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Event-Based Collision Avoidance Utilising a Channel Estimation Method

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Abstract: This paper proposes a networked event-based method for collision avoidance of moving objects in a leader-follower structure. It extends the results of a previous paper to cope with communication constraints from an information theoretical perspective. The objects are locally controlled and connected by a communication network, in which transmission delays and packet losses occur. In the considered setting, the leader can freely change its trajectory while the follower has to avoid collisions by predicting the leader movement, invoking communication at event times that indicate a large uncertainty of the prediction result and adapting its trajectory appropriately. The current properties of the network are determined at each event time by a channel estimation method and are taken into account when generating events and planning the trajectory. In contrast to the existing literature, trajectories are adapted online where the collision-free movement is guaranteed despite of the limited communication by considering the network effects. A simulation study with two quadrotors shows that collisions can only be avoided if the results of the channel estimation are considered.

Keywords: Coordination of multiple vehicle systems, Control under communication constraints, Multi-agent systems

1. INTRODUCTION

This paper deals with the collision avoidance of two independent moving objects in a leader-follower structure, which are connected by an unreliable communication network. The goal is to avoid collisions even in the presence of transmission delays and packet losses of the network.

This problem is examined in the scenario shown in Fig. 2: The leader $\bar{P}_{\mathrm{L}}$ and the follower $\bar{P}_{\mathrm{F}}$ are moving on locally planned trajectories. The leader chooses its path without regard to the follower and may change its trajectory at any time, which makes its position uncertain for the follower. The follower has to avoid collisions by suitable avoidance manoeuvres. It uses the event-based method presented by Schwung and Lunze (2019a) to predict the uncertain leader movement as a time-varying set. Communication is only invoked at event times and the follower trajectory is replanned to avoid a collision if necessary.

The original method requires a perfect communication network in which the desired information is communicated instantaneously whenever an event occurs. Such a reliable and instantaneous information transfer between the moving objects cannot be guaranteed by real networks because the quality of service (QoS) of the communication channel changes due to the movement of the objects. In order to handle these limitations the method is extended by a network estimator N, which performs a channel estimation at the event times to obtain the current transmission delay and the packet loss rate of the channel, which are used to adjust the data transmission dynamically. The results of the channel estimation are used for the event generation and the planning of an avoidance manoeuvre.

The main result of this paper combines these methods from communication theory and control theory to guarantee the collision-free movement of objects. Communication is only required at event times.

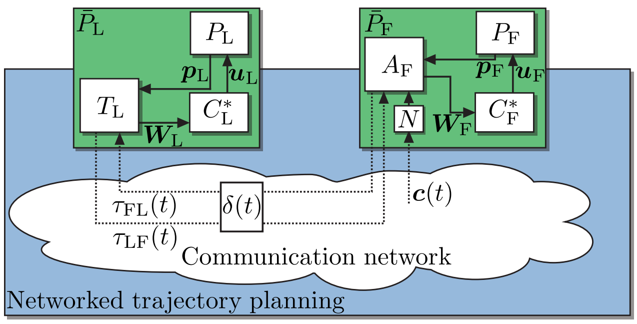

Fig. 1. Structure of the networked control system.

Figure 1 shows the structure of the networked leader-follower system. The objects $(\bar{P}_{\mathrm{L}}, \bar{P}_{\mathrm{F}})$ are independently controlled by local controllers $(C_{\mathrm{L}}^*, C_{\mathrm{F}}^*)$, which make the objects follow the local trajectories. The leader trajectory is planned in the trajectory planning unit T_{L}. The follower is provided with an event-based unit A_{F}, which ensures collision avoidance by considering the network effects $\boldsymbol{c}(t)$ estimated by the network estimator N and an appropriate planning of the follower trajectories. The units T_{L} and A_{F}

are able to communicate over the communication network if necessary. The data sent can be delayed by a variable time $\tau(t)$ or it can get lost.

Literature. The proposed approach combines a collision avoidance method as introduced by Schwung et al. (2019a) with an event-based communication scheme over an imperfect communication network.

The problem of collision avoidance has been explored with several approaches including methods based on speed adjustment (Mehdi et al., 2017), collision states (Fraichard and Asama, 2003) and reachable sets (Lin and Saripalli, 2015). Roelofsen et al. (2015) used a visual detection method with navigation functions to achieve collision avoidance.

To overcome transmission delays and packet losses of networks many approaches have been developed. Yoo and Johansson (2017) applied a machine learning technique to compensate random delays. A hybrid system framework has been stated by Heemels et al. (2010) that incorporates communication constraints, varying transmission intervals and varying delays to guarantee stability based on Lyapunov functions. Cuenca et al. (2019) proposed a periodic event-triggered sampling method to reduce the network utilisation. A slotted transmission classification model has been developed by Linsenmayer et al. (2019) for a communication abstraction. In Abichandani et al. (2011) and Beard and McLain (2003) collision avoidance under communication constraints has been adressed. Both approaches use a communication technique with a limited range but do not consider delays or packet losses.

All the mentioned approaches consider either the collision avoidance or deal with the stabilisation of a system over an imperfect communication channel. In contrast, this paper uses an online estimate of the properties of the imperfect communication channel for the event generation to guarantee collision avoidance. It uses information theoretical analyses to improve the control theoretical method.

Structure of this paper. The problem statement is stated in Section 2. The communication network is presented in Section 3. In Section 4 the event-based collision avoidance unit of the follower is illustrated. The event generation and the communication method are stated in Section 5. The method is illustrated by simulation results in Section 6.

