Acquiring a Global Lexicon for Identifying Landmarks in a Heterogeneous Multi-Robot System

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Abstract. This paper describes a multi-robot system in which mobile robots try to name landmarks distinctively using a discrimination game framework. Landmark-based navigation effectively reduces cumulative errors by identifying landmarks and adjusting robot's localization. Also it can be applied to a multi-robot system straightforward. However there is a significant problem on finding common names of landmarks among robots. In multi-robot planning, all the landmarks need to have unique names shared by all the robots. Since robots actually recognize only physical features of a landmark, each robot needs to obtain mappings between the names and the distinctive features of other landmarks. We call the search such mappings a landmark naming problem. In this paper, we propose the application of a discrimination game to solve the landmark naming problem in a heterogeneous multi-robot system in recognition. Robots autonomously name landmarks through local communications on the landmarks. First we define a landmark naming problem and explain a framework to which our approach is applicable. Then we describe a procedure of discrimination game applied to a multi-robot system. Using the procedure, multiple robots moves, communicates each other on landmarks, and gradually acquire lexicons as the mappings. They eventually obtain lexicons with names identifying unique landmark for every robot. Finally we made preliminary experiments and discuss the results.

1 Introduction

In robotics, a lot of studies on navigation for a mobile robot have been done thus far. One of the major navigation methods is landmark-based approach [5] [4][9] which copes with the cumulative errors due to dead-reckoning. The landmark-based navigation eliminates such errors by identifying the landmarks and adjusting robot's localization using the information on them. Though the landmark-based navigation can be also applied to a multi-robot system straightforward, there is a significant problem on landmark naming among robots with different recognition. In multi-robot path planning under the landmark-based navigation, all the landmarks need to have unique names and all the robots need to recognize the same landmark by the name. Since all that a robot actually recognizes on a landmark are its physical features, not names, each robot needs to have mappings between the names and the features. Furthermore the features must be distinctive of other neighbor landmarks for unique naming. However designing such mappings is difficult, and we call it a *landmark naming problem.*

The multiple mobile robots easily becomes heterogeneous in their recognition because of the difference in their sensors. Some robots may sense the color feature of a landmark using a vision system, others may sense its shape using a range finder. In such a heterogeneous multi-robot system, the features mapped from the same name may be different depending on robots and no common feature of the same landmark may be recognized by robots. In this case, a landmark naming problem may become more difficult. Though a landmark naming problem is a important issue in a multi-robot system, it hardly has been dealt with thus far.

In this paper, we propose the application of a discrimination game[6][7] to solve the landmark naming problem in a heterogeneous multi-robot system in recognition. In our approach, robots autonomously names landmarks through local communications on the landmarks. First we define a landmark naming problem in more detail and explain a framework to which our approach is applicable. Next we describe a procedure of discrimination game applied to a multi-robot system. Using the procedure, multiple robots moves, communicates each other on landmarks, and gradually acquire *lexicon*s: mappings from a name of a landmark to physical features. They eventually obtain global lexicons with names identifying unique landmark for every robot. Finally we made experiments and discuss the results.

Komoriya proposed a method to select useful landmarks from a set of various landmarks[3]. Unfortunately the landmark selection is used for a single robot navigation and did not deal with a landmark naming problem. Hager et al. proposed the image-based extraction method of landmarks[2][1]. However they did not propose the method for naming in a heterogeneous multi-robot system in recognition. Steels formalized discrimination game and made various experiments for investigating language development in A-Life fashion[6][7]. As results, interesting phenomena like the occurrence of dialect were observed. We extend the framework to deal with a multi-robot system.

2 A landmark naming problem

2.1 Framework

We define a framework to which our approach is applied. The framework is a system consisting of multiple mobile robots in which the following assumptions hold. We consider the assumptions are practical and satisfied in the most of real environments.

- *Local communication* : A robot is able to communicate with other robots within a certain distance from it. Most communication systems like wireless communication satisfy this assumption. Strings are available for communication.
- *Direct landmark recognition* : Even when robots can not identify the same landmark using lexicon, they recognize the landmark directly using a pointer like a robot arm or a laser pointer. Thus, when two robots communicate on a landmark which is recognized by them, the landmark is identified for them. However we need useful lexicon for identifying all the landmark even when two robots can not directly point them in path planning.
- *Heterogeneous recognition* : The features of a landmark which robots can recognize are different depending on the robots' sensors. No common feature of the same landmark may be recognized by robots.

