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Networked Event-Based Collision Avoidance of Mobile Objects

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1 Introduction

The increase of air traffic with autonomous objects leads to the problem of a collision-free movement along their trajectories. The standard method for a distributed planning satisfying the requirement on collision avoidance and a certain distance for safety between the objects involves a high amount of communication or the presence of a coordinator in the network. This project proposes a networked-based method to ensure collision avoidance between two objects, which uses an event-based communication scheme and does not necessitate the activity of a coordinator.

Figure 1 shows the structure of the system to be investigated. Both controlled objects $\bar{P}_{\mathrm{L}}$, $\bar{P}_{\mathrm{F}}$ consist of a local controller C^*, which makes the objects follow their local reference trajectories $\boldsymbol{W}$. The trajectories are planned in the trajectory planning unit T_{L} and the collision avoidance unit A_{F}. These units are able to communicate over an unreliable network. The network properties are estimated by the network estimator N.

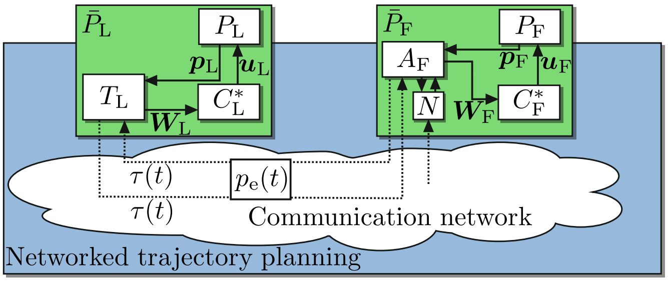

Figure 1: Structure of the networked control system.

2 Project aim

The following scenario is considered: Two quadrotors in a leader-follower structure move on circular trajectories as shown in Fig. 2.

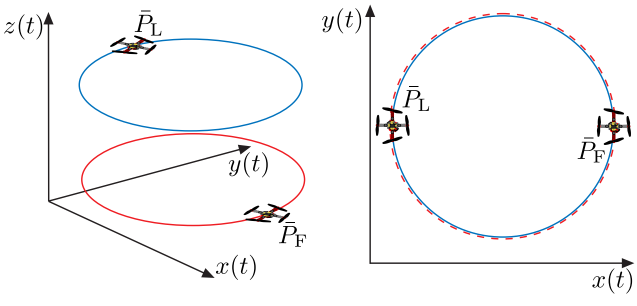

Figure 2: Scenario to be evaluated.

The leader follows its locally planned trajectory. It can change its trajectory at any time by varying the speed on the circular path or by changing the height of the circular movement. The follower moves on its own circular trajectory and it has to ensure a safety distance

$$s(t) = ||\boldsymbol{p}_{\mathrm{F}}(t) - \boldsymbol{p}_{\mathrm{L}}(t)|| \geq \bar{s}, \quad t \geq 0$$

and a height difference

$$z(t) = z_{\mathrm{F}}(t) - z_{\mathrm{L}}(t) \geq \bar{z}$$

between the quadrotors for collision avoidance with the leader. Communication should take place over an unreliable network with transmission delays and packet losses.

3 Event-based collision avoidance

For ensuring the collision-free movement, the follower is provided with an event-based collision avoidance unit shown in Fig. 3. Solid arrows depict a continuous signal transmission while the dashed arrows represent an event-based signal transfer. The parts of the unit execute the following tasks.

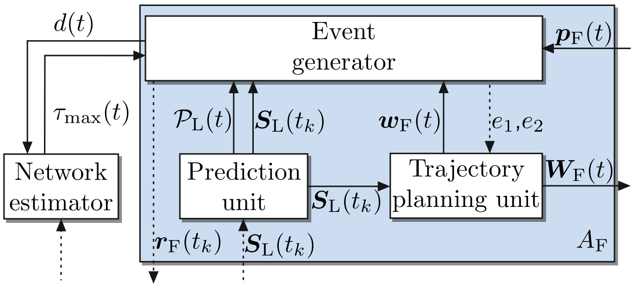

Figure 3: Structure of the event-based collision avoidance unit of the follower.

Network estimator. A channel estimation is performed at each event time t_k to estimate the current quality of service properties of the network. The variable estimated maximum transmission delay $\tau_{\max}(t)$ is passed to the event generator to consider it in the event generation.