2. PROBLEM STATEMENT

The problem to be investigated is depicted in Fig. 2 for two quadrotors. The leader $\bar{P}_\mathrm{L}$ follows its planned trajectory from a start point $S_\mathrm{A,L}$ to a destination $S_\mathrm{B,L}$. It can change its trajectory at any time as depicted as dotted line in the lower part of Fig. 2. The follower moves on its trajectory from a start point $S_\mathrm{A,F}$ to a point $S_\mathrm{B,F}$. It has to change its trajectory if necessary to satisfy the requirement

$$s(t) = ||\boldsymbol{p}_\mathrm{F}(t) - \boldsymbol{p}_\mathrm{L}(t)|| \geq \bar{s}, \quad t \geq 0 \tag{1}$$

for collision avoidance. Nevertheless, the follower has to reach its destination. $\boldsymbol{p}_\mathrm{L}(t)$ and $\boldsymbol{p}_\mathrm{F}(t)$ denote the leader position and the follower position, respectively. The following assumption is made:

Assumption 1. The speed of the leader and of the follower $\boldsymbol{v}_\mathrm{L}(t)$ and $\boldsymbol{v}_\mathrm{F}(t)$ have known upper bounds:

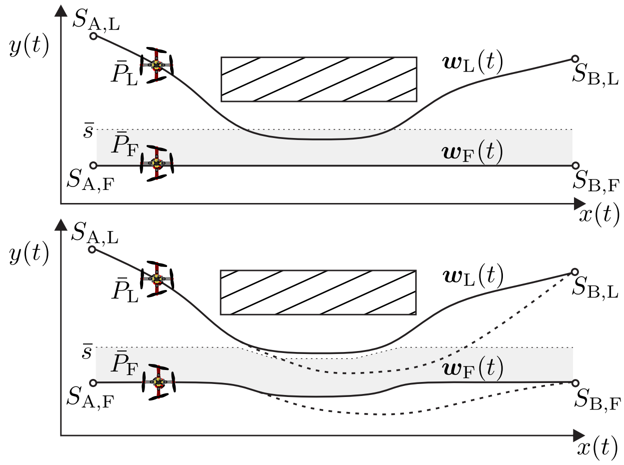

Fig. 2. Problem to be investigated.

$$||\boldsymbol{v}_\mathrm{L}(t)|| \leq v_\mathrm{L,max},\ ||\boldsymbol{v}_\mathrm{F}(t)|| \leq v_\mathrm{F,max},\ \text{and}\ v_\mathrm{L,max} \leq v_\mathrm{F,max}.$$

In order to achieve the collision-free movement, the follower executes the following four tasks:

(1) estimate the current QoS parameters,
(2) estimate the uncertain leader position $\boldsymbol{p}_\mathrm{L}(t)$,
(3) generate events with an event threshold $\bar{e}$ by considering the results of the network estimator and exchange information with the leader,
(4) replan the follower trajectory if necessary.

The proposed method should ensure the safety distance as stated in eqn. (1) by generating events with an appropriately chosen event threshold $\bar{e}$, which takes the transmission delays and packet losses into account.

3. COMMUNICATION NETWORK

The objects are connected through a communication network, which provides the communication channel for a data exchange between leader and follower as depicted in Fig. 3. The communication over the network is packet based in the sense that only discrete packages containing a finite amount of data are sent across the network at certain instants of time. Networked communication induces inherent imperfections such as time-varying transmission delays or packet losses. This means that a transmission sent by an object at time t_k is received by the other object after a delay $\tau(t)$ at time $t_k + \tau(t)$ or never.

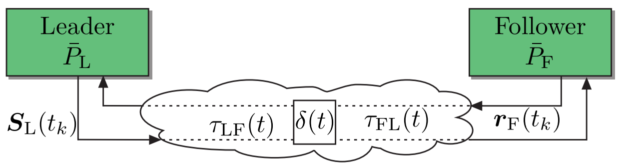

Fig. 3. Communication structure.

The connection between two objects is established automatically once the objects are in the transmission range of one another. The properties of the channel are variable and unknown to the objects due to their motion. Hence, a network estimator N is introduced to get upper bounds by a channel estimation at an event time for the quality of service (QoS) parameters, which include the transmission delay, the packet loss probability and the achievable data rate. These parameters are combined in the vector $\boldsymbol{c}(t)$ and taken into account in the collision avoidance method in order to generate communication events early enough to ensure the collision-free movement.

The channel capacity $C(t)$ describes the maximum data rate at which information can be transmitted without errors over a channel. It depends on the available bandwith $B(t)$ and the signal-to-noise-ratio SNR(t):

$$C(t) = B(t) \cdot \log_2(1 + \mathrm{SNR(t)}).$$

Based on the capacity, the data transmission scheme is adapted dynamically in order to maximize the QoS.

The transmission delay depends on the achievable capacity of the channel and the current distance between the objects. This distance can change considerably between two event times due to the movement of both vehicles. Hence, the transmission delay varies over time. The network estimator provides a time variable upper bound $\tau_{\max}(t)$ for this delay.

Assumption 2. The transmission delays $\tau(t)$ have a known upper bound:

$$0 \leq \tau(t) \leq \tau_{\max}(t).$$

Randomly, there might occur packet losses, for example due to possible collisions with packets from other devices communicating over the same network. Based on the last channel estimate the network estimator generates a time variable upper bound $\delta_{\max}(t)$ for the number of consecutive packet losses.

