

Safe Self-Triggered Control Based on Precomputed Reachability Sequences

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ABSTRACT

Self-triggered controllers have the potential to improve the state-of-the-art of Cyber-Physical Systems (CPSs) by enhancing the performance of the underlying closed-loop control systems. However, a major concern in deploying a self-triggered controller in a safety-critical CPS is that the stabilizing self-triggered controller may not always guarantee the satisfaction of the safety constraints. We propose a self-triggered control scheme that deals with the safe scheduling of control tasks for uncertain continuous-time linear systems. We derive a computationally efficient scheduling function that computes an upper bound on the next sampling period as a function of the current state in the presence of additive disturbance. To reduce the computational complexity of online reachability analysis and increase accuracy, we compute a large sequence of reachable sets offline and use these precomputed sets to derive a low-complexity online scheduling function that computes sufficiently large bounds in real time. We evaluate our algorithm on three high-dimensional benchmark control systems, where two of the examples have a twelve-dimensional joint state plus feedback input. Experimental results demonstrate that our self-triggered control algorithm guarantees the safety of the closed-loop control system through negligible online computation, establishing the feasibility of its practical implementation.

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1 INTRODUCTION

Feedback controllers are the core components of any safety-critical Cyber-Physical System (CPS). A feedback controller receives the state of the plant at some discrete time instants, computes the control signal based on the state, and transmits the control signal to the actuator [6]. A significant challenge in designing a feedback control system is to decide the time instants when the control-signal

updates should happen to ensure the desired behavior of the system [9].

Traditionally, the digital implementation of a feedback control system adopts either a time-triggered or an event-triggered approach. In the time-triggered approach, a fixed period is decided for the control computation based on the worst-case requirement [6, 13]. The main benefit of a time-triggered feedback control loop is its easy implementation using a timer. Moreover, a well-developed theory of discrete-time systems can be used for the implementation. The downside of the time-triggered implementation is the possible over-computation of feedback input than what is necessary. This is because the control computation and the associated sensor-to-controller and controller-to-actuator communications happen periodically. Thus, even if the system can remain in a safe state with stable dynamics without feedback updates for a long time, the feedback controller still performs unnecessary computations. This can result in under-allocation of computation time for other computation tasks, or else waste significant computation and communication resources, thus leading to performance degradation.

To deal with the over-provisioning of the time-triggered implementation, event-triggered implementation was introduced as a mechanism to perform the control computation only when necessary [17, 29, 36]. In this scheme, the state of the plant is monitored continuously, and a triggering condition is evaluated with each monitored state. Once the state satisfies the triggering condition, the state of the plant is communicated to the controller, and the control computation is activated. Unlike the time-triggered implementation, the event-triggered implementation reduces the computation and communication load significantly without any adverse effect on the control performance. However, the drawback of this implementation is that it requires monitoring the system state continuously, which requires additional hardware and also may not be a viable solution for energy-constrained CPSs.

The limitations in time-triggered and event-triggered implementation of control systems motivated the control researchers to find an alternative avenue, which led to the invention of self-triggered control [4, 5, 30]. In self-triggered control, apart from updating the control signal at the current time, the controller also computes the future time point when the feedback needs to be updated. Typically between two control computations, the actuation signal is held equal to the previously computed control signal (constant hold implementation), and the plant evolves in open-loop without observing its state. But the design of a self-triggered control scheme ensuring desired behavior of the closed-loop system is significantly challenging.

Most works on self-triggered control have aimed to ensure the stability of the closed-loop system [5, 19, 20, 25, 31, 32]. However, for

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This improves both the speed and accuracy of online reachability analysis involved in self-triggered scheduling. In our experiments, we demonstrate a significant speedup in the computation of the safe sampling period upper bound by our approach, compared to using a highly accurate reachability analysis technique like [15].

The contributions of this paper are summarized below.

- (1) We introduce a new approach of first precomputing offline a scalarized overapproximation of sets that are reachable between sampling periods and are required for scheduling, in addition to the invariant set. These sets are represented by scalars, thus the storage complexity is very low. Then we derive a less conservative and low time and storage complexity scheduling function for the self-triggered control.
- (2) At a theoretical level, we derive a new set-theoretic condition (Lemma 3.3) for linear systems that can be used to derive a low complexity safe scheduling function based on precomputing reachable sets in between sampling times.
- (3) We perform experiments on three higher-dimensional benchmark control systems from literature, including two examples with 12 dimensional state plus feedback input, to demonstrate the applicability and scalability of our algorithm.

Notation. The basic mathematical notation used in this paper is given in Table 1

2 SELF-TRIGGERED LINEAR CONTROL SYSTEM

In a self-triggered control system, a processor computes the feedback input as well as the next sampling time instant. In this paper, we consider the problem of computing in real time an upper bound on the next sampling time period at each sampling time instant, such that the system state lies within a safe set by respecting the threshold upper bound on sampling time. Note that the self-triggered controller can however update the feedback input much before the scheduled upper bound depending on additional requirements of the system. Since this computation happens in real time, the computation complexity of evaluating the threshold time should be very low. We tackle this problem for linear control systems with possible additive disturbance inputs bounded inside a box. So, we define a self-triggered linear control system as specified by a tuple

$$L = \langle A, B, C, K, \delta, \epsilon \rangle$$

where $A \in \mathbb{R}^{n \times n}$ is called *state action matrix*, $B \in \mathbb{R}^{n \times m}$ is called *input action matrix*, $C \in \mathbb{R}^{p \times n}$ is called *disturbance action matrix*, $K \in \mathbb{R}^{m \times p}$ is called *feedback matrix*, $\delta : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^+$ is called *sampling time threshold function* and $\epsilon \in \mathbb{R}^+$ is the minimum possible sampling time. A *state trajectory* of the system is a continuous function $x : \mathbb{R}^+ \rightarrow \mathbb{R}^n$ such that there exist piecewise continuous functions $u \in \text{Trj}(\mathbb{R}^m)$ and $v \in \text{Trj}(\mathbb{R}^p)$ (see Table 1), called *input trajectory* and *disturbance trajectory*, respectively, and a sequence of sampling times $\{t_\delta^i\}_{i=0}^\infty$ satisfying the following equations for all $i \in \mathbb{Z}_0$ and $t \in [t_\delta^i, t_\delta^{i+1})$.

