits:

- *disambiguation*: when multiple hypotheses about the state of an object are possible, or when multiple percepts could be associated with a certain object, complementary

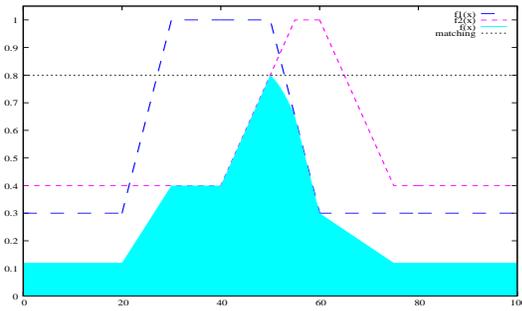


Fig. 2. The fuzzy set $f(x)$ is the result of fusing $f_1(x)$ and $f_2(x)$ using the product T-norm. One way to compute a matching level is to take the maximum point of $f(x)$, which is approximately 0.8.

information from another source can aid in isolating the correct hypothesis;

- *improved estimates*: when multiple sources of information are considered, redundancy in information can be used to reduce imprecision and inaccuracy.

The environment we use for developing and testing PEIS-Ecologies in various configurations is a small apartment, which we call the PEIS-Home. The experiment described here is based on a coarse 2D model of the PEIS-Home, shown in Figure 3(a). This model includes two rooms (a kitchen and a bedroom), as well as two tables. One of the tables, *Table-01*, is a PEIS, and possesses an RFID reader which can read the RFID tags of any object placed on its surface. There are two other PEIS used in this experiment. One is an overhead camera, placed in the kitchen, called *Camera-01*. The other is the robot *Pippi*, initially assumed to be in the bedroom.

In this discussion, the only dimensions of the anchoring spaces which are considered are X and Y (i.e. we deal only with 2D positions). Recall that the individual and shared anchoring spaces have the same dimensions and units here. In practice this means that all position information obtained in local coordinates (e.g., from *Pippi*'s vision system) is converted to global coordinates before being put into the anchoring space. This is done using the grounding functions described earlier.

This experiment is carried out using artificially generated data, and demonstrates a simple scenario involving the above mentioned PEIS. Using artificial data in this case allows us to carefully examine new items of information one at a time. In [12], the fusion algorithm itself was examined using online data. The scenario unfolds as follows.

- **Information 1 (Symbolic)**: *Pippi* is told to fetch a green cup, called *Cup-22*, from the kitchen. Figure 3(b) shows the fuzzy set used by *Pippi* to represent the information that the cup is in the kitchen (i.e. positions in the kitchen are possible, all other positions are impossible).
- **Information 2 (Perceptual)**: *Pippi* asks the ecology for information about all cups. *Camera-01* sees two green cups in the kitchen, which are the only cups in the ecology which match the information *Pippi* already has about *Cup-22*. The fuzzy set showing the positions of the

cups perceived by *Camera-01* is shown in Figure 3(c). The result of fusing this information with previous information is shown in Figure 3(d).

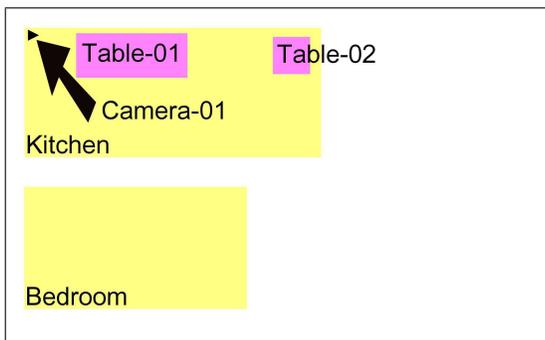
- **Information 3 (Symbolic)**: *Table-01* detects that *Cup-22* is on its surface with its RFID reader (Figure 3(e)). The result of fusing this information with previous information is shown in Figure 3(f). Note that this has led to disambiguation, since only one of the cups observed by the camera has a position which is consistent with that of the table.
- **Information 4 (Perceptual)**: *Pippi* now has enough information to approach *Cup-22*, and can thus perceive the cup with an on-board camera (Figure 3(g)). The result of combining all of the available information is shown in Figure 3(h). Combining the information from both cameras, which have different viewpoints, improves the final estimate considerably, since range estimates from the individual cameras are quite uncertain.

V. CONCLUSIONS

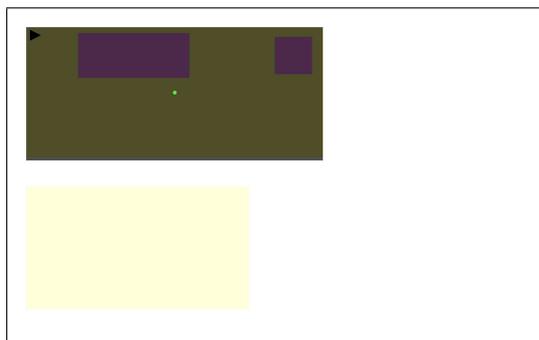
We have described a framework for fusing the information provided by several heterogeneous sources of information in a multi-robot setting. We have shown in particular an instantiation of this framework within PEIS-Ecologies, a type of network robot system, as well as an implementation of it based on fuzzy logic. Though other techniques might be used to implement the framework, the fuzzy logic approach has a number of important advantages. The anchoring spaces used in our fusion framework provide a general way of representing and treating various types of information.