Assumption 3. A packet is considered to be lost if it has not been received by an object within the time $\tau_{\max}(t)$. The number $\delta(t)$ of consecutive packet losses is bounded:

$$0 \leq \delta(t) \leq \delta_{\max}(t), \quad \delta_{\max}(t) \in \mathbb{N}.$$

The estimated transmission delay is composed of a fixed time for the channel estimation and a dynamic time for the amount of data to be transmitted and depends on the current quality of service of the network. The more data are sent, the larger is the delay. Hence, the upper bounded transmission delay of the communication link from the follower to the leader is time variable and given by

$$\tau_{\mathrm{FL}}(t) = \tau_{\mathrm{c}} + \tau_{\mathrm{DF}}(t).$$

The data transmission from the leader to the follower is delayed by

$$\tau_{\mathrm{LF}}(t) = \tau_{\mathrm{c}} + \tau_{\mathrm{DL}}(t).$$

Thereby, τ_{c} describes the time which is required for the channel estimation, while $\tau_{\mathrm{DF}}(t)$ and $\tau_{\mathrm{DL}}(t)$ denote the variable times for the transmission of the data of the follower and the leader, respectively. The channel is assumed to stay constant within a short time frame, so that the channel estimation must only be performed once at each event time. After that the delay only depends on the amount of data to be transmitted. The times for generating the information to be sent and for planning the trajectories of the leader and the follower are small compared to the delay times caused by the network. Therefore, these times are neglected.

4. EVENT-BASED COLLISION AVOIDANCE UNIT

The four tasks to ensure a collision-free movement stated in section 2 are performed by the event-based collision avoidance unit of the follower depicted in Fig. 4. Continuous signal transmissions are represented by solid arrows, whereas dashed arrows depict event-based signal transfers. Each part of the unit executes one task:

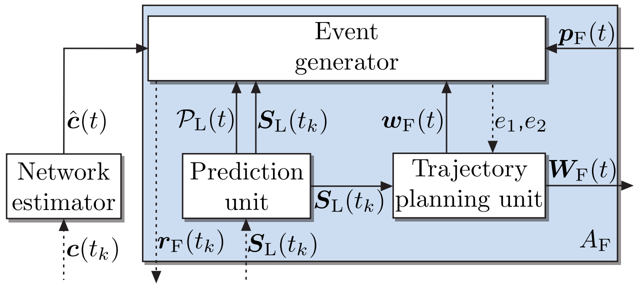

Fig. 4. Structure of the event-based collision avoidance unit A_{F} of the follower.

1) Network estimator: The channel estimation described in section 3 is performed at each event time to estimate the current quality of service properties $\boldsymbol{c}(t_k)$ of the network. These time variable estimated properties $\hat{\boldsymbol{c}}(t)$ are passed to the event generator to take the current QoS of the network into account in the event generation.

2) Prediction unit: As the leader can change its trajectory at any time, it can deviate from the planned trajectory that has been communicated to the follower. At an event time t_k the leader sends the matrix $\boldsymbol{S}_{\mathrm{L}}(t_k)$ to the follower, which is composed of the leader trajectory and its current position $\boldsymbol{p}_{\mathrm{L}}(t_k)$ and speed $\boldsymbol{v}_{\mathrm{L}}(t_k)$. This information is passed to the trajectory planning unit in order to calculate the trajectory of the follower. As the leader may change its trajectory at any time, its position is uncertain and the prediction unit generates a set $\mathcal{P}_{\mathrm{L}}(t)$ based on the position $\boldsymbol{p}_{\mathrm{L}}(t_k)$ and speed $\boldsymbol{v}_{\mathrm{L}}(t_k)$ of the leader, which includes all possible future leader positions:

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

In the event generator this set is used to generate the next event times.

3) Event generator: The decision when to invoke communication and when it is necessary to adapt the follower trajectory is made by the event generator. The event generator examines the distance between the communicated leader trajectory $\boldsymbol{w}_{\mathrm{L}}(t)$ and the follower trajectory $\boldsymbol{w}_{\mathrm{F}}(t)$ to identify possible future collisions as well as the distance between the set $\mathcal{P}_{\mathrm{L}}(t)$ of leader positions and the current follower position $\boldsymbol{p}_{\mathrm{F}}(t)$ to determine whether the leader deviated from its trajectory and thus a collision threatens immediately.

Three types of events are triggered, which are described in more detail in the next section:

(1) **Event e_0:** invoke communication.
(2) **Event e_1:** plan an evasive trajectory to avoid a future collision.
(3) **Event e_2:** plan an emergency evasive trajectory to avoid an imminent collision.

The follower invokes communication by sending the request $\boldsymbol{r}_{\mathrm{F}}(t_k)$, which is described in the following section.

4) Trajectory planning unit: The replanning of the follower trajectory $\boldsymbol{w}_{\mathrm{F}}(t)$ is executed in the trajectory planning unit depending on which event is triggered. When event e_1 is triggered, an evasive trajectory is planned so that a detected future collision is avoided. If event e_2 is generated, a collision threatens immediately and an emergency evasive trajectory is planned that exploits the actuator limitations of the object.

The unit generates the matrix $\boldsymbol{W}_{\mathrm{F}}(t)$, which contains the reference variables for the controller C_{F}^{*} to obtain the trajectory following.

Methods for the prediction of the leader movement and the trajectory replanning of the follower have been described in detail by Schwung and Lunze (2019a), while this paper focusses on the event generation for an imperfect communication network.

5. EVENT GENERATION IN THE PRESENCE OF TRANSMISSION DELAYS

5.1 Invoking communication

The method proposed in this paper differs significantly from methods used in earlier works. By considering the network induced effects the event generation must be improved in comparison to the method presented by Schwung and Lunze (2019a) to deal with transmission delays and packet losses. In order to reduce the communication effort the follower sends an extended request as a vector

$$\boldsymbol{r}_{\mathrm{F}}(t_{\mathrm{c},k}) = \left(t_{\mathrm{c},k}\ t_{\mathrm{c},k+1}\ t_{\mathrm{c},k+2}\ \ldots\right)^{\mathrm{T}}, \tag{2}$$

which contains all predicted future times at which communication must be invoked to ensure that the information is available at the event time t_k. These event times are determined based on the communicated leader trajectory as described in the next section. The request (2) is only sent at an event time that indicates that the leader trajectory or the follower trajectory has changed. Sending the extended request (2) prescribes the leader when to send the next information. This request reduces the communication effort and the transmission delay induced by the network as shown in the next section.