2.2 A landmark naming problem

We formalize the landmark naming problem. In such a multi-robot system satisfying the above assumptions, let $r \in R$ be a robot, $l \in L$ be a segmented landmark, $q \in Q$ be a name and a physical feature $f \in F$ which a landmark have and a robot recognizes. Feature f is not q named by a robot and robots try to assign q to f. Thus the same feature f may be assigned by different names depending robots.

A landmark l has physical features F_l, which is a subset of F, and a robot incompletely recognizes them. Thus a robot recognizes some features and not other ones. Also a robot r has features F^r : a subset of F which it can recognize. Hence the features of a landmark l which a robot r can recognize is described $F_l^r = F^r \cap F_l$. Since all that a robot r actually recognizes on a landmark l are a physical features F_l^r, not name. Since robots identify a landmark by communication using its name, they tries to construct a lexicon: a mapping from a name q of a landmark l to recognized features F_l^r.

The lexicon of a robot r is defined as X_r : a set of $q_l \Rightarrow E_l^r$: a mapping from a name q_l to $E_l^r \subseteq F_l^r$ for a landmark l. Several robots are able to identify the same landmark by the same name corresponding to different features in each robot's lexicon.

For implementing a multi-robot system in which robots does planning with interaction each other and have only local information, the lexicon needs to satisfy the following preconditions.

- *Globally common names*: The name of the same landmark needs to be common in all the robots' lexicons. This enables all the robots to identify the same landmark with the same name for multi-agent planning. This condition is necessary for multi-agent planning because all robots need to identify landmarks with the names for planning.
- *Locally distinctive features*: If several landmarks exist in the area in which a robot r can recognize, r needs to distinguish a target landmark t (called a *topic*) from others. Thus the E_t^r needs to be locally distinctive of other landmarks' E_l^rs, and such E_t^r is called a *distinctive feature set*. The recognized landmarks except t are called *background* B. Hence the distinctive feature set of r, t, B, is a set $D_{t,B}^r \subseteq F_t^r$ so that $\forall b \in B, D_{t,B}^r \not\subseteq F_b^r$.

We define a *landmark naming problem* as searching the lexicon satisfying the above two conditions in an environment mentioned earlier. Though this problem has hardly been dealt with thus far in a multi-robot system, we consider it an essential issue for a practical multi-robot system.

Fig.1 shows an example for a heterogeneous multi-robot system finding distinctive feature set. In this case, two robots r_1 and r_2 observe and point the topic t. Thus other two landmarks l_1 and l_2 construct the background $B = \{l_1, l_2\}$ to t. For each robot, F_l^rs are computed like in Fig.1. Since F^{r_1} is different from F^{r_2}, $F_l^{r_1}$ may be different from $F_l^{r_2}$. Using $F_t^{r_1}$, $F_{l_1}^{r_1}$, $F_{l_2}^{r_1}$, the r_1 determines $D_{t,B}^{r_1} \in \{\{f_5\}, \{f_1, f_5\}, \{f_4, f_5\}, \{f_1, f_4, f_5\}\}$. Then by $F_t^{r_2}$, $F_{l_1}^{r_2}$, $F_{l_2}^{r_2}$, the r_2 computes $D_{t,B}^{r_1} \in \{\{f_3\}, \{f_2, f_3\}, \{f_3, f_4\}, \{f_2, f_4\}, \{f_2, f_3, f_4\}\}$. After generating the distinctive feature sets, all the robot need to construct a lexicon with globally common names.