$$t_\delta \in \mathbb{R}^+, \epsilon \leq t_\delta, 1 - t_\delta \delta(x^1 t_\delta^0, u^1 t_\delta^0) \quad (1a)$$

$$x^1 t^0 = Ax^1 t^0 + Bu^1 t^0 + Cv^1 t^0, v^1 t^0 \in \mathbb{B}(0, 1) \quad (1b)$$

$$u^1 t^0 = 0, u^1 t_\delta^0 = Kx^1 t_\delta^0, \quad (1c)$$

Note that in (1c), there is a discontinuous change in the feedback input trajectory u at time t_δ . So, the above system is a hybrid dynamical system, and more specifically, a linear impulsive system

[3]. We call the joint, $\begin{pmatrix} x \\ u \end{pmatrix}$, as the *joint trajectory* of the system. We extend the notation for piecewise continuous functions in Table 1 to denote the set of all possible joint trajectories of L as $\text{Trj}(L)$. Then the reachable set of the system at time t originating from a set $I \subseteq \mathbb{R}^n \times \mathbb{R}^m$ is

$$\mathcal{R}(L, I, t^0) = \left\{ \begin{pmatrix} x \\ u \end{pmatrix} \in \text{Trj}(L), \begin{pmatrix} x \\ u \end{pmatrix} \Big|_{t^0} \in I \right\}$$

The problem of safe scheduling of a self-triggered controller in real time is defined as follows.

PROBLEM 2.1 (FINDING SAFE SAMPLING TIME THRESHOLD FUNCTION). We are given matrices $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, $C \in \mathbb{R}^{p \times n}$, $K \in \mathbb{R}^{m \times p}$, $T \in \mathbb{R}^{n \times n}$, an initial set $I \subseteq \mathbb{R}^n \times \mathbb{R}^m$ which is a hyper-rectangle, a positive real $\epsilon \in \mathbb{R}^+$ and a positive integer $N \in \mathbb{Z}_0$. Let us denote $S = \{z \in \mathbb{R}^n \mid \|z\| \leq 1\}$, called *safe set*, which is a linearly constrained set. We want to find a function $\delta : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^+$ that aims to increase the value of $\delta^1 z^0$ for any $z \in \mathbb{R}^n \times \mathbb{R}^m$ such that the following are true.

- (1) Let $L = \langle A, B, C, K, \delta, \epsilon \rangle$. Then $\exists t \geq 0, \mathbb{R}^+ \ni L, I, t^0 \in S$.
- (2) The number of arithmetic operations involved in computing $\delta^1 z^0$ for any $z \in \mathbb{R}^n \times \mathbb{R}^m$ is less than N .

The first condition above means that the state of the system should remain within a given linearly constrained safe set S at all times. The second condition means that the schedule for the next feedback update should be computed sufficiently fast in online execution. Here, the speed is measured in terms of the number of arithmetic operations, assuming that the arithmetic operations contribute majorly to the time complexity of evaluating $\delta^1 z^0$. This real-time complexity bound can ensure that very little time is spent in finding a schedule for the next feedback update so that more time can be allocated to other incumbent tasks.

Example 2.1 (Depth control of underwater vehicle). This example is adapted from [28]. The depth of an underwater vehicle is controlled by a feedback input. The state of the underwater vehicle at any time is represented by a vector $x^1 t^0 = [\theta^1 t^0, w^1 t^0, q^1 t^0, y^1 t^0]^T$, where $\theta^1 t^0$ is the pitch angle of the vehicle, $w^1 t^0$ is the heave velocity of the vehicle, $q^1 t^0$ is the rate of change of pitch angle, and $y^1 t^0$ is the depth of the vehicle. The matrices of the system specified as $L = \langle A, B, C, K, \epsilon \rangle$ are given below. All units are S.I.

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0.0175 & 1.273 & 3.559 & 0 \\ 0 & 0.052 & 1.273 & 2.661 \\ 0 & 5 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 \\ 0.0857 \\ 21.797 \\ 0 & 0 \end{bmatrix},$$

$$C = 0.02B, \quad K = \begin{bmatrix} 0.7214 & 0.0445 & 0.1873 & 0.2292 \end{bmatrix}$$

The dimension of combined state and feedback input is $4 \times 1 = 5$. The minimum sampling time period is $\epsilon = 0.001$ seconds. The initial set is the origin. The safe set is $S = \{z \in \mathbb{R}^5 \mid |z_j| \leq 1\}$, i.e., the deviation in the depth of the vehicle from a reference depth should be less than 2m. We want to find a scheduling function $\delta : \mathbb{R}^5 \rightarrow \mathbb{R}^+$ such that $\exists t \geq 0, \mathbb{R}^+ \ni L, 0, t^0 \in S$. Also, for any $z \in \mathbb{R}^5$, the number of arithmetic operations involved in evaluating

$\delta^1 z^0$ should be less than a user-defined limit $N = 666$. Here, N can be chosen based on the time constraint on evaluating δ online and the relation between the worst-case execution time for δ and the upper bound on the arithmetic complexity of δ . For instance, let us consider that the time constraint on evaluating δ is 10^{-3} seconds. We have a very low-power embedded processor where the worst-case execution time of each arithmetic operation is $1.49 \cdot 10^{-6}$ seconds. Then if the number of arithmetic operations in evaluation δ is less than $N = 666$, we get that the time of evaluating δ is less than $666 \cdot 1.49 \cdot 10^{-6} \approx 10^{-3}$ seconds, when a negligible time $e \cdot 10^{-6}$ is spent on other operations apart from arithmetic operations.

3 A NEW SET-BASED CONDITION FOR SAFE SCHEDULING

In this section, we derive a low complexity safe scheduling function solving Problem 2.1 based on the existence of a convex set and other mathematical quantities that express the effect of the system dynamics on the convex set between two consecutive updates. The condition is quite general in the sense that it does not assume a fixed set representation (such as zonotopes, polytopes and ellipsoids) for the convex set and can in principle be solved using any convex set representation. Such a set and the related mathematical quantities can be computed offline, and their computation does not contribute to the real-time computational complexity of evaluating δ . The derivation is as follows.

