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Agent formations in 3D spaces with communication limitations using an adaptive Q-structure

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ABSTRACT

In this article, we further extend the Queue-formation structure (or Q-structure) in 3D spaces with additional features including: (i) specifying orientation information, (ii) a mechanism for forming sub-formations before the convergence into the final formation, and (iii) adapting the communication structure when communications are limited. The virtual Bobber-agents are used to guide each vehicle toward the appropriate queue, by acting as intermediate targets. In addition, virtual constellation-agents bias the motion of each vehicle to within a user-defined cone to the front of the vehicle so that abrupt direction changes are avoided as far as possible. The proposed scheme relies mainly on simple behaviors between embodied and virtual agents and is computationally inexpensive method. Extensive simulations show the effectiveness of the proposed method.

1. Introduction

Research on multi-robot systems has been extremely active in recent years, including topics in communications, high level decision making, and low level behavioral-based control mechanisms. A tiered approach is generally used for such complex systems, with deliberation protocols (such as [1–3]) higher up in the hierarchy passing commands to lower, motion level controls like those used in [4,5]. Specifically, formations are typically accomplished on two levels: (i) describing the formation, which may or may not change during runtime and (ii) determining desired points/paths for each vehicle in the system. This article will mainly focus upon decentralized formation approaches that are more suited for teams in dynamic, uncertain environments. The following issues are considered: (i) the change of agent numbers in large teams; (ii) the change of the communication structure due to the communication limitations; and (iii) obstacles avoidance. Our proposed decentralized formation approach facilitates scaling and flexibility of the formation with emphasis on the appearance of the formation, and allows adaptation of the communication structure itself, by leveraging on the fact that the Q-structure provides a convenient high level organization of the robot team in terms of short term information flow.

Most formations are described using concepts from graph theory [6]. Each agent is associated with a node in the graph, and formation maintenance involves the tracking of each node. This can be seen in virtual structure approaches [7,8], formation constrained functions [9], planning for formations [10], controller synthesis for non-holonomic vehicles using point-referenced formations [11], and also used in the methods for formation controller design proposed in [12,13]. Such a representation is also implicit in reactive approaches that require an agent to follow others located at connected nodes at a specific distances and bearings [14–17]. Several reactive approaches, including virtual leaders [18], social potentials [19] and pure behavior- based approaches [20], also use such a representation. Studies have also revolved around formation stability and convergence, such as leader-to-formation stability [21], in navigation functions [22–24] and in the presence of obstacles [25].

Graphs offer an instinctive method for describing formations, in which node/edges may be added and removed dynamically in response to the addition/removal of robots. Such representations become difficult to track dynamically when agent numbers change in large teams. An algorithm for generating formations that conform to specified 2D patterns was proposed in [26]. By using virtual bodies and artificial potentials, an approach to gradient estimation

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Nomenclature

Symbol	Description
$\mathcal{Q}$	The set of all the queues in a formation $\mathcal{F}$
$\mathcal{Q}_j$	j-th queue in the set Q
$\mathcal{V}_F(N_{tot})$	The set of formation vertices
V_i	Formation vertex
N_v, N_q	Number of formation vertices and queues, respectively
N_{tot}	Total number of vehicles
$\mathcal{S}_j$	A set of points describing the shape of the queue
$\mathcal{C}_j$	The capacity of the queue $\mathcal{Q}_j$
$\mathcal{O}_j$	The set of functions describes the orientation of agents at each point along the length of the queue
r_i	Agent i
r_{qvj}, q_{qvj}	Queue-vertex agent and its position, respectively
$q_{toq,i}$	Target-on-queue of robot i
d_{ir}	Acceptable distance between agents
d_c	Communication range of the agent
$\bar{R}_{c,i}$	A set of agents within communication range of r_i
R_{Q_j}	Sub-queue vertices from a set of ranked vertices belonging to $\mathcal{Q}_j$
R_{sos}	The set of agents broadcasting the distress flag
$Z_{cst,i}$	Cast-zone of agents r_i
$q_{ba,i}$, $q_{tg,i}$	Position of virtual bobber-agent and immediate target of r_i, respectively
N_{cs}, $N_{cs,k}$	The set of virtual constellation-agents around the vehicle and its subset, respectively
$r_{cs,i0}$	Virtual constellation-agent that lies on all the guidelines
$r_{cs,ika}$	The repulsive-distance between a vehicle r_i and each of its virtual constellation-agents
d_{cs}	Distance between virtual constellation-agents belonging to each subset $N_{cs,k}$
d_s	The safety distance a vehicle has to keep from any obstacle

