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Time-varying formation control of a collaborative heterogeneous multi agent system

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HIGHLIGHTS

- A set of heterogeneous multi-agent systems is considered.
- The dynamics of different agents are studied.
- A virtual-leader structure is applied to the rigid formation.
- A time-varying formation is modeled.
- A Lyapunov based controller is proposed to achieve time-varying formation.

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ABSTRACT

In this paper, coherent formation control of a multi-agent system in the presence of time-varying formation is studied. For special application of rescue and surveillance, a set of agents, consisting of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) are considered. Due to different degrees of freedom of the UAVs and the UGVs, the collaboration between the agents confronts many problems. A Lyapunov based controller is presented to stabilize the swarming and lead the system to a rigid formation using decentralized control approach. In the proposed control signal of each agent, a signal of the neighbors' error is considered to cope with variation in performance and to provide synchronization, which means that the state error of the agents converges to zero nearly at the same time. The decentralized approach provides reliability of the performance in unknown environment, since the controller of each agent is designed based on local knowledge. This algorithm is evaluated in simulation and the results approve the accepted performance of the proposed approach.

1. Introduction

Multi-agent systems (MASs) include a group of robots which can collaborate together to accomplish complicated tasks that cannot be done by single agent. The applications of multi-agent systems are increasingly wide in many aspects of civilian domains, from rescue, surveillance to discovery. Enhancing the visibility zone by cooperating the UAVs with the UGVs is an important application of it. However, collaboration among multi agents with different dynamics has challenges in communication and behavior control.

The control strategy of a multi-agent system is developed based on centralized or decentralized algorithms. In central approaches, a central controller receives all required information and provides proper control signal for each agent. The mentioned algorithms rely on perfect communication and prone to fail due to connection failure or occurring fault in the controller [1,2]. In decentralized approaches, however, a local controller is designated for each agent and the control signals are provided by using local information of agents and their neighbors [3–5]. This approach is more robust on the communication failure and also the local processors stand less processing routines.

In the literature, three main approaches are introduced for formation control of multi-agent system. The most common form is *leader–follower* in which one agent is chosen as the leader that tracks the trajectory and the other agents should keep their distances from the leader and make the predefined formation. This method is easy. However, its main disadvantage is that the leader has no feedback from the followers and it may lead to instability when a fault occurs. Moreover, when the leader fails, the whole system will collapse [6–8]. Another structure is the *virtual* structure. It is similar to the leader–follower structure; however, the

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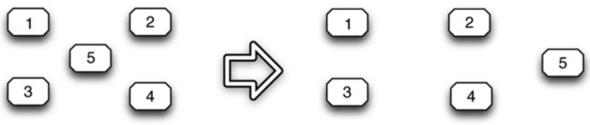

Fig. 1. Changing the formation due to coverage.

Fig. 2. Changing the formation for obstacle avoidance.

leader is virtual. Therefore, the leader never fails and the stability of the whole system is not depending on the leader [9–13]. The third structure is *behavioral* based method. It is based on the different behaviors that a single agent should perform in different situation. However, the computations of these methods are complicated [14].

Collaborative control is an interesting topic in robotics. Collaboration means, that no individual movement can profit up. Indeed, movement of all the agents should be in such a way that improves the whole performance of the system. A collaborative heterogeneous multi-agent system is one in which the agents dynamics can be different [15,16]. Few approaches have been reported in the field of heterogeneous MAS. In [17], targeting a UGV by UAVs is considered and a Lyapunov based approach is proposed. A problem of heterogeneous agents is considered in [18]. Stability of this scenario is studied in vicinity of central mass of UGVs. In [19], an excavation scenario consisting of UGVs and UAVs is considered and the agents shared their data about hazardous places, target, and obstacles position. In [20], a collaborative maneuver is considered in which, the UAV guides the UGVs in order to avoid the obstacles. This method is developed in [21] in which the swarming is robust. The main difference between this paper and the above papers is considering the rigid formation between the UGVs and the UAVs. None of the mentioned papers survey on the conditions that the heterogeneous systems can perform as one body, which means a rigid formation. In [22,23], a rigid 3D formation between the UGVs and the UAVs in the presence of velocity constraints and environmental disturbances was proposed, which are the two major problems in this research area. In this paper, the problem of time-varying formation is considered, which is another major problem for heterogeneous systems.