Furthermore, the method is extended to ensure the collision-free movement in the event of a packet loss by performing an appropriate emergency evasive manoeuvre.

5.2 Events

The events generated by the event generator have the following effects.

1) Event e_0**:** The event e_0 is generated whenever the uncertainty about the leader movement has become so large that new leader information must be communicated.

At $t = 0$ the initial event is generated by the follower to obtain the initial trajectory $\boldsymbol{w}_{\mathrm{L}}(t)$ of the leader. Based on $\boldsymbol{w}_{\mathrm{L}}(t)$ the event generator determines all future event times t_k, $(k \in \mathbb{N})$ at which new leader information are required if the leader follows its trajectory.

For the determination of these times the set $\mathcal{P}_{\mathrm{L}}(t)$ is generated with the method developed by Schwung and Lunze (2019b). To obtain the next event time t_{k+1} the set $\mathcal{P}_{\mathrm{L}}(t)$ is generated based on the position $\boldsymbol{p}_{\mathrm{L}}(t_k)$ and the speed $\boldsymbol{v}_{\mathrm{L}}(t_k)$. For the further future event times t_{k+i}, $(i = 2, \ldots, N)$ the set is generated using the position $\boldsymbol{w}_{\mathrm{L}}(t_{k+i-1})$ and the speed $\dot{\boldsymbol{w}}_{\mathrm{L}}(t_{k+i-1})$ given by the communicated leader trajectory at one predicted event time t_{k+i-1} before. An event e_0 is generated and a collision threatens if the condition

$$\mathrm{dist}(\boldsymbol{p}_{\mathrm{F}}(t), \mathcal{P}_{\mathrm{L}}(t)) = \min_{\boldsymbol{p}_{\mathrm{L}}(t) \in \mathcal{P}_{\mathrm{L}}(t)} \left(||\boldsymbol{p}_{\mathrm{F}}(t) - \boldsymbol{p}_{\mathrm{L}}(t)||\right) = \bar{s} + \bar{e} \tag{3}$$

is satisfied at an event time

$$t_{k+1} = \min_{t > t_k} \left\{\mathrm{dist}(\boldsymbol{p}_{\mathrm{F}}(t), \mathcal{P}_{\mathrm{L}}(t)) = \bar{s} + \bar{e}\right\}$$

Then, the follower requires the current leader information $\boldsymbol{S}_{\mathrm{L}}(t_k)$.

This method is depicted in Fig. 5, in which the trajectories of the leader and the follower and the generation of the set $\mathcal{P}_{\mathrm{L}}(t)$ are shown. The safety distance $\bar{s}$ together with the event threshold $\bar{e}$ is marked as a dotted line. The predicted event times are depicted as black beams in the lower part of the figure. The black dots mark the leader positions at the event times if the leader moves on its trajectory.

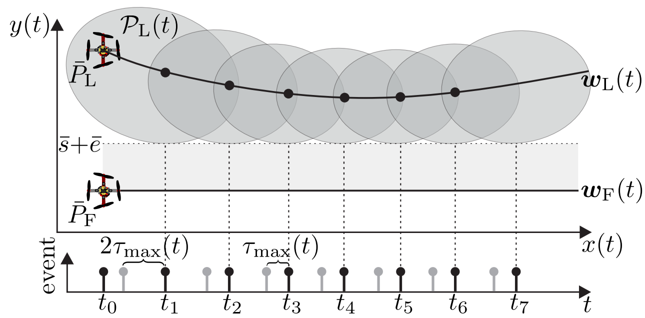

Fig. 5. Method for determining the event times.

The computation of the event threshold $\bar{e}$ can be found in (Schwung and Lunze, 2019a). The threshold is calculated in a way that it is ensured that the follower has sufficient time and space to avoid the leader while maintaining the safety distance $\bar{s}$. At the event times, the information of the leader must be available to the follower instantaneously. For a network with transmission delays, communication must be invoked earlier so that the information is available at the event times. Communication for the first event is invoked at the time

$$t_{\mathrm{c},1} = \min_{t > 0} \left\{\mathrm{dist}(\boldsymbol{p}_{\mathrm{F}}(t), \mathcal{P}_{\mathrm{L}}(t)) = \bar{s} + \bar{e}\right\} - 2\,\tau_{\max}(t) \tag{4}$$

marked as a grey beam in Fig. 5. The follower sends a request $\boldsymbol{r}_{\mathrm{F}}(t_{\mathrm{c},k})$ described by eqn. (2) to obtain the current and future leader data $\boldsymbol{S}_{\mathrm{L}}(t_k)$. As communication is invoked earlier by the worst case time $2\,\tau_{\max}(t)$, which includes the time for the channel estimation and the transmission of the follower request and the leader data, it is ensured that the follower receives the requested information at the event time. The upper bounded transmission delay $\tau_{\max}(t)$ is determined online by the network estimator. Communication for the further events is invoked at the times $t_{\mathrm{c},k+1}$, $(k = 1, \ldots, N)$:

$$t_{\mathrm{c},k+1} = \min_{t > t_k} \left\{\mathrm{dist}(\boldsymbol{p}_{\mathrm{F}}(t), \mathcal{P}_{\mathrm{L}}(t)) = \bar{s} + \bar{e}\right\} - \tau_{\max}(t), \tag{5}$$

As the leader sends its information autonomously at the predicted event times the maximum delay of the communication is reduced and the event can be generated closer to the event time.