and optimal formation geometry design and adaption were presented in [27]. Other methods such as that described in [28–31], while capable of supporting scaling, are more suited for flocking where mainly aggregation is considered for simple formations. In order to maintain a constant representation independent of team size, the Q-structure has been recently introduced [32] to facilitate scaling and flexibility in operating conditions with global communications. As with several methods mentioned above, direct wireless communications have often been used (e.g., in the works [33–35,1]), and the influence on agent cohesion and behavior have also been examined [36]. Global communications may not always be possible, and the convergence of a system based on the Q-structure has been examined in [37] when only limited communication is available. Since the Q-structure provides a convenient high level organization of the agent team in terms of short term information flow, in this article, it is further extended to allow adaptation of the communication structure itself. In addition, previously, only the problem of enabling agents to attain the shape of a specified formation, and have not paid much attention to the issue of orientation in the formation. All agents under the Q-formation scheme are made to follow the orientation of the virtual leader. However, depending on the application, more control over the final orientation of each agent may be desired, and is an important consideration in many cases. The desired orientation of each agent may be different, depending on each of their final position. In this article, our main contributions are as follows:

(i) The Q-formation scheme is extended into the 3D space and incorporates orientation information into the representation. Unlike our work in [37], the method proposed in this article exploits the organizational structure of the Q-structure to explicitly segregate short term information flow in the system and to adapt the short term communication structure according to communication ranges.

(ii) In contrast to our previous work in [32], we consider the limitations on the amount of direction changes each vehicle (or embodied agent) is capable of making at each instant, preferring to make gradual directional changes instead of abrupt turns. Constellation-agents are used by each vehicle to bias their motion to reflect such preferences.

(iii) Cast-zones and virtual bobber-agents are further used by each vehicle to generate suitable intermediate targets between the vehicle and their actual target on the queue. These intermediate targets are determined by the movement and convergence of the virtual bobber-agents in their associated cast-zones. The intermediate targets act as a more appropriate target for the vehicles by reducing the immediate need for sudden directional changes.

Remark 1. In this article, we are mainly concerned with formations involving embodied agents, which can be robots or autonomous vehicles, and would be referred to simply as ‘agents’ for the remainder of the article. This is distinguished from the virtual agents (i.e., virtual bobber-agents and virtual constellation-agents) that each of these vehicles is used for target determination and formation maintenance/tracking purposes.

Remark 2. In practice, there are two methods to get the postures and motions of other agents: (i) communication between agents, each agent broadcasts its states, such as velocity, position, and orientation, then other agents within its communication range can receive these information; and (ii) some sensors, such as sonar coupled with an infra-red (IR) sensor, laser scanner, camera and other motion detection sensors can be adopted to detect the postures and the motions of obstacles or other agents.

2. Q-structure representation

Formations are typically represented by graphs with each node corresponding to the exact position of a robot. On the other hand, the Q-structure puts emphasis on the appearance of the formation. It constrains the positions of robots in the formation, but does not dictate exact positions for them. A formation is described by the Q-structure, using queues and formation vertices as follows.

Definition 3 (*Formations [32]*). A formation is denoted by $\mathcal{F} = (\mathcal{Q}, \mathcal{V}_F(N_{tot}))$, where $\mathcal{Q}$ is the set of all the queues that make up the formation, and $\mathcal{V}_F(N_{tot})$ represents the set of formation vertices, V_i $(i = 1, \ldots, N_v)$, where N_{tot} is the total number of vehicles[1] and N_v is the number of formation vertices.

2.1. Incorporation of orientation information

In order to incorporate information regarding the desired orientation of agents in the final formation, an extra element, $\mathcal{O}_j$, is included in the definition of each queue. With this, each queue of a formation may be written as follows.

Definition 4 (*Queues*). A queue, $\mathcal{Q}_j \in \mathcal{Q}$, is denoted as $\mathcal{Q}_j = (\mathcal{V}_j, \mathcal{S}_j, \mathcal{C}_j, \mathcal{O}_j)$ and each of the elements that characterizes the queue is described as follows:

[1] Each formation vertex is defined in the coordinate frame of the target.