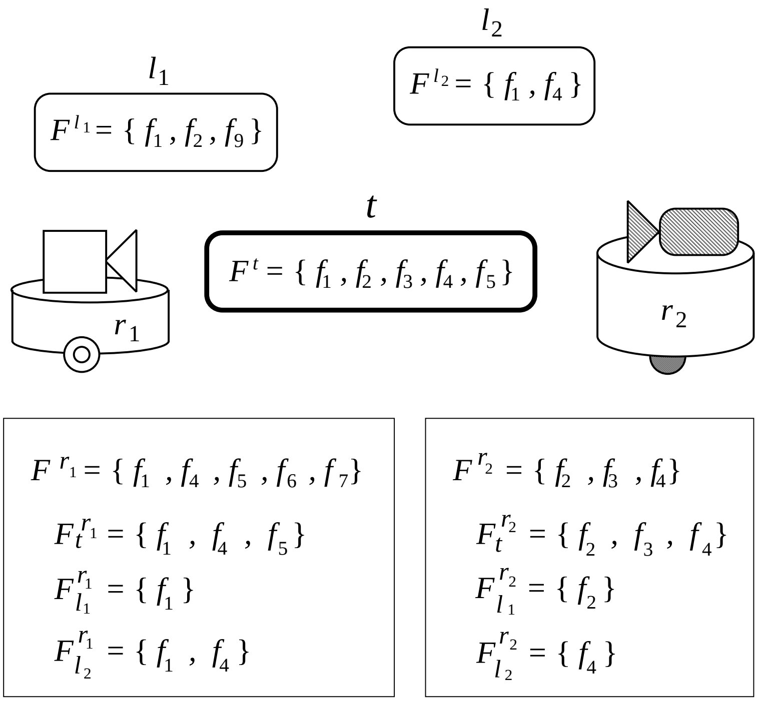

Figure 1 A heterogeneous multi-robot system in recognition.

3 Discrimination game for a multi-robot system

To solve the landmark naming problem, we utilize the discrimination game[6][7]. Unfortunately the general discrimination game was not constructed for a multi-robot system, thus we need to extend it. The followings show a procedure of discrimination game for a single mobile robot in a multi-robot system. Briefly a speaker robot sends a name corresponding to a distinctive feature set and the other hearer robot receives it. If the hearer can identify the landmark using features mapped from the sent name in its own lexicon, the communication is successful and the name is evaluated positively. Communications like this occur sufficiently between robots and the lexicons satisfying above two condition will be obtained gradually. Also the *cumulative success frequency* S is assigned to all the mappings in a lexicon.

1. A robot moves constantly with a *movement strategy*. A robot becomes a *speaker robot* r_s when landmarks and a *hearer robot* r_h are recognized within its communication area.

2. The r_s select one of recognized landmarks as a *topic* t and points it. Then the r_h identifies it directly, and the two robots identify the same landmark.

3. A *speaker procedure* and a *hearer procedure* are executed and the communication is processed.

- *Speaker procedure*

(s1) The r_s computes $D^{r_s}_{t,B}$s and selects one of them for communication.

(s2) For the selected $D^{r_s}_{t,B}$, the r_s extracts q_t from $q_t \Rightarrow D^{r_s}_{t,B}$ in X_{r_s}.
If no mapping for the $D^{r_s}_{t,B}$ in X_{r_s}, $q_t \Rightarrow D^{r_s}_{t,B}$ is added into X_{r_s}. The q_t is selected from Q. This communication finishes in failure.
If several mappings exist, r_s uses the mapping with maximum S.

(s3) The r_s sends the q_t to r_h. If the success acknowledgement is returned from r_h, this communication finishes successfully, and otherwise in failure. Then S of $q_t \Rightarrow D^{r_s}_{t,B}$ is updated.

- *Hearer procedure*

(h1) The r_h receives the q_t from r_s, and extracts corresponding features E_t in X_{r_h}. Furthermore it extracts all the own distinctive feature sets $D^{r_h}_{t,B}$s.

(h2) If the E_t is $Dr_{ht,B}$, the r_h can identify t by a name and this communication finishes successfully. Then r_h sends the success acknowledgement to r_s, and S of the mapping is increased.
If the E_t is not distinctive, this communication finishes in failure and r_h add all the $q_t \Rightarrow Dr_{ht,B}$ into X_{r_h}.

We explain an example for Fig.1. Let r_1 and r_2 have $X_{r_1} = \{\mathsf{au} \Rightarrow \{f_5\}, \mathsf{ba} \Rightarrow \{f_4, f_5\}\}$ and $X_{r_2} = \{\mathsf{au} \Rightarrow \{f_3\}, \mathsf{ba} \Rightarrow \{f_2\}, \mathsf{nu} \Rightarrow \{f_3, f_4\}\}$ respectively. At step1, let r_1 and r_2 be a speaker robot and a hearer robot. Then r_1 selects t as a topic, and l_1, l_2 become background B. Also r_1 points t, and r_2 recognizes it directly at step2. Next r_1 starts a speaker procedure. At step(s1), r_1 computes distinctive feature sets $D^{r_1}_{t,B} = \{f_5\}$, $\{f_1, f_5\}$, $\{f_4, f_5\}$, $\{f_1, f_4, f_5\}$ as mentioned in §2.2, and selects $\{f_5\}$. The r_1 finds a mapping au $\Rightarrow \{f_5\}$ for $\{f_5\}$ in its X_{r_1}, and extracts the name au at step(s2). As a result, r_1 sends au to r_2 and S is increased at step(s3). This speaker procedure finishes.