Let us consider a system $L = \{A, B, C, K, \delta, \epsilon^0\}$ for which we define the following mathematical quantities.

$$A_2 = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix}, A_A = \begin{bmatrix} I & 0 \\ K & 0 \end{bmatrix} \quad (2a)$$

$${}^1 t^0 = \begin{bmatrix} \emptyset & {}^1 C \\ \forall z \in \text{Trj}^1, {}^1 t^0 \in \emptyset \end{bmatrix} \exp \{A_2 {}^1 t - \tau^{00}\} \begin{bmatrix} C \\ 0 \end{bmatrix} \forall {}^1 \tau^0 d\tau \quad (2b)$$

We can get closed-form expressions for the joint state of the system reached within the next sampling time period as a function of the previous state for a given disturbance input trajectory. We can also derive approximations of the reachable set expressed as a function of ${}^1 t^0$ when the disturbance input trajectory is unknown but bounded as specified in (1b). These relations are given in the following lemma.

LEMMA 3.1. Let z be a joint trajectory of L where ${}^1 t_{\beta=0}^{01}$ is the sequence of sampling times and $v : \mathbb{R}^n \rightarrow \mathbb{R}^n, {}^1 t \in [t_{\beta-1}, t_{\beta}]$ is the associated disturbance trajectory. Then $\exists i \in \{1, \dots, M\}, \exists t \in [t_{\beta-1}, t_{\beta}]$, we get,

$$z^1 t^0 = \exp \{A_2 {}^1 t - t_{\beta}^{00}\} z^1 t_{\beta}^{00} + \int_0^{{}^1 t - t_{\beta}^{00}} \exp \{A_2 ({}^1 t - t_{\beta}^{00} - \tau^{00})\} \begin{bmatrix} C \\ 0 \end{bmatrix} \forall {}^1 \tau^0 d\tau \quad (3a)$$

$$z^1 t_{\beta,1}^{01} = A_A \exp \{A_2 {}^1 t_{\beta,1} - t_{\beta}^{00}\} z^1 t_{\beta}^{00} + \int_0^{{}^1 t_{\beta,1} - t_{\beta}^{00}} \exp \{A_2 ({}^1 t_{\beta,1} - t_{\beta}^{00} - \tau^{00})\} \begin{bmatrix} C \\ 0 \end{bmatrix} \forall {}^1 \tau^0 d\tau \quad (3b)$$

PROOF. The proof is given in the Appendix (Lemma A.1).

The following lemma allows us to represent reachable sets as uniformly scaled convex sets containing the origin. This result will be used later to derive a low-complexity scheduling function ensuring safety.

LEMMA 3.2. Let \emptyset be a convex set such that $0 \in \emptyset$ and there exists a function $\chi_{\min} : \mathbb{R}^n \rightarrow \mathbb{R}$ such that $\exists z \in \mathbb{R}^n, \chi_{\min}^1 z^0 = \min \{a \in \mathbb{R}^n \mid z \in a \cdot \emptyset\}$. Let us consider that there exist finite real valued sequences β_j, η_j satisfying $\exists j \in \{1, \dots, M\}$,

$$\beta_0 = 1, \eta_0 = 0, \beta_j, \eta_j \in \mathbb{R}^n \quad (4a)$$

$$\exp \{A_2 \tau^0\} \beta_j, \exp \{A_2 \tau^0\} \eta_j \quad (4b)$$

Let us consider a joint trajectory $z \in \text{Trj}^1 L^0$ for which ${}^1 t_{\beta=1}^{01}$ is the set of feedback sampling times. Then the following are true $\exists i \in \{1, \dots, M\}, t \in [t_{\beta-1}, t_{\beta}]$.

$$z^1 t_{\beta,1}^{01} \in \emptyset \quad (5a)$$

$$A_A \exp \{A_2 \epsilon^0\} \beta^1 \frac{{}^1 t_{\beta-1} - t_{\beta}^{00}}{\epsilon} \chi_{\min}^1 z^1 t_{\beta}^{00} + \eta^1 \frac{{}^1 t_{\beta-1} - t_{\beta}^{00}}{\epsilon} \in A_A \cdot {}^1 \epsilon^0 \quad (5b)$$

$$z^1 t^0 \in \beta^1 \frac{{}^1 t - t_{\beta}^{00}}{\epsilon} \chi_{\min}^1 z^1 t_{\beta}^{00} + \eta^1 \frac{{}^1 t - t_{\beta}^{00}}{\epsilon} \quad (5c)$$

The following lemma is a main result that gives a sufficient condition on the scheduling function δ that solves Problem 2.1.

LEMMA 3.3. Let us consider a set $S \subseteq \mathbb{R}^n$, called safe set and another set $I \subseteq \mathbb{R}^n$, called initial set. Let us consider that there exist a convex set $\emptyset \subseteq \mathbb{R}^n$, called sampling time invariant, a function $\chi : \mathbb{R}^n \rightarrow \mathbb{R}$, called inclusion scaling function, and finite increasing sequences of positive real numbers β_j, η_j such that (4a,4b) and the following are true.

$$0 \in \emptyset, \exists z \in \mathbb{R}^n, \chi^1 z^0 \in \emptyset \quad (6a)$$

$$A_A \exp \{A_2 \epsilon^0\} A_A \cdot {}^1 \epsilon^0 \in \emptyset \quad (6b)$$

$$I \subseteq \beta_1 \cdot {}^1 \eta_1 \cdot S \quad (6c)$$

Let us consider that the number of arithmetic operations involved in evaluating $\chi^1 z^0$ for all $z \in \mathbb{R}^n$ is less than N_j . Let us define a scheduling function $\delta : \mathbb{R}^n \rightarrow \mathbb{R}$:

$$\text{Inds}^1 z^0 = \{j \in \{1, \dots, M\} \mid \chi^1 z^0 \in \beta_j \cdot \eta_j \cdot \emptyset\} \quad (6d)$$

$$\text{if } \text{Inds}^1 z^0 \neq \emptyset, \text{ then } \delta^1 z^0 = \max \text{Inds}^1 z^0 \cdot \epsilon \quad (6e)$$

$$\text{otherwise } \delta^1 z^0 = \epsilon \quad (6f)$$

Then the following are true.

$$\text{h1i } \mathbb{R}^n \setminus I, \forall \tau^0 \in S.$$

$$\text{h2i } \text{The number of arithmetic operations for computing the value of } \delta^1 z^0 \text{ for all } z \in \mathbb{R}^n \text{ is not greater than } N_j \cdot 2 \log_2 M + 1.$$

PROOF. The proof is given in the Appendix (Lemma A.3).

