Robotics and Autonomous Systems 62 (2014) 1294–1304

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Multiple targets enclosure by robotic swarm

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HIGHLIGHTS

- Target enclosure robot swarm for multiple targets is proposed.
- The analytical verification of a small size swarm of the proposed robot for single target is described.
- The enclosure behavior for 1-, 2-, 3 targets by a larger group ($n < 80$) is examined by computer simulations.
- The capability to assign robots equally to 2 targets is shown by the extensive computer simulation ($n < 200$).

ARTICLE INFO

Article history:
Available online 3 April 2014

Keywords:
Swarm robotics
Task assignment
Target enclosure

ABSTRACT

Target enclosure by autonomous robots is useful for many practical applications, for example, surveillance of disaster sites. Scalability is important for autonomous robots because a larger group is more robust against breakdown, accidents, and failure. However, since the traditional models have discussed only the cases in which minimum number of robots enclose a single target, there has been no study on the utilization of the redundant number of robots. In this paper, to achieve a highly scalable target enclosure model about the number of target to enclose, we introduce swarm based task assignment capability to Takayama's enclosure model. The original model discussed only single target environment but it is well suited for applying to the environments with multiple targets. We show the robots can enclose the targets without predefined position assignment by analytic discussion based on switched systems and a series of computer simulations. As a consequence of this property, the proposed robots can change their target according to the criterion about robot density while they enclose multiple targets.

1. Introduction

In this paper, we propose a robotic swarm model that can allocate robots to an unspecified number of targets. This robotic swarm has no leader and no supervisor. In this model, each autonomous robot moves according to Takayama's target enclosure model but a new reference rule is introduced. By this reference rule, the robots do not need to keep the predefined assigned position of circular formation, so that it is possible for each robot to switch its target. Additionally, density based target selection rule is adopted to achieve stable target enclosure. The performance is verified by computer simulation. There are 3 advantages of this model over leader-following approaches [1,2] which are as follows. First, it is unnecessary to control the number of leaders. Second, the robots do need to be identified by other robots. Third, no communication between robots is required.

Target enclosure, is useful for monitoring disaster sites, and thus it has recently become an important goal for multiple robots. Robots can operate in dangerous circumstances, replacing human presence.

Disaster sites are usually far from an operator. In this case, a group of robots cannot confirm in advance the exact number of sites that should be surveilled. Therefore, redundancy in the number of robot employed is desirable, and this enables the group of robots to accept a larger number of targets. For this purpose, the tasks of target allocation and target enclosure must be performed simultaneously.

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http://dx.doi.org/10.1016/j.robot.2014.03.014

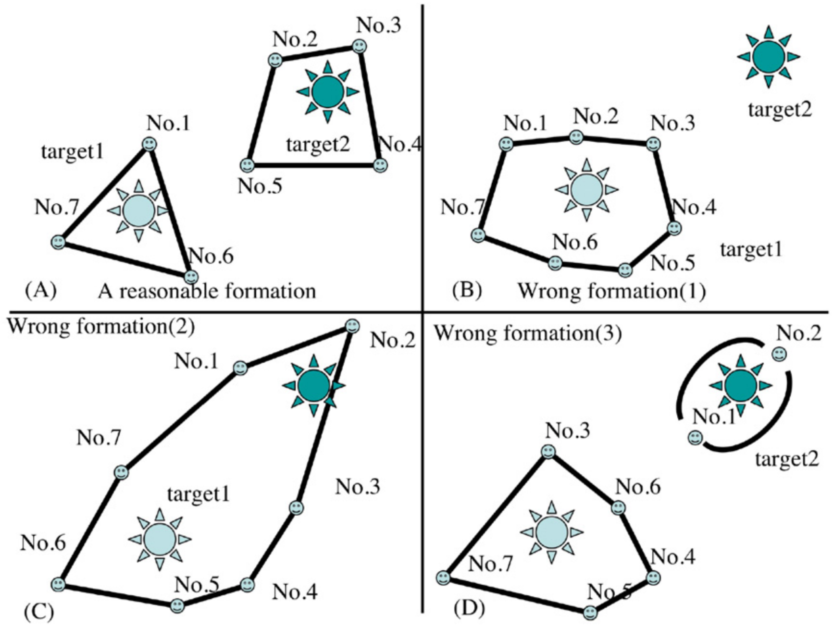

Fig. 1. Examples of enclosure formation for 2 targets.