Prediction unit. At an event time t_k the follower receives the leader information, which is passed to the event generator and the trajectory planning unit. The prediction unit generates a set $\mathcal{P}_{\mathrm{L}}(t)$, which includes all future leader positions as:

$$\boldsymbol{p}_{\mathrm{L}}(t_k) \in \mathcal{P}_{\mathrm{L}}(t), \quad t \geq t_k. \tag{1}$$

Event generator. The event generator triggers three types of events:

- Event e_0: Invoking of communication. The distance between the follower position $\boldsymbol{w}_{\mathrm{F}}(t)$ given by its trajectory and the set (1) is determined with

$$\mathrm{dist}(\boldsymbol{w}_{\mathrm{F}}(t), \mathcal{P}_{\mathrm{L}}(t)) = \min_{\boldsymbol{p}_{\mathrm{L}}(t) \in \mathcal{P}_{\mathrm{L}}(t)} (||\boldsymbol{w}_{\mathrm{F}}(t) - \boldsymbol{p}_{\mathrm{L}}(t)||).$$

The events are generated at times

$$e_0 : \quad t_{k+1} = \min_{t_k}\{\mathrm{dist}(\boldsymbol{w}_\mathrm{F}(t), \mathcal{P}_\mathrm{L}(t)) = \bar{s} + \bar{e}\} \tag{2}$$

at which the communication request $\boldsymbol{r}_\mathrm{F}(t_k)$ is sent, which includes all future event times. $\bar{e}$ denotes an appropriately chosen event threshold.

- Event e_1: Planning of an evasive trajectory. The distance between the leader trajectory and the follower trajectory is determined with

  $$\mathrm{dist}(\boldsymbol{w}_\mathrm{F}(t), \boldsymbol{w}_\mathrm{L}(t)) = ||\boldsymbol{w}_\mathrm{F}(t) - \boldsymbol{w}_\mathrm{L}(t)||, \quad \forall t,$$

  while the height difference is evaluated with

  $$\mathrm{dist}(w_{\mathrm{F,z}}(t), w_{\mathrm{L,z}}(t)) = |w_{\mathrm{F,z}}(t) - w_{\mathrm{L,z}}(t)|, \quad \forall t.$$

  If the condition

  $$e_1 : \begin{cases} \mathrm{dist}(\boldsymbol{w}_\mathrm{F}(t), \boldsymbol{w}_\mathrm{L}(t)) \leq \bar{s} + 2\,\bar{e} \\ \vee\, \mathrm{dist}(w_{\mathrm{F,z}}(t), w_{\mathrm{L,z}}(t)) \leq \bar{z} \end{cases} \tag{3}$$

  is fulfilled a collision threatens and the planning of an evasive trajectory is invoked.
- Event e_2: Planning of an emergency evasive trajectory. If the condition on the current distance between leader and follower is fulfilled

  $$e_2 : \quad \mathrm{dist}(\boldsymbol{p}_\mathrm{F}(t_k), \boldsymbol{p}_\mathrm{L}(t_k)) = ||\boldsymbol{p}_\mathrm{F}(t_k) - \boldsymbol{p}_\mathrm{L}(t_k)|| = \bar{s} + \bar{e}$$

  a collision threatens immediately and the planning of an emergency evasive trajectory is invoked.

Trajectory planning unit. The circular trajectories are planned based on piecewise Bézier curves. Due to the relative degree 4 of the quadrotors, trajectories of order $m = 9$ need to be planned. A Bézier curve of degree $m = n - 1$ is a polynomial

$$\boldsymbol{w}(t) = \sum_{i=0}^{m} \boldsymbol{b}_i \cdot B_i^m(t), \quad t \in [t_0, t_\mathrm{e}]$$

defined over the intervall $[t_0, t_\mathrm{e}]$ by n control points $\boldsymbol{b}_i \in \mathbb{R}^3$. The positions of the control points are determined by conditions on the trajectory at this point. The Bernstein polynomials $B_i^m(t)$, $(i = 1, \ldots, m)$ are given by

$$B_i^m(t) = \frac{1}{(t_\mathrm{e} - t_0)^m} \binom{m}{i} (t - t_0)^i (t_\mathrm{e} - t)^{m-i}, \; t \in [t_0, t_\mathrm{e}].$$

For the trajectory planning the circle is divided into four quarter circles. The endpoint of one quarter circle corresponds to the start point of the next one. The requirement of the C^4-continuity is ensured by fulfilling the conditions on the trajectory at this point.