On the other hand, the hearer robot r_2 receives au and obtains the corresponding feature $\{f_3\}$ from au $\Rightarrow \{f_3\}$ in X_{r_2} at step(h1). Since the $\{f_3\}$ is a distinctive feature set $D^{r_2}_{t,B}$, r_2 can identify the topic and this communication finishes successfully at step(h2). Then S of au $\Rightarrow \{f_3\}$ is increased.

If the speaker robot r_1 selects $\{f_4, f_5\}$ and its name ba is sent to r_2, this communication finishes in failure. Because the corresponding feature set $\{f_2\}$ to ba in X_{r_2} is not distinctive. As a result, r_2 adds all the ba $\Rightarrow D^{r_2}_{t,B} \in \{\{f_3\}, \{f_2, f_3\}, \{f_3, f_4\}, \{f_2, f_4\}, \{f_2, f_3, f_4\}\}$ into X_{r_2} at step(h2).

4 Experiments

4.1 Experimental Settings

For investigating the utility of our approach, we made preliminary experiments in a simple multi-robot system. The following experimental settings were used. The F_r and F_l are shown in Table.1. Using these settings, we investigated the acquisition of a global common lexicon.

- *Movement strategy* : random walk.
- *Robots* : $R = \{r_1, r_2, r_3\}$
- *Landmarks* : $L = \{l_1, l_2, l_3\}$. Landmarks are positioned randomly.
- *Names* : $Q = \{$ci, du, ba$\}$

- *Feature set* : $F = \{f_1, \cdots, f_9\}$
- *Environment size* : 10×10 cells.
- *Communication area size* : a circle with radius 4.
- *The terminal number of communications* : 1,000 times.

4.2 Experimental results

Fig.2 shows the average success rates = $\frac{\text{the cumulative number of success communications.}}{\text{the cumulative number of communications.}}$ for landmarks. Seeing from this graph, the communications gradually became better. Also we observed the communications got almost successful eventually.

The lexicons obtained finally are shown in Table.2, where only the mappings with the highest S are indicated. In the lexicons, the same landmark is assigned with the same name and all the feature sets mapped from the names are distinctive. This means that the lexicons satisfying the two conditions: Globally common names and Locally distinctive features, have been obtained by robots. Note that through the acquiring the lexicons, no centralized mechanism is necessary and all the robots autonomously behave. Though the experimental results were obtained under a single initial condition, we verified the feasibility of our approach to the landmark naming problem.

In landmark-based navigation, such a common naming system is quite necessary to multi-robot planning because robots need to identify landmarks using common names for planning and recognize the landmarks using physical features as executing a plan.

5 Conclusion

We defined the landmark naming problem in a heterogeneous multi-robot system in recognition and proposed a method to solve it using a discrimination game framework. In our system, robots autonomously name landmarks through local communications on the landmarks. We explained the background causing a landmark naming problem and described a framework to which our approach is applicable. Then we extended the procedures of a discrimination game for applying to a multi-robot system in which agents may move and sense locally. Using the procedure, multiple robots moves, communicates each other on landmarks, and gradually acquire lexicons as the mappings. Finally we made preliminary experiments in a simple multi-robot system and found out our approach is promising to solve the landmark naming problem.

Unfortunately there are open problems as the followings.

- *Strategy for efficiency*: Since the random walk is not efficient movement strategy for our framework, we are currently developing more efficient and effective movement strategy. We also consider selective communication strategy in which

F_{r_1}	$\{f_4, f_7, f_5, f_8, f_6, f_9\}$	F_{l_1}	$\{f_1, f_4, f_7\}$
F_{r_2}	$\{f_1, f_7, f_2, f_8, f_3, f_9\}$	F_{l_2}	$\{f_2, f_5, f_8\}$
F_{r_3}	$\{f_1, f_4, f_2, f_5, f_3, f_6\}$	F_{l_3}	$\{f_3, f_6, f_9\}$

Table 1 F_r and F_l.