However, it seems to be difficult for most of the target enclosure models proposed so far to realize this requirement because of following 2 reasons. Firstly, there are no researches which discuss multiple targets enclosure environment. Secondly, except for the study of Kobayashi et al. [3], all other studies require that a particular arrangement of the robots be maintained in order to build a target enclosure.

For example, Yamaguchi [4] discussed a target capturing task in which the robots must maintain a chain structure. Kim et al. [5] discussed the target enclosure problem; in their solution, each robot needs information on the relative speed of one robot and relative geographical relation to its target to determine its behavior. If the relationship between a robot and its reference robot is considered as a link in graph theory, the graph of the group of robots must follow a Hamiltonian cycle.

When a robot changes the target to be enclosed, the following two events should be considered: withdrawal and join a group of robots. In the former, the remaining robots in the group must maintain the constraint of the Hamiltonian cycle without the removed robot. In the latter, a group that satisfies the Hamiltonian cycle condition and the new member must form a new Hamiltonian cycle. Fig. 1 shows these events by the example when 7 robots have to enclose 2 targets. When the robots with wrong formation (B) will change to the reasonable formation (A), they have to decide who bears off. When the robots are with formation (D), one robot of around Target 1 should go by withdrawal and join the cycle of No. 1 and No. 2 around Target 2. As far as we know, discussion of these events is very few when there are no restrictions on the timing of withdrawal and accedence of robots.

Therefore, firstly, we propose a new reference rule which makes this condition of maintaining a Hamiltonian cycle to achieve target enclosure relaxed. We focused on the study of Takayama et al. [6]. In their model, each robot needs information of one neighbor and its target. As in other studies, this model also requires the Hamiltonian cycle constraint. However, in this paper, we show that this model can realize target enclosure without this constraint when each robot bases its behavior on information from its nearest neighboring robot [7]. Therefore, in our model, robots can change targets without considering the above two events.

Note that the reference relationships among more than four robots in the proposed nearest neighbor model are often unconnected in the graph theoretical sense [8,9]. Therefore, it is not easy to discuss this issue using a graph laplacian, which is the primary analytical approach used for multi-robot systems. In this paper, the theory of switched systems [10] is adopted for analyzing groups of less than five robots. A series of computer simulations are used for larger groups.

Target assignment function for a group of robots is achieved also by distributed manner. Robots can change their target by themselves. However, they fail to enclose multiple targets when too many robots change their target simultaneously. Therefore, we introduce density based target change rule which is inspired by the task allocation mechanism of swarm robotics research [11]. This work proposed a method to collect a necessary number of robots from a group of robots without bidirectional communication and high individual identification capabilities.

This paper is composed as follows. First, Takayama's work is introduced. Next, our method based on the reference of the nearest neighbor is shown. In Section 3.2, the practical asymptotic stability of the small size group is proved analytically. Then, by the computer simulations, we show the ability of the target enclosure task of the larger group. Finally, the target allocation capability of this model by using a simple local interaction based task allocation method [11] is shown by computer simulations.

2. Takayama's target enclosure model

Firstly, Takayama's target enclosure model is explained.

2.1. Takayama's target enclosure model

In this section, we assume that all agents choose the same target. We assume that on a two-dimensional (2D) plane, there is only one target O at the origin and n agents. Additionally, we suppose that all of agents have same ability and they can know relative position to the targets and the other robots. Fig. 2 illustrates the case of $n = 5$. Robots are numbered counterclockwise as $P_1, \ldots, P_n$, and r_i is the position vector of the robot P_i. In the target enclosure task, each robot moves to the corresponding white marker.

To achieve this task, Takayama et al. [6] proposed the following model. Each robot determines its control input, speed v_i, and