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Research paper

Collective circular motion in synchronized and balanced formations with second-order rotational dynamics

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ABSTRACT

This paper considers collective circular motion of multi-agent systems in which all the agents are required to traverse different circles or a common circle at a prescribed angular velocity. It is required to achieve these collective motions with the heading angles of the agents synchronized or balanced. In synchronization, the agents and their centroid have a common velocity direction, while in balancing, the movement of agents causes the location of the centroid to become stationary. The agents are initially considered to move at unit speed around individual circles at different angular velocities. It is assumed that the agents are subjected to limited communication constraints, and exchange relative information according to a time-invariant undirected graph. We present suitable feedback control laws for each of these motion coordination tasks by considering a second-order rotational dynamics of the agent. Simulations are given to illustrate the theoretical findings.

1. Introduction

There are various engineering applications such as tracking, surveillance, environmental monitoring, searching, sensing and data collection, where it is required for multi-agent systems to perform a particular collective motion [1–5]. A multi-agent system might comprise ground vehicles, air vehicles, underwater vehicles or a combination of these. In this paper, we focus on achieving collective circular motion that can be applied in the scenario where vehicles are required to enclose, capture, secure or monitor a target or a search region.

The central question in these applications is to design distributive control algorithms to drive the group of agents to a desired configuration in an autonomous manner. An interesting formation problem could be one, where agents are required to be uniformly distributed around a target location or around a region of interest to sense/collect data more effectively. The task is trivial if the agents are controlled individually to reach the pre-computed positions within the chosen formation. To solve such problems in this fashion, one would require a central controller that can gather all information and send commands to all agents of the group. The main disadvantage of this method is that one needs to design a new controller whenever the formation objectives change. All these issues limit the applicability of centralized control design methodology for practical applications. However, it would be more desirable to have the agents automatically arrange themselves in the desired formation while exchanging only relative or individual information [6].

Motivated by these applications and issues, in this paper, we study a problem where agents are not only required to move on a circle (or individual circles), but are also required to maintain a formation. In particular, the paper aims to study

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the collective motion where all the agents traverse i) different circles, or ii) a common circle at the prescribed angular velocity such that they are either in synchronized or in balanced formation. Synchronization refers to a situation when all the agents, at all times, move in a common direction. A complementary notion of synchronization is balancing, in which all the agents move in such a way that their positional centroid remains fixed. It is evident in synchronized formation that agents and their centroid move in the same direction. Note that, in this paper, “collective motion” and “collective formation” are used interchangeably.

There exists an ample literature related to the study of collective circular formation control. In [7], control laws are proposed to stabilize collective circular motion of nonholonomic vehicles around a virtual reference beacon, which is either stationary or moving. In [8], authors propose a distributed circular formation control law for ring-networked nonholonomic vehicles with local coordinate frames. In [9], Chen and Zhang propose a decentralized control algorithm to form a class of collective circular motion, in which the vehicles are evenly distributed over the motion circle, and have the same rotational radius. The latter assumption is relaxed in [10], where the agents move in circles around a common center, but with different radii. In [11] and [12], control algorithms to stabilize the collective motion around a circular orbit, which has either a fixed radius and time-varying center [11], or a fixed center and time-varying radius [12], are proposed. An extension of these results is given in [13], where a new framework based on affine transformations, to achieve more complex time-varying formations, is discussed. In [14], the splay circular formation, characterized by equally spaced arrangement of multiple robots, is stabilized by using a modified Kuramoto model [15]. The stabilization of circular motion under cyclic pursuit is given in the seminal paper [16]. In [17], a Lyapunov guidance vector field approach is used to guide a team of unmanned aircraft to fly a circular orbit around a moving target with prescribed inter-vehicle angular spacing. In [18], a control algorithm is developed such that a team of robots can spread evenly on the circle centered at a target at a desired radius. An interesting problem of boundary patrolling on a circle is studied in [19].

It is to be noted that in the above literature, considerable attention is given to the problem of achieving a particular type of collective circular formation in a multi-agent system. However, in the present work, a general problem pertaining to collective circular formation is discussed, where the agents are not only moving around a desired circular orbit (or individual circular orbits), but also maintain a synchronized or balanced formation. The controller design methodologies are further modified to achieve a combination of both synchronized and balanced formations (usually called as symmetric phase pattern), which can be put to good use in applications related to sensor networks. Moreover, these formations serves as motion primitives, and can be utilized to get more general motion patterns.

Earlier work in [20] and [21] has focused on achieving synchronized and balanced formations in a group of agents under all-to-all and limited communication scenarios, respectively. In these papers, it is considered that the angular velocities of initial rotations of all the agents are the same and remains constant at all times. However, unlike these works, in this paper, it is considered that the angular velocities of the initial rotational motion of the agents are nonidentical and can vary with time. In a similar context, the authors in [22], by assuming an all-to-all coupling among agents, propose feedback controls to stabilize synchronized and balanced circular formations at a desired angular velocity. However, in this paper, we further assume that the communication among agents is restricted and can be modeled as a time-invariant and undirected graph. Some related work, but with all-to-all communication, has been presented in [23].

The main contribution of this paper is to propose a limited communication based control strategy to stabilize aforementioned collective circular motion in a group of agents with their phase arrangements either in synchronized or in balanced formation, while allowing the angular velocities of individual, initial circular motions, performed by the agents, to be different. With this purpose, in this paper, we consider a multi-agent system where agents move in a planar space at constant unit linear speed, and are governed by second-order rotational dynamics. Thus, the dynamics of each agent is represented by a state vector, which includes the position, heading angle and angular velocity of each agent as its elements. The second-order rotational model is particularly relevant in the context of planar rigid-body motion, where a dynamic vehicle model must account not only for motion of the agent's center of mass, but also for rotational motion about the center of mass [22]. We use second-order rotational model to derive feedback controls that are adequate to regulate the orientations as well as the angular velocities of the agents.

The outline of the paper is as follows. In Section 2, we describe the system model and formulate the problem. In Section 3, control laws are proposed to stabilize collective motion of agents on different circles at desired angular velocity with their phase arrangement either in synchronized or in balanced formation. The control laws to stabilize collective motion around a common circle of desired radius as well as center with their phase arrangement, again either in synchronized or in balanced states, are proposed in Section 4. The control strategy to stabilize symmetric balanced patterns is proposed in Section 5. In Section 6, we combine the results of the previous sections and propose control algorithms to stabilize symmetric circular formations suitable for mobile sensor network applications. Finally, Section 7 concludes the paper.