Robotics and Autonomous Systems 74 (2015) 30–39

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Distributed motion misbehavior detection in teams of heterogeneous aerial robots

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HIGHLIGHTS

- A distributed misbehavior detection algorithm is proposed.
- The algorithm detects autonomous robots that violate agreed interaction rules.
- The algorithm is based on topologies-based consensus.
- The algorithm detects anomalies in high-level maneuvers.
- The algorithm has been successfully tested in a collision-avoidance scenario involving UAVs.

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
4 June 2015
Accepted 15 June 2015
Available online 13 July 2015

Keywords:
Multi robot coordination
Distributed misbehavior detection
Topologies-based consensus
Rule-based collision avoidance
UAV experiments

ABSTRACT

This paper addresses the problem of detecting possible misbehavior in a group of autonomous mobile robots, which coexist in a shared environment and interact with each other and coordinate according to a set of common *interaction rules*. Such rules specify what actions each robot is allowed to perform in order to interact with the other members of the group. The rules are distributed, i.e., they can be evaluated only starting from the knowledge of the individual robot and the information the robot gathers from neighboring robots. We consider *misbehaving* those robots which, because of either spontaneous failures or malicious tampering, do not follow the rules and whose behavior thus deviates from the nominal assigned one. The main contribution of the paper is to provide a methodology to detect such misbehavior by observing the congruence of actual behavior with the assigned rules as applied to the actual state of the system. The presented methodology is based on a consensus protocol on the events observed by robots. The methodology is fully distributed in the sense that it can be performed by individual robots based only on the local available information, it has been theoretically proven and validated with experiments involving real aerial heterogeneous robots.

1. Introduction

The availability of distributed systems gave rise in the late 80s to a profound rethinking of many decision making problems and enabled solutions that were impossible before. A similar trend is now happening in control and will soon enable a formidable number of new robotic applications. Various distributed control policies have been proposed for formation control, flocking, sensor coverage, and intelligent transportation (see e.g. [1–3]). The adoption of similar notions of decentralization and heterogeneity in Robotics is advantageous in many tasks, where a cooperation among agents with analogous or complementary capabilities is necessary to achieve a shared goal. More specifically, we are interested in distributed multi-agent systems where each agent is assigned with a possibly different private goal, but needs to coordinate its actions with other neighboring agents.

The flexibility and robustness of such distributed systems, and indeed their ability to solve complex problems, have motivated

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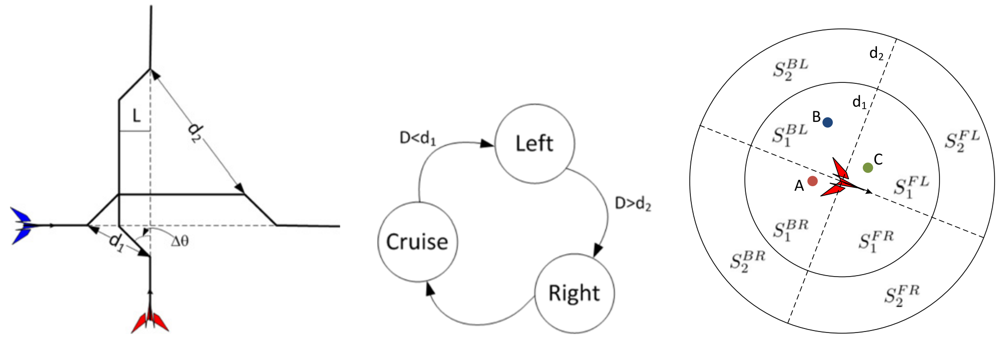
http://dx.doi.org/10.1016/j.robot.2015.06.008



(a) Evolution of aircraft based on the collision avoidance policy.

(b) Hybrid system associated to the collision avoidance policy.

(c) Sectors associated to each aircraft.

Fig. 1. Simplified version of collision avoidance strategy proposed in [15] reported in Example 1.

many works that have been presented in literature (see e.g., [4–9]). Although in most cases agents are modeled as identical *copies* of the same prototype, this assumption is often restrictive as the different agents that form a society may be implemented by different makers, and with different technologies etc. Heterogeneity in these artificial systems is advantageous when, for example, a problem requires interaction of agents with similar skills as well as agents with complementary capabilities. Most important, heterogeneity may be introduced to model the existence of malfunctioning agents, also called *intruders* [10,11]. The complexity needed to represent such behaviors can be successfully captured by hybrid models, in which a continuous-time dynamics describes the physical motion of each agent, while an event-based one describes the sequence of interactions with its neighbors.

