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Engineering Notes

Decentralized Receding Horizon Control for Cooperative Multiple Vehicles Subject to Communication Delay

Hojjat A. Izadi,* Brandon W. Gordon,† and Youmin Zhang‡
Concordia University, Montreal, Quebec H3G 1M8, Canada

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I. Introduction

IN this paper, a new approach is proposed for the decentralized receding horizon control (DRHC) of multiple cooperative vehicles with the possibility of communication failures leading to large intervehicle communication delay. Such large communication delays can lead to poor performance and even instability. The neighboring vehicles exchange their predicted trajectories at each sample time to maintain the cooperation objectives. It is assumed that the communication failure is partial in nature, which in turn leads to large communication delays of the exchanged trajectories. The proposed fault-tolerant DRHC is based on two extensions of existing work for the case of large communication delays. The first contribution is the development of a new DRHC approach that estimates the trajectory of the neighboring vehicles for the tail of the prediction horizon, which would otherwise not be available due to the communication delay. In this approach, the tail of the cost function is estimated by adding extra decision variables in the cost function. A relatively small amount of existing work has investigated the implementation issues associated with exchange of trajectory information, but so far no work has proposed a tail estimation process to compensate for large delays. For instance, in [1–3], no prediction or estimation for the trajectory of neighboring vehicles is performed, and it is assumed that the neighboring vehicles remain at the last delayed states broadcasted by them. Such assumptions may yield poor performance for large communication delays because the constant state vector is not a good estimation of a trajectory of states in general. Similar issues are also investigated in [4,5].

The second contribution of this paper is an extension of the tube-based model predictive control (MPC) approach [6,7] for the case of the large communication delays in order to guarantee the safety of the fleet against possible collisions during formation control problems. The concept of the tube MPC [or tube receding horizon control (RHC)] in existing work [6,7] is normally used to calculate a robust bound on the states due to system uncertainty, whereas in this paper, the approach is used to calculate bounds that arise from large communication delays of the exchanged neighbor trajectories.

The proposed algorithms in this paper are presented in the context of fault-tolerant control, as the communication delay/break may occur due to any failure and malfunction in the communication devices. Some examples of communication failures for the team of cooperative vehicles can be found in [8–10]. In [8], the wireless communication packet loss/delay is considered; once the packet loss/delay occurs, the previous available trajectory of the faulty unmanned aerial vehicle (UAV) is extrapolated to predict the future reference trajectory. Also, in [9], the communication failure in formation flight of multiple UAVs leads to a break in the communicated messages that forces the fleet to redefine the communication graph.

This paper is organized as follows. Section II deals with a general formulation of the decentralized receding horizon controller, and the corresponding algorithm for a fault-free (delay-free) condition. In Section III, a faulty condition is first defined, and a reconfigurable fault-tolerant controller is developed. A safety guarantee method for the faulty condition is also developed based on the concept of tube RHC. In Section IV, the proposed algorithms are tested through simulation of a leaderless formation controller for a fleet of unmanned vehicles.

II. Decentralized Receding Horizon Control Formulation

Consider a team of vehicles with uncoupled dynamics. Each vehicle in the team is equipped with measurement sensors, a communication channel, and a computation resource. Moreover, each vehicle has a dynamic model of its neighboring vehicles available to predict their trajectory when required. It is also assumed that there are no sensor errors, actuator errors, model uncertainty, or communication noise. These assumptions allow the paper to focus on the main problem of communication delays. However, it is thought that the proposed approach can be extended to the preceding cases by suitably modifying the tube calculation approach to account for these nonideal effects.

The following indirect graph topology [11,12] is used to present the interaction among vehicles:

$$G(t) = \{V, E\} \tag{1}$$

where V is the set of nodes (vehicles) and $E \subseteq VV$ is the set of arcs (i, j), with $i, j \in V$. Also, let N_n^i denote the number of neighbors of vehicle i.

A. Decentralized Receding Horizon Control Notation and Terminology

In RHC, a cost function is optimized over a finite time called the prediction horizon T. The first portion of the computed optimal input is applied to the plant during a period of time called the execution horizon δ or the sampling period. The reader is referred to [13] for a comprehensive review of RHC schemes.

It is assumed that the execution horizon δ is equal to the communication period. The discrete timing is then given by t_k, where $t_{k+1} = t_k + \delta$ (or $t_k = k\delta$) and $t_0 = 0$.

The possible state vectors are introduced as follows:

1) $x^i(t)$ is the actual state vector of the ith vehicle at time t.

2) $x_{t_k}^{j,i}(t)$ is the state vector of the jth vehicle at time t, computed (estimated) by the ith vehicle at time step t_k.

The state of vehicle i calculated by itself at time t_k is represented by $x_{t_k}^{i,i}(t)$ (predicted). Further, the sequence of these states over the prediction horizon is called the state trajectory of vehicle i calculated by itself and is represented by $x^i(t_k\colon t_k + T)$; for example

$$\begin{aligned} x^i(t_k\colon t_k + T) &= \{x_{t_k}^{i,i}(t) \mid t \in [t_k, t_k + T]\};\\ u^i(t_k\colon t_k + T) &= \{u_{t_k}^{i,i}(t) \mid t \in [t_k, t_k + T]\} \end{aligned} \tag{2}$$

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*Ph.D. Candidate, Mechanical and Industrial Engineering Department, 1515 St. Catherine. Student Member AIAA.

†Associate Professor, Mechanical and Industrial Engineering Department, 1515 St. Catherine.

‡Associate Professor, Mechanical and Industrial Engineering Department, 1515 St. Catherine. Senior Member AIAA.