2) Event e_1**:** The event e_1 induces a planning of an evasive trajectory of the follower in the collision area to avoid the collision as described in Schwung and Lunze (2019a).

Initially at time $t = 0$ the distance between the trajectories of the leader and the follower is determined with

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

If the condition

$$\mathrm{dist}(\boldsymbol{w}_\mathrm{F}(t), \boldsymbol{w}_\mathrm{L}(t)) \leq \bar{s} + 2\,\bar{e} \tag{6}$$

is satisfied, a possible future collision is detected and the event is generated.

Condition (6) is only checked at an event time t_k and events are generated if the leader trajectory or the follower trajectory has changed to reduce the computation effort.

3) Event e_2**:** The event e_2 invokes a planning of an emergency evasive trajectory, which exploits the actuator limitations to avoid an imminent collision as shown in Schwung and Lunze (2019a). The event is generated by two conditions:

1) After reception of the leader information at an event e_0 the current distance between the leader and the follower is evaluated with

$$\mathrm{dist}(\boldsymbol{p}_\mathrm{F}(t_k), \boldsymbol{p}_\mathrm{L}(t_k)) = ||\boldsymbol{p}_\mathrm{F}(t_k) - \boldsymbol{p}_\mathrm{L}(t_k)||.$$

If the condition

$$\mathrm{dist}(\boldsymbol{p}_\mathrm{F}(t_k), \boldsymbol{p}_\mathrm{L}(t_k)) = \bar{s} + \bar{e} \tag{7}$$

is fulfilled, the leader deviated from its primary trajectory and a collision threatens immediately.

2) Due to a packet loss no information about the leader position is available, so it is supposed that a collision might be imminent.

5.3 Handling of packet losses

A packet is considered to be lost if the object that sent the data does not receive an acknowledgement or an equivalent other information within a time interval.

In the case of a packet loss, the leader sends the data $\boldsymbol{S}_\mathrm{L}(t_k)$ to the follower again. The follower receives this data after the transmission delay $\tau_\mathrm{LF}(t)+\tau_\mathrm{DF}(t)+\tau_\mathrm{DL}(t)$, because the leader waits the time $\tau_\mathrm{DF}(t)$ for the acknowledgement. The retransmission of the information lasts the time interval $\tau_\mathrm{DL}(t)$, since the channel has already been estimated. Similarly, if a request $\boldsymbol{r}_\mathrm{F}(t_k)$ sent by the follower gets lost, the request is sent to the leader again after the time interval $\tau_\mathrm{FL}(t) + \tau_\mathrm{DL}(t)$ if no data has been received.

As no exact information about the leader position is known to the follower if a packet gets lost as indicated by a red flash in Fig. 6, the worst-case scenario must be assumed that a collision of the objects threatens. Automatically the event e_2 is generated. Due to the packet loss the leader information is not available at the event time, but in the worst-case scenario the time span $2\,\tau_\mathrm{max}(t)$ later. The leader can cover the distance

$$d_\mathrm{L} = ||\boldsymbol{v}_\mathrm{L,max}|| \cdot 2\,\tau_\mathrm{max}(t) \tag{8}$$

towards the follower in this time interval, as shown in Fig. 6.

The follower plans an emergency evasive trajectory to increase the distance to the leader in the time interval $2\,\tau_\mathrm{max}(t)$ by d_L and to maintain the safety distance $\bar{s}$ between the objects. After receiving the information from the leader either the follower returns to its former trajectory when the leader is still on its trajectory or an evasive trajectory is planned when the leader changed its trajectory.

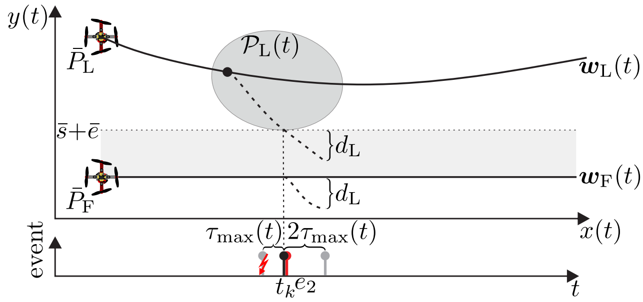

Fig. 6. Reaction of the follower after packet losses.

If several consecutive packets get lost, the method described above is carried out multiple times.

5.4 Execution of the communication protocol

The execution of the communication protocol described in the last sections is shown in the flow chart in Fig. 7. Leader and follower are indicated by 'L' and 'F', respectively. The transmission delays or the times when communication is invoked are written at the arrows. The protocol is split in an initialisation phase and a execution phase. In the initialisation phase the follower sends a request to the leader to obtain its initial trajectory. The follower confirms the receipt of the data by sending an acknowledgement (ACK).