This paper addresses the problem of detecting possible misbehavior in a group of autonomous robots, which coexist in a shared environment and interact with each other while coordinating according to a set of common *interaction rules*. The objective is to provide robots the capability of detecting agents whose behavior deviates from the assigned one, due to spontaneous failures or malicious tampering. The objective is ambitious and indeed very difficult to be achieved without a-priori knowledge of the interaction rules, but a viable solution can be found if the hybrid models describing the behavior is known in advance. The proposed methodology is fully distributed in the sense that it can be performed by individual robots based only on the local available information. It is based on a two-step process. First, agents combines the information gathered from on-board sensors and from neighbors by using communication and compute an a-priori prediction of the set of possible trajectories that the observed agent should execute based on the cooperative rules (*prediction phase*). Then, the predicted trajectories are compared against the one actually executed and measured by the observed robot itself and if none results close enough, the observed robot is selected as uncooperative (*verification phase*). The motion misbehavior detection ability of a single local monitor (used in the verification phase) is limited by its partial visibility. Robots need hence to combine the locally available information and reach an agreement on the reputation of the observed robot. To do this, we propose a Boolean consensus protocol that differs from those provided in [12–14]. Indeed, in this paper a consensus protocol on the events (more precisely on the encoder map defined in the following) observed by robots is proposed. In contrast to the other works, the consensus was on the reconstruction of the surrounding area of the observed robot [10]. In other words, we use the consensus to reconstruct the possible presence of a robot in an area that is not visible from all observing robots while in the other approaches a consensus protocol was used to reconstruct the robot position in the area. Hence, in our approach the computational cost is limited.

Although the proposed method is general and can be applied to a wide range of applications, it has been tested with experiments involving real aerial robots where the problem of detecting an intruder is fundamental for the safety of the system.

The paper is organized as follows. We start introducing in Section 2 a case study example to help the reader follow the notation introduced in Section 3 where the hybrid model of the proposed cooperation protocol is reported. The misbehavior detection problem is formally defined in Section 4. The Boolean consensus misbehavior detection strategy is described in Section 5 where the convergence in a finite number of steps is formally proved. Finally, Section 6 discusses a case-study and the related experimental results.

2. A case study example

In order to introduce the formal definitions and concepts of the paper we first start introducing a case study example that will be used to give an intuitive idea of the formalism introduced in next sections. The example is a simplified version of the collision avoidance strategy proposed in [15] and proved to be safe for two aircraft. The example has only illustrative purposes and by no means has to be intended as a description of a realistic UAV scenario.

Example 1. Consider two identical aircraft cruising at a given altitude with constant and equal linear velocity v. Aircraft can be represented by vector $(x, y, \theta) \in \mathbb{R}^2 \times S^1$. Referring to Fig. 1(a), each aircraft flies straight in *Cruise* mode until the other aircraft is detected at a distance closer than d_1. Whenever it occurs, it changes instantaneously its heading angle of amount $\Delta\theta$ and proceeds straight until a distance L from nominal trajectory is reached. Then, it changes its heading of amount $-\Delta\theta$ and proceeds straight (*Left* mode). As soon as the other aircraft is at distance larger than d_2 (where $d_1 < d_2$) the aircraft changes instantaneously its heading angle of amount $-\Delta\theta$ and proceeds straight until nominal trajectory is reached. Then, it changes its heading of amount $\Delta\theta$ (*Right* mode) and then switches to the *Cruise* mode.

Let $D(t)$ be the distance between the two aircraft at time t, the behavior of each aircraft is reported in Fig. 1(a) with a graphical representation of the associated hybrid model in terms of operating modes and switching conditions, see Fig. 1(b).

To describe the motion of aircraft based on those rules we may consider a configuration vector $(x, y) \in \mathbb{R}^2$ and the control input $\theta \in \{0, \pm\Delta\theta\}$ with kinematics equations

$$\begin{cases} \dot{x} = v\cos\theta \\ \dot{y} = v\sin\theta. \end{cases} \quad (1)$$