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Cooperative circular pattern target tracking using navigation function

Jinsung Hong, Youngjoo Kim, Hyochoong Bang *

Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

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ABSTRACT

This paper demonstrates a guidance law of multiple UAVs for circular pattern target tracking using only range sensors in a fully connected network using the navigation function. The navigation function consists of a goal function and an obstacle function to arrive at the goal point while avoiding obstacles during navigation. The decentralized navigation function for multiple UAVs is modified to create evenly spaced positions at the so-called sweet spot, with which the information of the target can be maximized while collision avoidance is achieved. The proposed navigation function is verified by simulation studies.

1. Introduction

In recent years, the problem of collision free navigation of multiple agents (or UAVs) to achieve a desired formation has attracted considerable attention. The basic issue arises from the fact that multi-agent navigation is part of a system that requires coordination to achieve a certain task. There have been many studies on area formation control for multi-agent systems [1–3]. Artificial potential field-based approaches that employ attractive and repulsive potentials have been extensively utilized to guide the movement of multiple agents for formation. A common problem with artificial potential field-based control algorithms is the existence of local minima when attractive and repulsive forces are combined. To avoid the local minima, a specific type of artificial potential, called a navigation function, achieves a unique minimum. Navigation functions (NFs) were originally developed in the seminal work of Rimon and Kodischeck to enable a single point mass agent to move in an environment with spherical obstacles [4]. The NF is a smooth real-valued map realized through a suitably chosen scalar-valued cost function. Integrating the negated gradient vector field of the cost function automatically gives rise to trajectories that guarantee collision free motion and convergence to the destination from almost all initial conditions [5–8]. The primary control objective in these problems is to guide a team of autonomous agents to a desired configuration (formation) while avoiding collisions with both teammates and obstacles. Ref. [9,10] developed a decentralized controller that demonstrated that a multi-agent system can achieve an arbitrary desired configuration from a connected initial graph (agents are considered as nodes on the graph) within a specified neighborhood while avoiding collisions with other agents and external obstacles and maintaining global network connectivity.

On the other hand, there have been substantial efforts to solve the target localization problem using the optimal control theory to design observer trajectories [11–17]. The Fisher Information Matrix (FIM) was used to express the amount of information sensed by range sensors as a criterion in the optimization problem to design trajectories of multiple agents. More information implies that an error covariance becomes smaller as explained by the Cramer–Rao Lower Bound (CRLB). Thus, the inverse of an FIM is essentially equivalent to reducing the uncertainty in the estimation. The most popular scalar measure is the determinant of the inverse of the FIM for a D-optimality criterion. As the determinant of an FIM is given by the multiplication of its eigenvalues, the D-optimality criterion results in the minimization of the volume of the uncertainty ellipsoid. In [12,14,18], it was proved that the optimal configuration is the one in which the agents are uniformly placed in a circular fashion around the target if the UAVs measure the range from the target in two-dimensional space and the range sensor has a minimum error covariance at some distance from the target (the so-called sweet spot). However, the determinant of the FIM is very sensitive to changes in range but it exhibits far less sensitivity to changes in angular separation [14]. If we use the gradient descent method, which is an appropriate algorithm for real-time applications, it tends to reduce the range as much as possible. It results in an agent configuration that is placed at the same distance from the target but not in evenly spaced positions according to the initial conditions. Moreover, these approaches cannot deal with collision avoidance while the agents are moving toward a target.

* Corresponding author.
E-mail address: hcbang@ascl.kaist.ac.kr (H. Bang).

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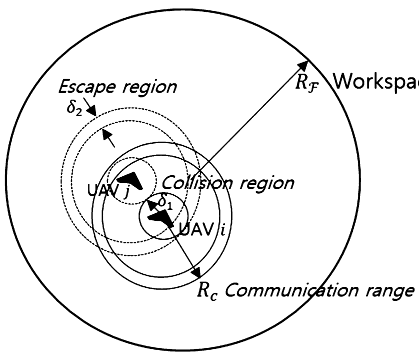

Fig. 1. Communication range and escape region.

In this paper, we address an information point of view for cooperative target tracking of multiple agents equipped with range sensors. In [19,20], the NF was modified for target tracking and has multiple minima on the circular shaped sweet spot from a certain distance from the target, while most of the NFs have only one global minima for the desired configuration (or formation). The NF deals with inter collision avoidance as well. However, the multiple minima of the NF in [19,20] can be achieved at the same distance from the target but does not guarantee the agents to be at evenly spaced positions. From the information point of view, it is necessary that the multiple agents be placed at evenly spaced positions around the target to maximize information. Inspired by the above, we modified a parameter as a function of the number of neighbors in the decentralized navigation function from [19,20] to make evenly spaced positions at the sweet spot as well as at the same distance from the target. It enabled the information of the target to be maximized and collision avoidance.

The remainder of the paper is structured as follows. Section 2 presents the problem formulation for multiple UAVs, the range sensor model, the Fisher Information Matrix and the navigation function. In Section 3, the proposed algorithm is presented. Section 4 briefly introduces convergence analysis and shows that the proposed algorithm guides multiple UAVs to evenly spaced positions on the sweet spot. In Section 5, some examples are given to demonstrate the effectiveness of the proposed algorithm. Summary and conclusions are presented in Section 6.