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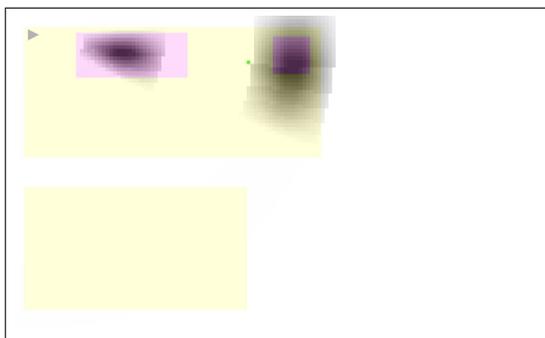
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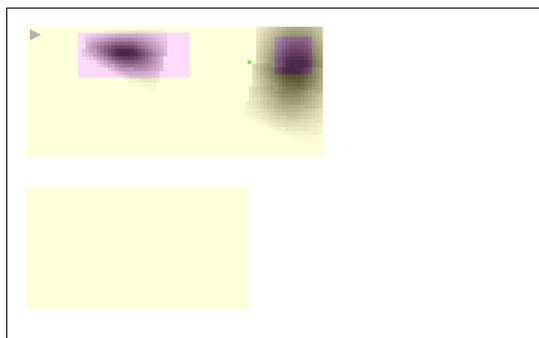
(a) A coarse model of the PEIS apartment.



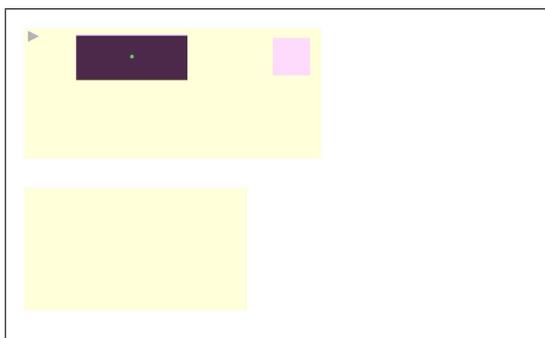
(b) **Information 1:** *Cup-22* is in the kitchen.



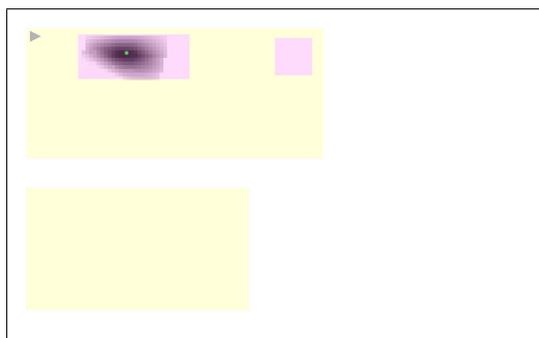
(c) **Information 2:** *Camera-01* sees two green cups.



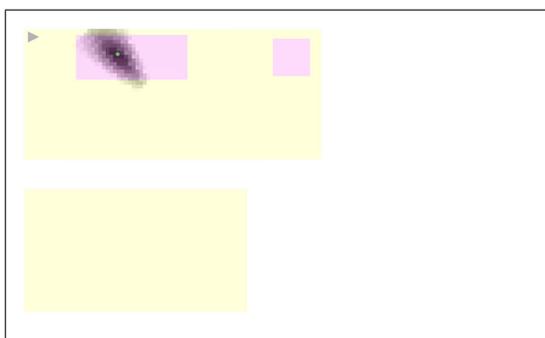
(d) **Information 1,2:** Combination of items 1 and 2.



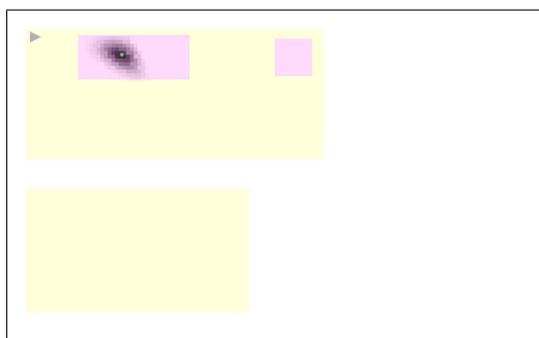
(e) **Information 3:** *Table-01* detects *Cup-22*.



(f) **Information 1,2,3:** Combination of items 1, 2 and 3.



(g) **Information 4:** *Pippi* sees *Cup-22*.



(h) **Information 1,2,3,4:** Final position estimate.

Fig. 3. Progression of estimates for the position of *Cup-22*, as new items of information arrive. The darker areas are more possible, the light areas are less possible. The dots indicate the center of gravity of the possible areas.