The unit generates the matrix $\boldsymbol{W}_\mathrm{F}(t)$, which contains the reference variables for the local controller C_F^* to make the quadrotor follow the planned trajectory.

4 Example

An experiment illustrates the proposed method. In the scenario the leader starts from $\boldsymbol{p}_\mathrm{L}(0) = \begin{pmatrix}-0.7\,\mathrm{m} & -0.7\,\mathrm{m} & 2\,\mathrm{m}\end{pmatrix}^\mathrm{T}$ and moves on the blue circular trajectory with a radius of $r = 1\,\mathrm{m}$ as shown in Fig. 4. The follower starts from $\boldsymbol{p}_\mathrm{F}(0) = \begin{pmatrix}0.7\,\mathrm{m} & 0.7\,\mathrm{m} & 1\,\mathrm{m}\end{pmatrix}^\mathrm{T}$ and moves on the red circular trajectory with a radius of $r = 1\,\mathrm{m}$.

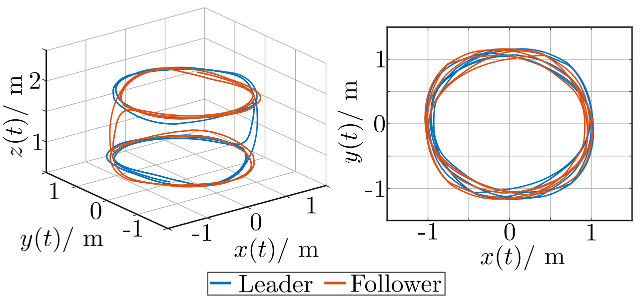

Figure 4: Trajectories of the leader and the follower.

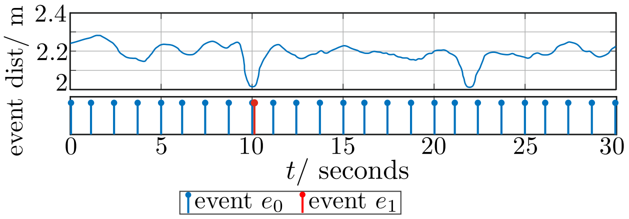

Figure 5: Distance between leader and follower.

After $t = 10\,\mathrm{s}$ the leader changes its height and continues moving in a height of $z = 1\,\mathrm{m}$. After $t = 22\,\mathrm{s}$ the leader returns on the height $z = 2\,\mathrm{m}$. The follower reacts by a replanning of its trajectory as shown in Fig. 4.

Figure 5 illustrates the distance $||\boldsymbol{p}_\mathrm{F}(t) - \boldsymbol{p}_\mathrm{L}(t)||$ between the objects. The blue beams in the lower part of the figure indicate the generation of the events e_0 with (2), the single red beam indicates the event e_1. In the case of the altitude change the distance decreases because the quadrotors are on the same height for a short amount of time so that the objects have only a distance of two times the radius of the circle between them. As the distance nearly stays constant the communication events occur almost equidistantly. Fig. 6 shows that the actuator limitations and the restrictions on the angles are satisfied all the time.

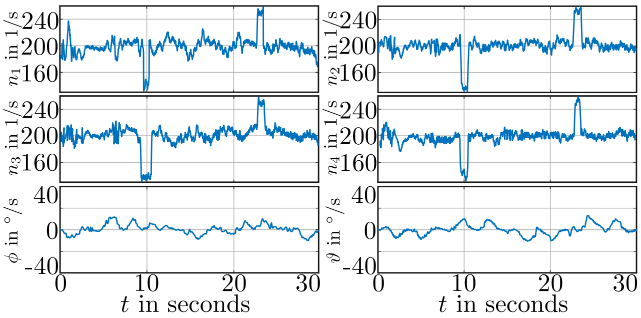

Figure 6: Rotor speeds and angles of the follower.

References

[1] M. Schwung, F. Hagedorn, and J. Lunze. Networked event-based collision avoidance of mobile objects. *European Control Conference*, pages 63–70, 2019.

[2] M. Schwung, Y. Karacora, J. Lunze, and A. Sezgin. Event-based quality-of-service parameter estimation of a wireless channel. *EBCSSP (submitted)*, 2020.

[3] M. Schwung and J. Lunze. Networked event-based control of moving objects with improved position estimation. *NECSYS*, pages 133–138, 2019.

[4] M. Schwung and J. Lunze. Experimental evaluation of an event-based collision avoidance method with application to quadrotors. *CCTA (submitted)*, 2020.