4 OFFLINE COMPUTATIONS

We can improve the accuracy of online reachability analysis by precomputing a large sequence of reachable sets and using this sequence to approximate reachable sets online. Then the key idea in reducing the complexity of online scheduling while utilizing pre-computed reachable sets is that we represent the reachable set as scalar multiples of a common convex set and use binary search on scalar variables to perform scheduling. This was shown in Lemma 3.3. In this regard, in this section, we describe the procedure to compute offline the convex set and scalar sequences $\beta_{g=0}$ and $\eta_{g=1}$ satisfying Equations (6b,6c, 4a, 4b) which are preconditions in Lemma 3.3. The time of these offline computations does not add to the online computation time for the evaluation of the scheduling function δ . To solve for δ , we need to parameterize the encoding of the set and solve for the parameters that satisfy (6b,6c, 4a, 4b). In this paper, we choose the real projection of the complex zonotope [2] for encoding because the class of complex zonotopes is guaranteed to contain solutions sets to fixed point equations like (6b) for stable systems with full rank eigenstructure (see Theorem 7 [2]). Also, they are closed under linear transformations and Minkowski sums, which benefits in improving the accuracy of approximating reachable sets of linear systems under additive disturbance.

A complex zonotope is an encoding of a set of complex-valued points where each point is a linear combination of complex-valued vectors such that the combining coefficients are complex-valued and bounded. The real projection of a complex zonotope can represent some non-polytopic sets in addition to usual polytopic zonotopes, and hence are more expressive than usual (real-valued) zonotopes.

Definition 4.1 ([2]). Let $G \in \mathbb{C}^{rows \times cols}$ be a complex matrix, called generator matrix, $c \in \mathbb{R}^{rows}$ be a real vector, called center and $s \in \mathbb{R}^{cols}$ be a non-negative vector, called scale vector. The tuple $\langle G, c, s \rangle$ is a complex zonotope that represents the following set of points.

$$Z \langle G, c, s \rangle = \{ G \zeta + c \mid \zeta \in \mathbb{C}^{cols}, |\zeta_j| \leq s_j \} \quad (7)$$

We shall revisit a relation between complex zonotopes, which can be used as a sufficient condition for checking the inclusion between complex zonotopes. This relation and other properties will be used later in this paper to solve for δ , $\beta_{g=0}$, $\eta_{g=1}$ in (6b, 6c, 4a,4b).

Definition 4.2 ([1]). Let us consider two complex zonotope sets $Z \langle G, c, s \rangle \in \mathbb{C}^{rows \times cols}$ and $Z \langle H, e, r \rangle \in \mathbb{C}^{rows \times cols}$. Let us define a relation “ \preceq ” between the two complex zonotope encodings as $\langle H, e, r \rangle \preceq \langle G, c, s \rangle$ if the following is true.

$$\begin{aligned} & \exists X \in \mathbb{C}^{cols \times cols}, \exists y \in \mathbb{C}^{cols} : \\ & GX = H \text{Diag } \langle r \rangle, \quad Gy = r + c \\ & \exists j \in \{1, \dots, cols \}, \exists g \in \{1, \dots, rows \} : \\ & \quad |X_{gg}| \leq 1, \quad |y_g| \leq s_g \end{aligned} \quad (8a)$$

Then the following implication holds between any two complex zonotopes $\langle G, c, s \rangle$ and $\langle H, e, r \rangle$.

$$\langle H, e, r \rangle \preceq \langle G, c, s \rangle \Rightarrow Z \langle H, e, r \rangle \subseteq Z \langle G, c, s \rangle \quad (9)$$

Algorithm 1 Offline computation of a set and sequences $\beta_{g=0}$ and $\eta_{g=1}$ satisfying (6b,6c, 4a, 4b)

```

Choose  $l \in \mathbb{Z}_{>0}$  and  $M \in \mathbb{Z}_{>0}$ .
% order of complex zonotope and length of reachability sequence
1:  $G = I_{l \times l}$ .
2: for  $i \in \{2 : l\}$  do
3:    $G = G \oplus \text{Eigenvectors } \langle A_i \rangle \exp \langle A_i t \rangle$ 
4: end for
5:  $s = \arg \max_{\beta} \| \beta \|_1 \mid j \in \mathbb{Z}_{>0} \text{ (G is constant)}$ ;
   (12a-12c) are satisfied % convex optimization
6:  $\rho = \min \rho \mid \rho \geq 0, \rho \leq 1, \rho \in \mathbb{Z}_{>0} \mid \exp \langle A_i t \rangle s \in \rho \langle G, 0, s \rangle$ 
7:  $\beta_0 = \rho$ 
8:  $\eta_0 = \min \eta \mid \eta \geq 0, \eta \leq 1, \eta \in \mathbb{Z}_{>0} \mid \exp \langle A_i t \rangle G, 0, s \in \eta \langle G, 0, s \rangle$ 
9: for  $j = 1 : M$  do
10:   $\beta_j = \max \beta \mid \beta \geq 0, \beta \leq 1, \beta \in \mathbb{Z}_{>0} \mid \exp \langle A_j t \rangle G, 0, s \in \beta \langle G, 0, s \rangle$ 
   (15e):  $\exp \langle A_j t \rangle G, 0, s \in \beta \langle G, 0, s \rangle$ 
11:   $\eta_j = \max \eta \mid \eta \geq 0, \eta \leq 1, \eta \in \mathbb{Z}_{>0} \mid \exp \langle A_j t \rangle G, 0, s \in \eta \langle G, 0, s \rangle$ 
   (15g):  $\exp \langle A_j t \rangle G, 0, s \in \eta \langle G, 0, s \rangle$ 
12: end for
13: return  $\langle Z \langle G, 0, s \rangle, \beta_{g=0}, \eta_{g=1} \rangle$ 

```

The linear transformation of a complex zonotope by a matrix P followed by Minkowski sum with another complex zonotope is a complex zonotope, computed as follows:

$$P Z \langle G, c, s \rangle \oplus Z \langle H, e, r \rangle = Z \langle PG + H, Pc + e, s + r \rangle \quad (10)$$

The interested reader may go through [1] for the proofs of the above properties of complex zonotopes. Now we describe the offline computations to find a complex zonotopic set centered at the origin $Z \langle G, 0, s \rangle$ and sequences $\beta_{g=0}$ and $\eta_{g=1}$ satisfying Equations (6b,6c, 4a, 4b), the preconditions in Lemma 3.3.