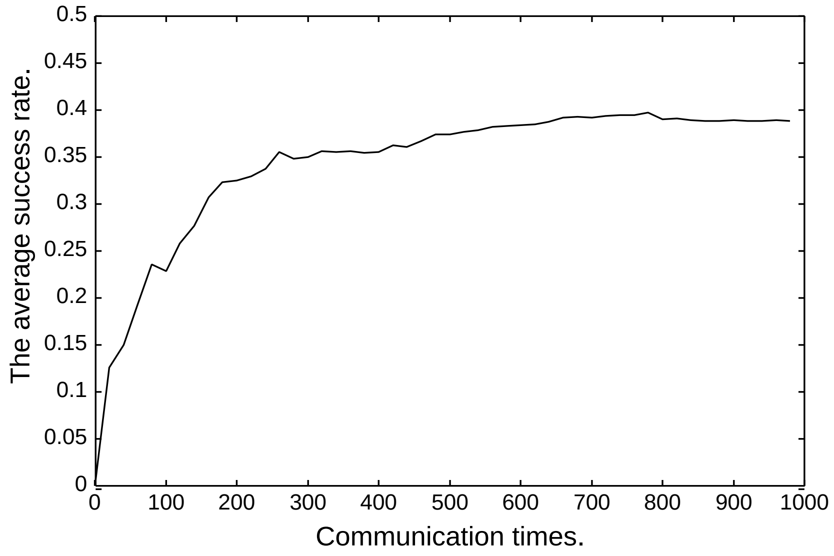

Figure 2 The average success rate through communications.

	X_{r_1}	X_{r_2}	X_{r_3}
l_1	ci $\Rightarrow \{f_4\}$	ci $\Rightarrow \{f_1\}$	ci $\Rightarrow \{f_1\}$
l_2	du $\Rightarrow \{f_8\}$	du $\Rightarrow \{f_8\}$	du $\Rightarrow \{f_5\}$
l_3	ba $\Rightarrow \{f_9\}$	ba $\Rightarrow \{f_3\}$	ba $\Rightarrow \{f_6\}$

Table 2 The obtained global lexicon.

a robot communicates with the other robot depending on its success rate, lexicon and so on. Furthermore we may be able to apply evolutionary robotics approach like [8] to automatically acquire suitable behavior rules for efficient solution of the landmark naming problem. By coding behavior rule validly and designing a fitness function, genetic algorithm/programming searches efficient strategy.

– *Systematic experiments*: The experiments are preliminary because they are restricted in a simple environment with a small number of robot, landmarks and features. Thus we need to systematically make large experiments using simulation. By the experiments, we investigate the coverage, the limitation of our approach and the robustness against initial positions of robots, landmarks.

– *Implementation on real mobile robots*: Our final target is to implementation of our system into a real multi-robot system. For achieving this purpose, we need to refine the formalization of our framework and the assumption on the environment. By experiments with real mobile robots, we can find out the gap between simulation and a real environment and the efficiency of acquiring the global lexicons becomes still more significant.

References

[1] Z. Dodds and G. Hager. A color interest operator for landmark-based navigation. In *Proceedings of the Fourteenth National Conference on Artificial Intelligence*, 1997.

[2] G. Hager, D. Kriegman, E. Yeh, and C. Rasmussen. Image-based prediction of landmark features for mobile navigation. In *Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, pages 1040–1046, 1997.

[3] K. Komoriya, E. Oyama, and K. Tani. Planning of landmark measurement for the navigation of a mobile robot. In *Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1476–1481, 1992.

[4] S. Maeyama, A. Ohya, and S. Yuta. Outdoor landmark map generation through human assisted route teaching for mobile robot navigation. In *Proceedings of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 957–962, 1996.

[5] T. D' Orazio, M. Ianigro, E. Stella, and A. Dstante. Self-location of a mobile robot using visual landmarks. In *Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1869–1874, 1992.

[6] L. Steels. Emergent adaptive lexicon. In *Proceedings of the Fourth International Conference on Simulation of Adaptive Behavior*, pages 562–567, 1996.

[7] Luc Steels. Perceptually grounded meaning creation. In *Proceedings of the Second International Conference on Multi Agent Systems*, pages 338–344, 1996.

[8] S. Yamada. Evolutionary design of behaviors for action-based environment modeling by a mobile robot. In *Genetic and Evolutionary Computation Conference*, 2000. to appear.

[9] T. Yamamoto, S. Maeyama, A. Ohya, and S. Yuta. An implementation of landmark-based position estimation function as an autonomous and distributed system for a mobile robot. In *Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1141–1148, 1999.