2. Problem formulation

2.1. Problem definition

It is assumed that the target remains fixed and each UAV can move according to the following single integrator kinematics.

$$\dot{\boldsymbol{q}}_i = \boldsymbol{u}_i, \quad i = 1, \ldots, N \tag{1}$$

where $\boldsymbol{q}_i = (q_{ix}, q_{iy})^T \in \mathbb{R}^2$ denotes the position of the i-th UAV in a two-dimensional plane, and $\boldsymbol{u}_i = (u_{ix}, u_{iy})^T \in \mathbb{R}^2$ denotes the velocity of the i-th UAV (i.e., the control input). It is assumed that each UAV is equipped with wireless communication capabilities to exchange its own position information. Fig. 1 shows that two moving UAVs can communicate with each other if they are within a communication range, R_c. Meanwhile, each UAV should not collide using the collision region, δ_1. Even though there has been much research that dealing with both collision avoidance and communication range limitation, we only address the collision avoidance issue in this paper. Consequently, we assumed that the collision region is the same for all UAVs and the communication range is large enough so that UAVs are considered fully connected.

Let $\boldsymbol{z}_i$ be the measurement of the i-th UAV for the target, $\boldsymbol{x} = (x_t, y_t)^T$. We have

$$\boldsymbol{z}_i = h_i(\boldsymbol{x}, \boldsymbol{q}_i) + \boldsymbol{v}_i \tag{2}$$

$$h_i(x, q_i) = \sqrt{(x_t - q_{ix})^2 + (y_t - q_{iy})^2} \tag{3}$$

where $\boldsymbol{v}_i \in \mathbb{R}^2$ is a zero-mean Gaussian observation noise whose covariance matrix with $\boldsymbol{R}_i = E[\boldsymbol{v}_i \boldsymbol{v}_i^T]$ is given by

$$\boldsymbol{R}_i = b_1 \big(b_2 - \|\boldsymbol{q}_i - \boldsymbol{x}\|\big)^2 \boldsymbol{I}_{2\times 2} = \sigma_i \boldsymbol{I}_{2\times 2} \tag{4}$$

where $\boldsymbol{I}_{2\times 2}$ is a two-dimensional identity matrix, b_1 is a positive constant and $b_2 > 0$ is the sweet spot radius that produces the best sensing quality. In realistic target tracking scenarios, maintaining a certain distance from the target may result in the best observation of the target while reducing the probability of being detected [13].

The objective of this paper is to develop a decentralized guidance law, $\boldsymbol{u}_i$, for multiple UAVs to move to a sweet spot with evenly spaced positions where the sensor information can be maximized using the relative position information of the UAVs while inner collision avoidance is satisfied. We assumed that the obstacles are ignored or located far from the sweet spot and the workspace is large enough.

2.2. Fisher information matrix

The Fisher Information Matrix (FIM) encodes the information related to a set of measurements in estimating a state. Since the error covariance matrix is bounded from below by the Cramer–Rao lower bound (CRLB), the minimization of the inverse of the FIM is equivalent to reducing the uncertainty in the estimation [21].

Let $\hat{\boldsymbol{x}}$ be an estimate of the target state. The cost function J for the system (1) is given by

$$J(\hat{\boldsymbol{x}}, \boldsymbol{q}) = \det \boldsymbol{S}(\hat{\boldsymbol{x}}, \boldsymbol{q}) \tag{5}$$

$$\boldsymbol{S}^{-1} = \sum_{i=1}^{N} \boldsymbol{F}_i \tag{6}$$

where $\boldsymbol{F}_i$ is the FIM associated with the measurement of the i-th UAV defined in (7). Note that for a fully connected system, $\boldsymbol{S}$ is the sum overall i. If UAVs only measure the distance from the target, $\boldsymbol{x} = (x_t, y_t)^T$, with a range sensor, the measurement equation for the Kalman filter is set to (3). Since the error covariance is a function of the target state, the FIM is obtained as follows [21].

$$\boldsymbol{F}_i = \frac{1}{\sigma_i} \nabla_x^T h_i \nabla_x h_i + \frac{1}{2\sigma_i} \nabla_x^T \sigma_i \nabla_x \sigma_i \tag{7}$$

If we set the cost function as (5), the UAVs should reach a configuration such that the cost function reaches a minimum provided that the step size is small enough. In order to examine the nature of the minima, an explicit form of the cost function is considered.

$$\boldsymbol{F}_i = \alpha_i \begin{bmatrix} \cos^2 \beta_i & \cos\beta_i \sin\beta_i \\ \cos\beta_i \sin\beta_i & \sin^2 \beta_i \end{bmatrix} \tag{8}$$

where $\alpha_i = \frac{1}{\sigma_i} + \frac{b_1^2 (r_i - b_2)^2}{\sigma_i^2}$, $\beta_i = \tan^{-1} \frac{y_t - q_{iy}}{x_t - q_{ix}}$.

In order to compute the determinant of $\boldsymbol{S}$, the relationship $\det \boldsymbol{S} = (\det \boldsymbol{S}^{-1})^{-1}$ is used as (9).

$$\det \boldsymbol{S}^{-1} = \det \sum_{i=1}^{N} \boldsymbol{F}_i = \frac{1}{2} \sum_{i,j=1}^{N} \alpha_i \alpha_j \sin^2(\beta_i - \beta_j) \tag{9}$$

From (9) and (8), let $b_1 = 1/2$ for obtaining three distinguished solutions, and we find the maximum at $r_i = b_2$ and the optimal relative angular position when any two vectors $\{(\cos 2\beta_i, \sin 2\beta_i\}_{i=1}^{N}$ are aligned.