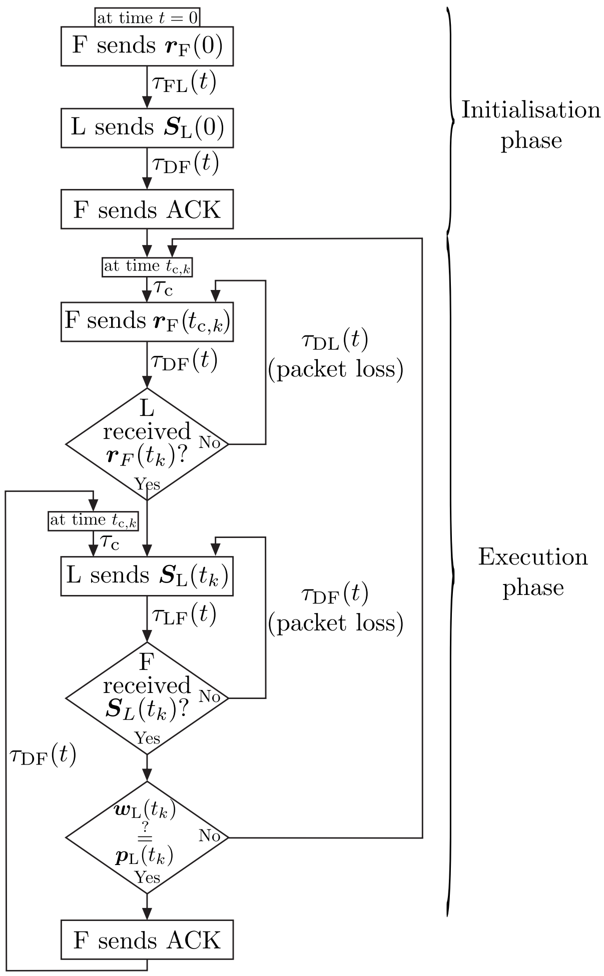

Fig. 7. Communication flow of the collision avoidance method.

After this initialisation phase the follower predicts the future event times and sends them with a request $\boldsymbol{r}_{\mathrm{F}}(t_{\mathrm{c},k})$ to the leader before the first event time. If the leader does not respond within the time span $\tau_{\mathrm{DL}}(t)$ the request is considered to be lost and is sent again. Otherwise the leader responds by sending its current data $\boldsymbol{S}_{\mathrm{L}}(t_k)$ and waits for an acknowledgement from the follower. If the leader does not receive the acknowledgement after the delay time $\tau_{\mathrm{DF}}(t)$ it sends the data again, because the previously sent data is considered to be lost.

If the follower received the data it checks whether the leader is at the predicted position. If this is the case, the follower sends an acknowledgement and waits for the leader information at the next predicted event time t_{k+1}. On the other hand if the leader deviated from its trajectory as $\boldsymbol{w}_{\mathrm{L}}(t_k) \neq \boldsymbol{p}_{\mathrm{L}}(t_k)$ or the future leader trajectory $\boldsymbol{w}_{\mathrm{L}}(t)$, $(t > t_k)$ has changed or the follower changed its future trajectory $\boldsymbol{w}_{\mathrm{F}}(t)$, $(t > t_k)$, the follower determines new future event times and sends these as a request $\boldsymbol{r}_{\mathrm{F}}(t_{\mathrm{c},k})$ to the leader. After that the leader sends its data $\boldsymbol{S}_{\mathrm{L}}(t_{k+1})$ at the next predicted time.

The advantage of sending future event times is a reduction of the communication effort. As the leader sends the data at the predicted times automatically, the follower does not have to send a request at all event times.

The method for collision avoidance using an unreliable communication network is summarised in the following algorithm.

Algorithm 1. Collision avoidance algorithm

Given: $\boldsymbol{p}_{\mathrm{F}}(t)$, $\boldsymbol{w}_{\mathrm{F}}(t)$, $\boldsymbol{p}_{\mathrm{L}}(t_k)$, $\boldsymbol{w}_{\mathrm{L}}(t)$, $\hat{\boldsymbol{c}}(t)$, $\bar{s}$, $\bar{e}$

(1) **If** $t = 0$ or $\boldsymbol{w}_{\mathrm{L}}(t_k) \neq \boldsymbol{p}_{\mathrm{L}}(t_k)$ or change of $\boldsymbol{w}_{\mathrm{L}}(t)$ or $\boldsymbol{w}_{\mathrm{F}}(t)$:
- follower generates set $\mathcal{P}_{\mathrm{L}}(t)$ with the method from Schwung and Lunze (2019b) over the entire time interval.
- follower checks condition (3).
- follower determines future times to invoke communication with (4), (5).
- follower sends request $\boldsymbol{r}_{\mathrm{F}}(t_{\mathrm{c},k})$ as (2).

(2) **If** $t = t_{\mathrm{c},k}$, $(k \in \mathbb{N})$ given by (5):
- leader sends information $\boldsymbol{S}_{\mathrm{L}}(t_k)$.

(3) **If** condition (6) is satisfied:
- follower generates event e_1.
- follower plans an evasive trajectory with the method of Schwung and Lunze (2019a).

(4) **If** condition (7) is fulfilled:
- follower generates event e_2.
- follower plans an emergency evasive trajectory with the method of Schwung and Lunze (2019a).

(5) **If** packets get lost:
- follower generates event e_2.
- follower sends $\boldsymbol{r}_{\mathrm{F}}(t_{\mathrm{c},k})$ again or the leader sends $\boldsymbol{S}_{\mathrm{L}}(t_k)$ again autonomously.
- follower plans an emergency evasive trajectory to avoid the leader about the distance (8).

Result: Collision-free movement of the networked objects.

5.5 Comparison to previous methods

The following tabular comparison of the method proposed in this paper with the earlier method of Schwung and Lunze (2019a) shows the improvements with the handling of network induced imperfections. In section 6 it is demonstrated that the collision-free movement of the objects can only be achieved by using the extended method.

	Method by Schwung and Lunze (2019a)	Method proposed in this paper
Event generation	based only on the current predicted leader movement in relation to the follower movement	predicts all future event times; takes transmission delays into account in event generation
Packet losses	are not considered; information must be available at event times	can be handled with a suitable emergency evasive manoeuvre

6. SIMULATION RESULTS

Two identical quadrotors are used in this paper for a simulation study. A quadrotor has six degrees of freedom, which allows it to move in 3D space by controlling the individual rotor speeds n_i, $(i = 1, \ldots, 4)$ of the four motors. The schematic structure and the degrees of freedom of such an unmanned aerial vehicle (UAV) are shown in Fig. 8.

