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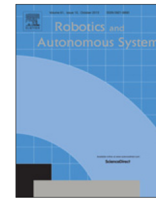

Multi-target trapping with swarm robots based on pattern formation

Shuai Zhang [a,*], Mingyong Liu [a], Xiaokang Lei [b], Yunke Huang [a], Feihu Zhang [a]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, PR China
[b] School of Information and Control Engineering, Xi'an University of Architecture and Technology, Xi'an, Shaanxi, 710055, PR China

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A B S T R A C T

A significant limitation of most previous target trapping algorithms for swarm robots is that the target shape needs to be predefined and only some regular Euclidean shapes can be applied. Besides, splitting and merging of multiple shapes depending on moving targets have not been considered by previous methods. This may be inadequate for dealing with the problem of entrapment in dynamic targets. This paper proposes a flexible shape formation algorithm by using Radial Basis Implicit Function (RBIF) to realize the multi-target trapping task that needs the transformation of trapping shape response to dynamic targets. With this flexible shape formation method, we improve previous methods by allowing most distribution of group targets to be entrapped without a predefined shape and robots to split/merge with regards to the moving targets. The previous bound on the number of reference points for a target shape is triple the number of targets, while it becomes less by considering the convex hulls of targets in the new method. Numerical simulations of static/dynamic scenarios, obstacle avoidance, noise and self-reorganization have been performed to validate the effectiveness and flexibility of the proposed approach for multi-target trapping.

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1. Introduction

Using swarm intelligence for cooperative task is one of significant applications in the field of multiple robots. This application is motivated by the fact that partly or fully complete tasks by a single complex system could be replaced by simple, modular and flexible structured interacting robots [1]. This collective behavior based on self-organization is inspired by nature, and implies that distributed control algorithm is robust, flexible, and scalable. Multi-target trapping is one of the typical challenging research areas of the swarm robot system, which takes the advantage of cooperation of simple agents (robots) in large numbers to entrap multiple targets. This phenomenon is also common in nature, and is routinely demonstrated by ants: the prey retrieval task requires the ants to generate a trapping pattern and then each ant grips the prey and pulls it coordinately [2]. This behavior can also be observed in pack of wolves which usually form a circle-like pattern to hunt the more stronger single prey. Specific applications of multi-target trapping include, but not limited to, search and rescue [3], collective transportation and construction [4], deployment of sensor networks [5], convoy/escorting missions [6,7] and area/border coverage [8].

The main mission of multi-target trapping is to generate an appropriate trapping shape depending on the changing targets, which implies that the strategy of pattern formation can be used. An application-oriented definition for pattern formation considers pattern formation as the coordination of a group of robots to initiate and maintain a formation with a certain shape, such as a circle or a chain [9]. Once a swarm robot system generates a closed pattern adapting to changing targets, the target trapping problem becomes a special pattern formation problem. However, in most literatures of shape formation, the shapes generated by robots are regular and can only implement limited transformations. For example, the circle-like trapping shape is widely used, and the transformations of circle shape are limited to be regular polygon formations [10]. Another trapping shape is elliptical surface which provides more flexibility for shape transformation compared to circle by changing the minor axis and the major axis (such as arc and line formation) [6]. Additional methods can be found in [11]. This limit is subject to the shape describing method. Note that an arbitrary shape is better than regular shapes (such as circle, ellipse and regular polygon) because it is more flexible and adaptive to various dynamic-target situations. In a real trapping scenario, the number and distribution of targets may change and the movement of targets is also maneuvering, hence a fixed or a regular shape with limited changes is not able to meet the demand of dynamic trapping. Adaptively generating/transforming trapping patterns in a dynamic-target situation, and controlling the robots for such flexible trapping still remain challenges.

This paper presents an adaptive pattern formation method for a swarm of robots to entrap multiple targets. The trapping shapes are described by radial basis implicit function (RBIF) which can display

* Corresponding author.
E-mail address: shuaizhang@mail.nwpu.edu.cn (S. Zhang).

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an arbitrary shape and provide flexible transformations among different shapes. The main contributions of the proposed method are: (1) it not only adapts to conventional trapping scenarios (multiple robots entrap one target or single cluster), but also adapts to split–merge scenario (which needs robots to transform patterns between mother pattern and multiple sub-pattern). (2) it provides another obstacle avoidance strategy named pattern generation strategy which could keep the obstacles outside of the perimeter. The first contribution improves previous works by ensuring that robots are able to redeploy trapping resource by dividing or integrating the agents of a swarm. The second contribution improves previous works by providing a flexible approach for those special obstacle avoidance situations such as tunnel/door scenario and burrow-like scenario.

1.1. Related work

The target trapping methods can be divided into four categories: (1) behavior-based control, (2) leader–follower control, (3) optimization methods and (4) artificial potential field.

For behavior-based control, individual robot selects one behavior from a predefine set by local rules [12,13]. Although this method is easy to implement with the basic "if-then" thinking, it is hard for a programmer to design a set of proper behavior rules if given a specific task. If the agents want to improve performance from the trial and error step by step with learning skills, the main problem is how to decompose global reward into individual rewards. This challenging issue is called spatial credit assignment [14,15].