In a time interval $[j\epsilon, (j+1)\epsilon]$ where $j \in \{0, \dots, M\}$, the contribution of the disturbance set to the reachable set approximation in that time interval is $\mathcal{C}_{2, \eta_{n-1} g_{n-1} \epsilon} \langle 1 \rangle t^0$ according to (3a). For a small value of ϵ , this set can be approximated by a zonotope with very good accuracy using the algorithm of Girard [15]. We subsume this algorithm in this paper, and denote the resulting zonotopic over-approximation as $Z \langle J^j, 0, \mathbb{1}_{\otimes} \rangle$ where J^j is the generator matrix of the zonotope over-approximation of $\mathcal{C}_{2, \eta_{n-1} g_{n-1} \epsilon} \langle 1 \rangle t^0$ for any $j \in \mathbb{Z}_{>0}$, 0 is the center of the zonotope over-approximation, and q is the number of columns in the generator matrices, i.e.,

$$\mathcal{C}_{2, \eta_{n-1} g_{n-1} \epsilon} \langle 1 \rangle t^0 \subseteq Z \langle J^j, 0, \mathbb{1}_{\otimes} \rangle \quad (11)$$

The following lemma is to be used to compute a set satisfying (6b,6c).

LEMMA 4.3. Let $G \in \mathbb{C}^{rows \times cols}$ be a complex matrix, $T \in \mathbb{R}^{rows \times cols}$ be a real matrix, $S = \{z \in \mathbb{R}^{rows} \mid \exists k T z \leq 1\}$ be a linearly constrained set and $I = \{r, r\}$ for some $r \in \mathbb{R}^{rows}$ be a hyper-rectangle. Let $s \in \mathbb{R}_{>0}$ be a solution vector to the following convex constraints.

$$jTGj s \text{ } jTA_2Gj se \text{ } 1 \text{ } \text{ } 1 \quad (12a)$$

$$Z \text{ } A_A \exp^1 A_2 \epsilon^0 G \text{ } A_A J^1 0^0 \text{ } , 0, \text{ } \text{ } 1 \text{ } \text{ } \text{ } \vee Z^1 G, 0, s^0 \quad (12b)$$

$$Z^1 |_{\text{ } , <, 0, r^0} \vee Z^1 G, 0, s^0 \quad (12c)$$

Then $\text{Re } Z^1 Z^1 G, 0, s^0$ satisfies Equations (6b, 6c).

PROOF. By the formula about linear transformation and Minkowski sum of a complex zonotope in (10) (see also Lemmas 2.2.1 and 2.2.3 of [1]) and (11), we get that the L.H.S. of (6b) is equal to the real projection of L.H.S. of (12b). Next by the sufficient condition for inclusion between complex zonotopes given in (9) (see also Lemma 2.3.6 of [1]), we get (6b) and also that I . Next, by Lagrange's form of Taylor remainder (see Section 5.2 of [7]), we get that for any $\tau \geq 0, \epsilon \in \mathbb{K}$ and $z \in \mathbb{R}^{\text{ } , <}$, by Taylor expansion w.r.t τ ,

$$T \exp^1 A_2 \tau^0 z \text{ } Tz \text{ } \text{ } jTA_2zj \epsilon, jTA_2zj \epsilon \text{ } \quad (13)$$

So, for any $z = \text{Re } Z^1 G \zeta^0 \text{ } 2 \text{ } = \text{Re } Z^1 Z^1 G, 0, s^0 \text{ } : j \zeta \text{ } s$, we get $T \exp^1 A_2 \tau^0 z \text{ } Tz \text{ } \text{ } jTA_2zj \epsilon \text{ } \text{Re } TG \zeta^0 \text{ } jTA_2G \zeta \text{ } j \epsilon \text{ } jTGj s \text{ } jTA_2Gj se \text{ } 1 \text{ } \text{ } 1$. This proves (6c).

Solving for set optimally satisfying Equations (6b, 6c): We first fix the generator matrix G of the complex zonotope. For this, we first choose the eigenvectors of $A_A \exp^1 A_2 i \epsilon^0$ for a few different values of $j \in Z^1 0$ to be among the columns of G , including $j = 0$. This is because according to Theorem 7 of [2], the existence of s satisfying the conditions (6b,6c) are guaranteed under certain stability and rank conditions, when G contains the eigenvectors of $A_A \exp^1 A_2 \epsilon^0$ among its columns. Then we can augment any number of additional generators to G because the scale factors can be adjusted to regulate the effect of each generator on the satisfaction of the above constraints. We therefore augment the identity matrix to generators of G . Now for the fixed G , the constraints above are convex in s and other auxiliary variables involved in the relations. So, we can use convex optimization to solve the constraints for the fixed G . While solving the convex constraints, we want to maximize the size of $\text{ } ,$ so that we can find a large bound on the sampling time period. So, we perform the following convex optimization to find a large-sized real projection of complex zonotope $= \text{Re } Z^1 Z^1 G, 0, s^0$ satisfying (6b, 6c). The sum of projections of the complex zonotope along the different axes is given by $\text{ } \text{ } 1 \text{ } \text{ } ; jGj s$ based on Lemma 12 of [2]. So, we maximize this sum to increase the size of the complex zonotope.

$$\max \text{ } \text{ } 1 \text{ } \text{ } ; jGj s : (12a-12c) \text{ are satisfied.} \quad (14)$$

Next, we shall compute the non-decreasing sequences $\beta_g \text{ }_{g=0}^{\text{ } }$ and $\eta_g \text{ }_{g=1}^{\text{ } }$ satisfying (6b,6c, 4a, 4b) inductively using convex optimizations according to the following lemma.