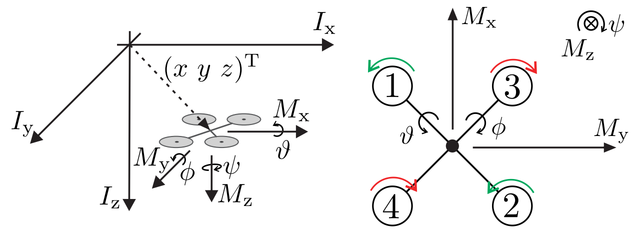

Fig. 8. Schematic structure of the quadrotor.

The derivation of the model can be found in (Schwung et al., 2019b).

Three scenarios are investigated with two quadrotors to illustrate the proposed method and to show the improvements compared to the previous method (Schwung and Lunze, 2019a). In the first scenario the objects are connected by a perfect network without delays and packet losses using the method presented by Schwung and Lunze (2019a). For the second scenario the quadrotors use an unreliable network in which transmission delays and packet losses occur. In the third scenario the method proposed in this paper is uesd to guarantee the collision-free movement despite using an unreliable network.

The quadrotors have to maintain a safety distance of $\bar{s} = 0.6\,\mathrm{m}$. In order to achieve it, the event threshold is computed to be $\bar{e} = 0.5\,\mathrm{m}$. When planning the trajectories the objects have to satisfy their dynamic constraints given by the restrictions of the rotor speeds $\underline{n} \leq n_i \leq \bar{n}$, $(i = 1, \ldots, 4)$, with $\underline{n} = 0$ and $\bar{n} = 124$ and the limitation of the roll and pitch angle to $\phi(t) = \pm 60°$ and $\vartheta(t) = \pm 60°$.

In each scenario the quadrotors move in a constant height of 1 m. The leader starts from $\boldsymbol{p}_{\mathrm{L}}(0) = (0\ 5\ 1)^{\mathrm{T}}$ and moves on the red trajectory, which is initially communicated to the follower. After $t = 1.5\,\mathrm{s}$ the leader changes its trajectory and continues following the red, dotted trajectory as depicted in fig. 9. The follower has the initial position $\boldsymbol{p}_{\mathrm{F}}(0) = (0\ 2.2\ 1)^{\mathrm{T}}$ and starts moving on the blue, dotted trajectory. Depending on the scenario the follower changes its trajectory accordingly. Figure 9 shows the evasive trajectory of the follower for scenario 3.

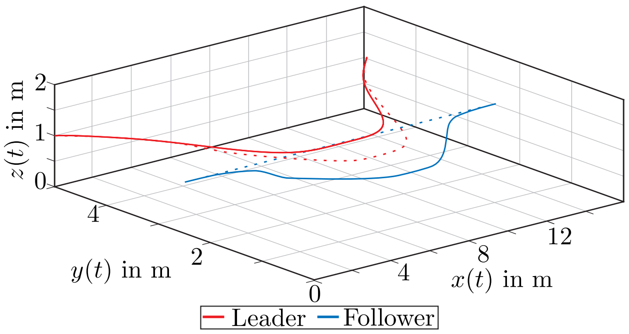

Fig. 9. Trajectories of leader and follower for scenario 3.

Scenario 1. In this scenario the quadrotors are connected by a perfect communication network and are using the method of Schwung and Lunze (2019a).

Figure 10 illustrates the movement of the quadrotors in the xy-plane along their trajectories. The safety distance $\bar{s}$ and the distance $\bar{s}+\bar{e}$ are marked as dotted lines in dependence upon the current follower position. The black beams in the lower part of the figure indicate the times for the communication event e_0. The events are generated online. As the objects get closer the communication frequency increases and as the objects depart the frequency decreases. The red beam indicates a generation of the event e_1.

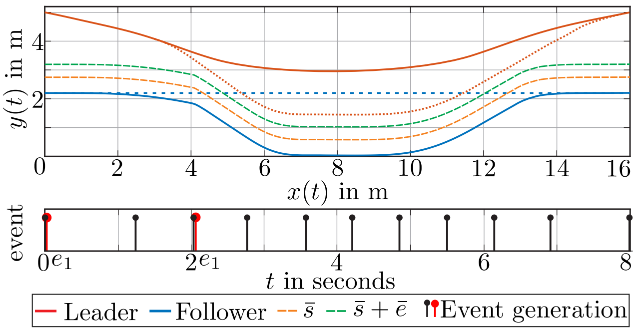

Fig. 10. Event generation of the follower for scenario 1.

After $t = 1$ s the follower leaves its initial trajectory and continues moving on the evasive trajectory to ensure the safety distance between the objects. The leader changed its trajectory after $t = 1.5$ s, which is detected by the follower after the communication to the event time $t = 2$ s. The event e_1 is generated again and the follower adapts its trajectory to the new leader trajectory. After $t = 7$ s the follower returns to its initial trajectory.

Scenario 2. This scenario considers the case in which an unreliable network is used with the method from Schwung and Lunze (2019a). Figure 11 shows the trajectories of the objects in the xy-plane.

As in the first scenario the follower plans an evasive trajectory after $t = 1$ s to avoid a collision with the leader, which deviates from its trajectory after $t = 1.5$ s. At the event time $t = 2$ s a packet gets lost. The follower does not receive new information from the leader and continues moving on its trajectory although the leader approaches the follower. Hence, after $t = 2.8$ s the safety distance $\bar{s}$ is deceeded and the objects collide. At the same time the next event e_0 appears and the event e_2 is generated to plan an emergency evasive manoeuvre. This happens too late due to the packet loss and the collision cannot be avoided.