For leader-follower control, some robots carrying relative important information are defined as leaders, and the followers are supposed to follow the leaders to self-organizing an expected pattern [16,17]. This method is easy to understand because of human-concept. A local re-voting approach is always used to define the leader and other rules in homogeneous groups of robots are demonstrated in [18].

For optimization methods, a team of robots search the optimal positions according to targets in the plane. Huan and Pathirana tried to find the best matching position and orientation of the target pattern by making into an optimization problem [19]. This optimization method is also presented in the work of [20] which highlights various patterns. The drawback of this strategy is that, these patterns must be predefined and cannot transform adaptively. Kassabalidis et al. proposed an enhanced Particle Swarm Optimization (PSO) for dynamic security border identification [21]. The trapping shape is described by objective function, and with punishment or reward item to the objective function, special attention could be paid to strengthen the entrapment of certain local areas. Yang et al. [22] proposed a decentralized control algorithm of swarm robots for target search and trapping inspired by bacteria chemotaxis, in which a single target is considered and the trapping pattern is a predefined circle.

For artificial potential field, the robot moves along the gradient of a potential field governed by target shape. This method is widely used in which attractive and repulsive forces are introduced. However, potential field is well known for local minimum or deadlocks, many strategies have been studied to solve this disadvantage [10,23,24]. Rezaee and Abdollahi considered cooperative entrapment of a team of robots based on the virtual structure [10]. The mobile robots move toward a circle, and due to the repulsive forces among robots and robots to the virtual center of circle, regular polygon formations of mobile robots are realized. Similarly, Barnes et al. [6] proposed an approach for organizing elliptical trapping shapes by utilizing artificial potential fields that were generated from normal and sigmoid functions. It is still limited to entrap complex distributed targets although the elliptical surfaces can transform into line or arc. Zhifu and Tianguang [25] used the artificial potential field method in which the interactions among robots are assumed to be globally repulsive and selectively attractive, so the pattern could be formed by choosing appropriate interactive topologies. However, the expected patterns are limited to few special shapes, such as line, circle and ring. Another more easier approach is proposed in [26], in which attractive force between hunters and preys, repulsive force among hunters are only introduced to achieve entrapment task. There is no need of target shape in this approach while the robots can only entrap the single target with circle shape. Hesieh et al. [27,28] used implicit function to describe an arbitrary pattern. However, the pattern is static and has no transformation according to the changing targets. Guo et al. [29,30] proposed a gene regular network (GRN) based control model for pattern formation and the expected pattern is described by a non-uniform rational B-spline function. Although this approach could entrap any distribution of multiple robots with irregular shapes, amounts of feature points which are not simple to obtain according to the moving targets are required to generate the target shape.

Deriving from Guo's works, we still use the GRN control model for the motion of each robot, the non-uniform rational B-spline function (NURBS) is replaced by the radial basis implicit function (RBIF). The benefits of replacing the NURBS with the RBIF are: to require fewer feature points, to design an adaptive shape formation mechanism more easily, and to describe the entrapment corresponding to pattern formation. In our approach, there is no need to predefine a fixed trapping shape (such as circle or elliptical), the target trapping shapes are irregular and allowed to transform including splitting and merging procedures, while this split–merge behavior in multi-target trapping is seldom considered in existing works. In our previous work, we studied the influence of asymmetric information collected by robot for static pattern formation and pattern formation in constrained environments [31–33]. In this paper, we improve the shape formation strategy by reducing the reference points. The bound on the number of reference points is reduced from $3N_{nt}$ to $N_{nt} + 2N_v$, where N_{nt} is the number of targets and N_v is the number of convex hulls of targets, $N_{nt} > N_v$. The work focus on dynamic multi-target trapping when targets experience split–merge behavior.

1.2. Outline of this paper

The rest of this paper is organized as follows: Section 2 presents the problem statement and its assumptions for multi-target trapping. The motion of each robot controlled by GRN model is introduced in Section 3. In Section 4, we propose an implicit function method to represent the dynamic shape. The flexible shape formation method allows a swarm of robots to generate or transform their trapping shapes according to changing targets; Simulations and analysis are presented in Section 5; Conclusions and potential future work are drawn in the last section.

2. Problem statement and assumptions

Consider a group of mobile robots and a group of targets moving in a 2D boundless space. The targets can be moving vehicles, other robots, or living agents. All robots and targets are regarded as point agents. The agent has limited visibility range but has the global information in its detected area. The computation is performed synchronously with a centralized way and each agent uses a common coordinate system. More details about the constraint conditions for the swarm robotic systems could be found in [34–37]. The task assigned to the swarm robot system is to entrap the targets, i.e., move around a target in a circle formation or move around a group of targets in an irregular formation, often referred to as escort/entrapment problem [7]. We assume that the most primary entrapment requires 3 robots and 1 target, a general

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