LEMMA 4.4. *Let us consider a set $\text{ } = \text{Re } Z^1 Z^1 G, 0, s^0$. Let us consider a positive real $\rho \in \mathbb{R}^{\text{ } , 0}$ and finite sequences $\beta_g \text{ }_{g=0}^{\text{ } }$ and $\eta_g \text{ }_{g=0}^{\text{ } }$ defined inductively as optimal solutions to the convex optimization problems (15a-15f) below.*

$$\rho = \min \rho \geq 0, 1^0 : |_{\text{ } , <, 0, jA_2Gj se^0} \vee \rho^0 G, 0, s \quad (15a)$$

$$\beta_0 = \rho \text{ } , \min \beta \geq 0, 1^0 : \text{ } \exp^1 A_2 j \epsilon^0 G, 0, s^0 \vee \beta G, 0, s^0 \quad (15b)$$

$$\eta_0 = \min \eta \geq 0, 1^0 : J^1 0^0, 0, \text{ } \text{ } 1 \text{ } \text{ } \vee \eta G, 0, s^0 \quad (15c)$$

$$\delta_j \geq 2 Z^1 \beta_g = \max \beta_{g-1}, \rho \text{ } , \min \beta \geq 0, 1^0 : \text{ } 15e^0 \text{ } , \quad (15d)$$

$$\text{ } \exp^1 A_2 j \epsilon^0 G, 0, s^0 \vee \beta G, 0, s^0 \quad (15e)$$

$$\delta_j \geq 2 Z^1 \eta_g = \max \eta_{g-1}, \min \eta \geq 0, 1^0 : \text{ } 15g^0 \quad (15f)$$

$$J^1 j^0, 0, \text{ } \text{ } 1 \text{ } \text{ } \vee \eta G, 0, s^0 \quad (15g)$$

Then the finite sequences $\beta_g \text{ }_{g=0}^{\text{ } }$ and $\eta_g \text{ }_{g=0}^{\text{ } }$ satisfy (4a,4b).

PROOF. By (15b,15c,15d,15f), we have $\delta_j \geq 2 Z^1 0, \beta_{g-1} \text{ } \beta_g$ and $\eta_{g-1} \text{ } \eta_g$, which proves (4a).

Next, let us consider a $t \geq j \epsilon, \text{ } j \text{ } 1^0 \epsilon \in \mathbb{K}$ for some $j \in Z^1 0$. By Taylor remainder theorem, for any $z \in \mathbb{R}^{\text{ } , <}$, we can write

$$\exp^1 A_2 t^0 z \text{ } \exp^1 A_2 j \epsilon^0 \text{ } \text{ } jA_2zj \epsilon, jA_2zj \epsilon \text{ } \quad (16a)$$

$$= \exp^1 A_2 j \epsilon^0 Z^1 G, 0, s^0 \text{ } Z^1 |_{\text{ } , <, 0, jA_2Gj se^0} \quad (16b)$$

$$= Z^1 \exp^1 A_2 j \epsilon^0, 0, s^0 \text{ } Z^1 |_{\text{ } , <, 0, jA_2Gj se^0} \text{ } \% \text{ by (10)} \quad (16c)$$

By (15a), we get that

$$Z^1 |_{\text{ } , <, 0, jA_2Gj se^0} \text{ } \rho Z^1 G, 0, s^0 \quad (16d)$$

So, by (10,15b,15d,16d), and that $Z^1 G, 0, s^0$ is a convex set containing 0 , we get that $\delta_j \geq 2 Z^1 0$,

$$Z^1 |_{\text{ } , <, 0, jA_2Gj se^0} \text{ } \exp^1 A_2 j \epsilon^0 Z^1 G, 0, s^0 \text{ } \beta_g Z^1 G, 0, s^0$$

% By (16c)

$$\Rightarrow \delta t \geq 2 \text{ } j \epsilon, \text{ } j \text{ } 1^0 \epsilon \in \mathbb{K} \text{ } \exp^1 A_2 t^0 \text{ } \beta_g \quad (16e)$$

The above proves that (4b) is satisfied. Next by (15c,15f), we get that $\delta_j \geq 2 Z^1 0, \delta t \geq 2 \text{ } j \epsilon, \text{ } j \text{ } 1^0 \epsilon \in \mathbb{K}, \text{ } 1^0 \text{ } \text{Re } Z^1 G, 0, s^0 = \text{ }^0$. This proves (4b).

5 DERIVING ONLINE SCHEDULING FUNCTION

After computing the complex zonotopic projection set according to Equation (14) and Lemma 4.4, we have to first derive the inclusion scaling function χ given in Lemma 3.3. The function checks the amount of scaling required to include a given point inside the set $\text{ } .$ This function will be evaluated online, thus we want the computational complexity of evaluating χ to be very small. Such a function is given in the following lemma, and the complexity of evaluating the function is also given.

LEMMA 5.1. *Let $Z^1 G, 0, s^0 \in \mathbb{C}^{\text{ } , <}$ be a complex zonotope such that $Z^1 G \text{ } \text{Diag } 1^s 0^0$ has rank $n \text{ } , m$ and $Z^1 G \text{ } \text{Diag } 1^s 0^0 \text{ } ^y$ denote the Moore-Penrose pseudo-inverse of $Z^1 G \text{ } \text{Diag } 1^s 0^0$. Let us define a function,*

$$\chi : \mathbb{R}^{\text{ } , <} \rightarrow \mathbb{R}^{\text{ } , 0}, \delta z \in \mathbb{R}^{\text{ } , <}, \chi^1 z^0 = Z^1 G \text{ } \text{Diag } 1^s 0^0 \text{ } ^y z \text{ } 1 \quad (17)$$

Then $z \text{ } \chi^1 z^0 \in Z^1 G, 0, s^0$.

Since G, s are precomputed offline, so the matrix $Z^1 G \text{ } \text{Diag } 1^s 0^0 \text{ } ^y$ can be precomputed offline before evaluating $\delta^1 z^0$ online. Then the number of arithmetic operations required for computing $\chi^1 z^0$ for any $z \in \mathbb{R}^{\text{ } , <}$ is not greater than $18 \text{ } n \text{ } , m \text{ } , 3^0 \text{ } \text{cols } Z^1 G^0$.