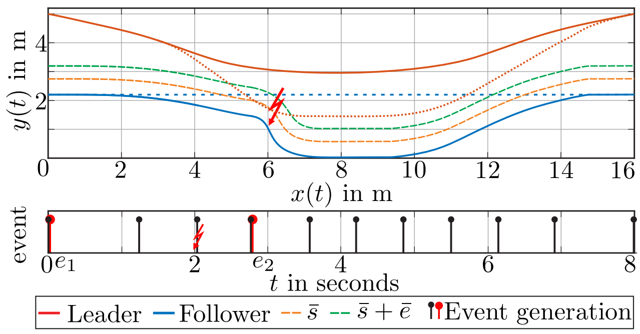

Fig. 11. Trajectories of leader and follower for scenario 2.

Scenario 3. In this scenario the results by using an unreliable network and the method proposed in this paper are stated. The maximum transmission delay induced by the communication network, which occurred over the entire time course is $\tau_{\max} = 150$ ms, where the channel estimation takes $\tau_{\mathrm{c}} = 90$ ms. In addition, the highest number of consecutive packet losses that occurred is $\delta_{\max} = 1$. Figure 12 illustrates the movement of the quadrotors in the xy-plane.

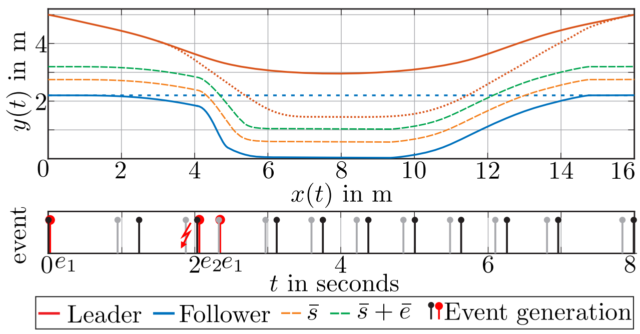

Fig. 12. Event generation of the follower for scenario 3.

The black beams indicate the times t_k for the communication event e_0, which are determined at the beginning ($t = 0$ s) and sent to the leader. The grey beams state the times $t_{\mathrm{c},k}$ when communication is invoked to ensure that the required data is available at the event times. After $t = 1.9$ s the packet gets lost. At the event time $t = 2$ s automatically the event e_2 is generated. The follower performs an emergency evasive trajectory due to the lack of leader information. At $t = 2.15$ s the follower receives the leader information, which was sent again. Based on this information the follower generates the event e_1 and plans an evasive trajectory. New future event times are generated and sent to the leader. After $t = 7$ s the follower returns to its initial trajectory.

Figure 13 shows the rotor speeds n_i, $(i = 1, \ldots, 4)$, the roll angle $\phi(t)$ and the pitch angle $\vartheta(t)$ for this scenario. It can be seen that both the actuator limitations $\underline{n}$, $\bar{n}$ and the restrictions on the angles $\phi(t)$, $\vartheta(t)$ are satisfied. The peak of the rotor speeds and the angles after $t = 2$ s results from the emergency evasive manoeuvre, which exploits the dynamical limitations of the quadrotor.

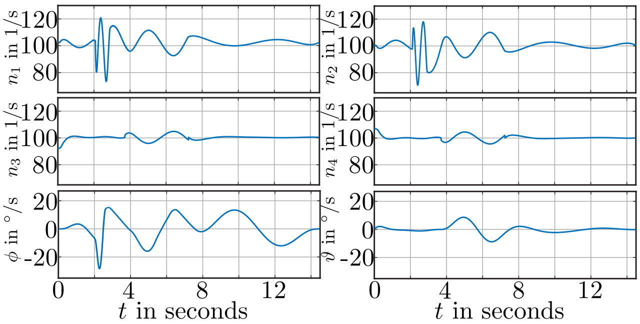

Fig. 13. Rotor speeds and angles of the follower for the second scenario.

These scenarios show that the improvements of the method proposed in this paper are necessary and that the collision-free movement of the objects can be ensured by using this method even in the presence of an unreliable communication network. No more frequent communication is required. To the contrary, since the leader sends its information autonomously at the event times the communication effort is reduced.

7. CONCLUSION

This paper deals with an event-based method to ensure collision avoidance of objects in a leader-follower structure. The leader can change its trajectory at any time, which makes its movement uncertain, whereas the follower has to ensure collision avoidance by an appropriate change of its trajectory. The objects are connected by an unreliable communication network, which induces transmission delays and packet losses. The quality of the provided communication channel varies due to the movement of the objects.

The paper improves an earlier method to take the network effects into account. For this, the estimated maximum networked induced imperfections are taken into account in the event generation with a channel estimation method performed by a network estimator, which provides the current quality of service of the channel. The idea is to predict the leader movement based on the communicated leader trajectory to determine all future event times at which communication must be invoked. Communication events are generated earlier based on the estimation method and an avoidance manoeuvre is performed whenever packets gets lost. The simulation results show that collisions can only be avoided if the network properties are used in the collision avoidance method.

The main advantage of the approach compared to previous results is the online estimation of the network parameters, which are used for the event generation to cope with network induced effects. By estimating these parameters events can be generated in order to guarantee collision avoidance. Furthermore, a low communication effort results in the sense that the data must be sent less frequently despite communication over an unreliable network. Thus, a lower energy consumption results, as no further sensors are required for a distance measurement.

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