Time-varying formation means that a multi-agent system is able to change its formation in specific conditions without losing its stability. Changing the formation can be caused by two reasons:

1 Covering the greater part of the environment: In some application such as mapping an area, it is important that the multi-agent system has the ability to spread out or gather. Therefore, by having the ability to change the formation, the agents can successfully accomplish the predefined mission. In Fig. 1, an example of changing the formation is depicted.
   In Fig. 1, the fifth agent moves to a new position in the formation and by this action, the result is the coverage of greater part of area.
2 Moving along an obstacle: Changing the formation in case of facing an obstacle is a preferable way to avoid collision.
   In Fig. 2, the square formation is changed into the horizontal one in order to pass the obstacle.

In [24], the problem of varying formation due to the variation of connection graph is solved based on the differential game approach. The problem of coordinating multi agent systems is studied in [25] and a Lyapunov based controller is proposed to deal with the time-varying connection structure. Also, this problem is studied under condition of saturation limit on the control signal in [26]. None of the mentioned references propose a time-varying approach in Heterogeneous MAS.

Due to different work space and dynamics of the agents, there are some challenges in control of these systems. The differences may affect synchronized behavior of the agents. The synchronization means that the error of position and the velocity of the agents converge to zero approximately at the same time [27]. In [28], a synchronization approach is introduced to adapt the flying wings of UAV and also the approach introduced in [29] makes a formation under the virtual structure. In [30], a synchronized formation of a multi-agent system is considered in the presence of communication delay and is solved by synchronization approach.

In this paper, multi agent systems with different dynamics are synchronized in the presence of topology variation. Through this paper, a controller is proposed based on virtual leader structure to provide a rigid formation. Following the fact that the UAVs and UGVs can hardly cooperate, a decentralized controller based on a synchronization signal is designed to achieve a predefined formation. To accomplish this goal, a Lyapunov-based approach is employed to minimize the tracking error.

The rest of this paper is organized as follows: In Section 2, the dynamical model of the UGV and the UAV is given. In Section 3, the problem is stated and formulated in the virtual leader structure. In Section 4, a brief introduction on back-stepping approach is provided. The main contribution of this paper which is design a decentralized and synchronized controller is also provided in this section. The simulation results are presented in Section 5.

2. Dynamical models of heterogeneous MAS

Considering homogeneous agents makes designing the control signal less challenging comparing to heterogeneous agents, where each has different dynamics and constraints.

In this section, this challenge is illustrated for a system consists of some UGVs and UAVs. A model of two-wheeled mobile robot is considered as UGV and a quadrotor is used as the UAV.

A. *Mobile Robot*

Consider a group of N UGVs which the dynamical model of the ith UGV can be presented by 2-DOF point mass model as follows [31]:

$$\begin{aligned}
\dot{p}_{xi}(t) &= V_i(t)\cos\theta_i(t),\\
\dot{p}_{yi}(t) &= V_i(t)\sin\theta_i(t),\\
\dot{\theta}_i(t) &= \omega_i(t),\\
\dot{V}_i(t) &= \frac{F_i(t)}{M_{ri}},\\
\dot{\omega}_i(t) &= \frac{\tau_i(t)}{J_{ri}},
\end{aligned} \tag{1}$$

where $\mathbf{p}_i(t) = \begin{bmatrix} p_{xi}(t) & p_{yi}(t)\end{bmatrix}^\top$ denotes the position of the ith UGV. $V_i(t)$ is the linear velocity, $\omega_i(t)$ is the angular velocity, and $\theta_i(t)$ is the orientation of the ith UGV. M_{ri} and J_{ri} are the mass of mobile robot, and the moment of inertia. τ_i is the input torque of the mobile robot, and $F_i(t)$ is the force input.

Therefore, the control input for the ith mobile robot, $\mathbf{C}_{ri}(t)$, can be considered as below:

$$\mathbf{C}_{ri}(t) = \begin{bmatrix} F_i(t) & \tau_i(t)\end{bmatrix}^\top . \tag{2}$$

B. *Quadrotor*

In [32], a quadrotor is modeled by considering rigidness, and the symmetric shape of the whole body. However, by considering M quadrotors as the UAVs, the equation of ith UAV can be stated