PROOF. Let us consider $z \in \mathbb{R}^{n \times 1}$ and $\zeta = \frac{\text{Diag}^1 B^{o1} \text{Diag}^1 B^{o0} l}{j^1 l^o}$.
As $\chi^1 z^o = {}^1 G \text{Diag}^1 s^{o0} z$, we get $|\zeta| = \frac{\text{Diag}^1 B^{o1} \text{Diag}^1 B^{o0} l}{j^1 l^o}$
$$|\text{sj}| \frac{{}^1 G \text{Diag}^1 s^{o0} z}{\chi^1 z^o} = |\text{sj}| \frac{\chi^1 z^o}{\chi^1 z^o} = |\text{sj}| \quad (18a)$$

Then we can write

$$z = {}^1 G \text{Diag}^1 s^{o0} {}^1 G \text{Diag}^1 s^{o0} z = G \chi^1 z^o \zeta \quad (18b)$$

$$\chi^1 z^o \zeta = \chi^1 z^o \zeta, 0, s^o \quad \% \text{ (as } |\zeta| \text{ by (18a))} \quad (18c)$$

Next, the upper bound on the arithmetic complexity of computing $\chi^1 z^o$ is an upper bound on the arithmetic complexity of computing the complex-valued matrix multiplication plus the complexity of computing the infinity norm in (17). The number of complex number multiplications involved in the complex-valued matrix multiplication is less than ${}^1 n \times m^o \text{ cols } {}^1 G^o$. So, the number of real-valued multiplications is less than 4 times the former, which is $4 {}^1 n \times m^o \text{ cols } {}^1 G^o$. During a single complex-valued scalar multiplication, there are 2 real-valued additions involved. So, the number of real-valued additions resulting from complex-valued multiplications is $2 {}^1 n \times m^o \text{ cols } {}^1 G^o$. Also, during complex-valued matrix multiplication, there are less than ${}^1 n \times m^o \text{ cols } {}^1 G^o$ complex-valued additions, which amounts to another $2 {}^1 n \times m^o \text{ cols } {}^1 G^o$ real-valued additions. So, the total number of arithmetic operations resulting from the complex-valued matrix multiplication is less than ${}^1 4 \times 2 \times 2 {}^1 n \times m^o \text{ cols } {}^1 G^o = 8 {}^1 n \times m^o \text{ cols } {}^1 G^o$. Next, we have to compute the maximum of the absolute values of the complex vector after the matrix multiplication. For each absolute value calculation, there will be two real-valued multiplications and one addition. So, the total number of arithmetic operations is bounded by ${}^1 8 {}^1 n \times m^o \text{ cols } {}^1 G^o \times 2 \times 1^o \text{ cols } {}^1 G^o = {}^1 8 {}^1 n \times m^o \times 3^o \text{ cols } {}^1 G^o$.

Now we derive an online scheduling function δ that solves Problem 2.1. The derivation makes use of the function χ derived in Lemma 5.1 and the sequences ${}^1 \beta_{\delta=0}^o, {}^1 \eta_{\delta=0}^o$ computed according to Lemma 4.4. This is given in the following theorem.

THEOREM 5.2. *Let us consider an integer $N \geq 0$. Let us choose hyperparameters $l \geq 2$ (order of complex zonotope) and M (length of reachability sequences) in Algorithm 1 such that*

$${}^1 8 {}^1 n \times m^o \times 3^o l^1 n \times m^o \times 2 \log_2 {}^1 M^o \times 1 \leq N \quad (19)$$

Let us consider the complex zonotope tuple $(G, 0, s^o)$ and the sequences ${}^1 \beta_{\delta=0}^o, {}^1 \eta_{\delta=0}^o$ computed by Algorithm 1, and the inclusion scaling function $\chi: \mathbb{R}^{n \times 1} \rightarrow \mathbb{R}^n$ defined in Equation (17). Let us define a scheduling function $\delta: \mathbb{R}^{n \times 1} \rightarrow \mathbb{R}_0$ according to Equation (6d-6f) of Lemma 3.3 for the above sequences ${}^1 \beta_{\delta=0}^o, {}^1 \eta_{\delta=0}^o$. Then we have $\mathbb{R}^1 I, \forall 0, 1^o \in S$ and the number of arithmetic operations required for evaluating $\delta^1 z^o$ for any $z \in \mathbb{R}^{n \times 1}$ is not greater than N .

PROOF. According to Lemmas 4.3 and 4.4, we get that the set $= \mathbb{R}^1 Z \text{ } {}^1 G, 0, s^{o0}$ and sequences ${}^1 \beta_{\delta=0}^o, {}^1 \eta_{\delta=0}^o$ satisfy the Equations (6b, 6c, 4a,4b) of Lemma 3.3. Therefore, by Lemma 3.3, we have $\mathbb{R}^1 I, \forall 0, 1^o \in S$.

Next, by Lemma 3.3h2i, we get that the arithmetic complexity of evaluating δ is bounded above by $N_j \times 2 \log_2 {}^1 M^o \times 1$ where N_j is the arithmetic complexity of evaluating χ . But by Lemma

5.1, we have $N_j = {}^1 8 {}^1 n \times m^o \times 3^o \text{ cols } {}^1 G^o$, and by Algorithm 1, we have $\text{cols } {}^1 G^o = l^1 n \times m^o$. Thus the complexity of evaluating δ is bounded above by ${}^1 8 {}^1 n \times m^o \times 3^o l^1 n \times m^o \times 2 \log_2 {}^1 M^o \times 1$. Then by (19), this complexity is bounded above by N .

Reducing complexity while improving accuracy. According to the above theorem, the online computational arithmetic complexity is bounded by ${}^1 8 {}^1 n \times m^o \times 3^o l^1 n \times m^o \times 2 \log_2 {}^1 M^o \times 1$. This online complexity is negligible compared to an accurate reachability analysis algorithm like [15]. For example, in a step-by-step reachability analysis of Girard, we have to perform at least $\delta^1 z^o \cdot \epsilon$ matrix multiplications of an $n \times n$ matrix with $n \times \text{cols } {}^1 G^o$ generator matrix G , assuming a time step size ϵ . The latter requires at least ${}^1 n \times m^o \text{ cols } {}^1 G^o$ multiplications by school book style matrix multiplication. Since $\delta^1 z^o \cdot \epsilon$ is upper bounded by M , so the worst case complexity of [15] is at least M times the worst case complexity of our algorithm. So, we can reduce the complexity of the scheduling function by M times compared to performing online accurate reachability analysis. But will still improve the accuracy of online reachability analysis because of precomputing a large sequence of reachable sets.

6 EVALUATION

We evaluate our procedure on three examples: an underwater vehicle depth control model having 4-dimensional state and 1-dimensional feedback input, a quadcopter height control model having 8-dimensional state and 4-dimensional feedback, and a vehicle platoon having 9-dimensional state and 3-dimensional feedback. For these examples, we derive a scheduling function based on Theorem 5.2. Our aim is to show that the scheduling function based on precomputed reachable set sequences significantly improves the computation speed of finding a safe upper bound on sampling time as compared to performing an accurate reachability analysis online. For this purpose, we first compute the upper bounds on the sampling time period for a large number of randomly sampled points in the state space using the scheduling function. Next, we verify the schedules for all sampled points using the highly accurate reachability algorithm developed by Girard [15]. For a fair comparison, the length of time step used in the reachability analysis by [15] is the same as the length of time step used in computing the reachability sequences in (4b). The maximum order of the zonotopes resulting from additive disturbance (see (11)) is also kept the same. Then we note the ratio of the computation times of both approaches on the same computing platform, an M1 Macbook Pro laptop with 16 GB RAM. We take the value of l and M in Algorithm 1 to be 3 and 400, respectively. So, the number of generators of invariant complex zonotope is $l^1 n \times m^o = 3^1 n \times m^o$, where n and m are the state and input dimensions, respectively. The numbers are given in Table 2.

Implementation software. The software implementation is available in the following Github repository:
<https://github.com/asarvind/SafeSelfTriggered.jl>

6.1 Underwater vehicle depth control

The dynamics of an underwater vehicle with the dimension of state space $n = 4$ and the dimension of feedback input $m = 1$ was

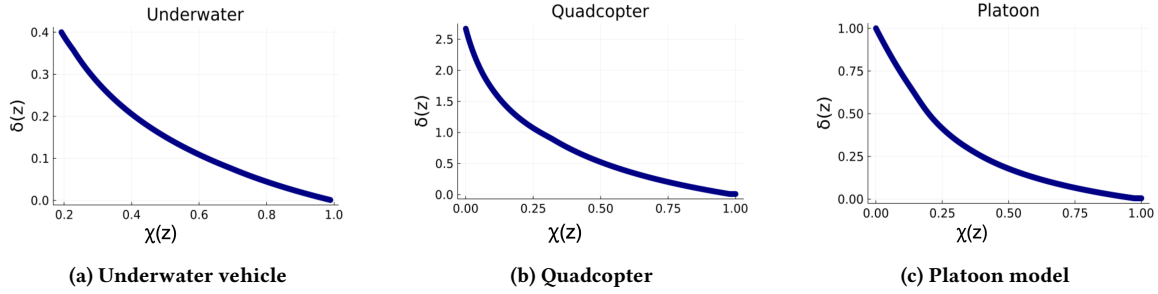


Figure 5: Sampling period bound $\delta^1 z^0$ as a function of scale factor $\chi^1 z^0$

Table 2: Offline computation time and upper bound on arithmetic complexity of evaluating scheduling function (19)

Example	Sequence length M	State Dimension n	Input Dimension m	Number of generators	Offline computation time	Bound on no. of arithmetic operations for evaluating $\delta^1 z^0$
8 Underwater	400	4	1	15	12.58	665
Quadcopter	400	8	4	36	79.41	3584
Platoon	400	9	3	36	119.24	3584

Table 3: Comparison of speed of computing a schedule by our method vs verification of the schedule by [15]

Example	Sampling Region	No. of Samples	Comp. time evaluating scheduling function on all samples (secs)	Verification time of all schedules (secs)	Speed gain
Underwater	1.000	100000	0.240556250	21.739955500	90
	0.500	100000	0.219049833	26.390020125	120
	0.250	100000	0.220316167	26.239419416	119
	0.100	100000	0.211023375	25.963317625	123
Quadcopter	0.100	100000	0.279739083	24.817588417	88
	0.050	100000	0.288304709	27.913212791	96
	0.025	100000	0.257196333	29.552534042	114
	0.010	100000	0.304468167	30.960938000	101
Platoon	0.100	100000	0.264170208	24.051463250	91
	0.050	100000	0.236778500	25.753608916	108
	0.025	100000	0.254564208	26.545361000	104
	0.010	100000	0.253303708	27.205094000	107

quadcopter. The feedback input tries to keep the height and quadcopter state orientation within a safe set where $y \geq 1, 1\% m$, $\phi \geq 0.1, 0.1\% rad$, $\theta \geq 0.2, 0.2\% rad$ and $\psi \geq 1, 1\% rad$. So, the combined state space has $8 \times 4 = 12$ dimensions. The lower bound on the sampling period is $\epsilon = 0.01$. The matrices of the system dynamics A, B, C, K are,

$$2 \times 8 \times 8, \quad ij = \begin{pmatrix} 1 & 18 \cdot 10^{-2} & f^1 \cdot 1 \cdot 2^0 \cdot 13 \cdot 4^0 \cdot 17 \cdot 8^0 g \\ 0 & > C & 4A F B B4 \end{pmatrix}, \quad (20a)$$

$$2 \times 8 \times 4, \quad ij = \begin{pmatrix} 1 & 18 \cdot 10^{-2} & f^1 \cdot 2^0 \cdot 14 \cdot 2^0 \cdot 16 \cdot 3^0 \cdot 18 \cdot 4^0 g \\ 0 & > C & 4A F B B4 \end{pmatrix}, \quad (20b)$$

$$= 0 \cdot 001 \cdot \quad (20c)$$

$$2 \times 4 \times 8, \quad ij = \begin{pmatrix} 0 \cdot 6325 & 18 \cdot 10^{-2} & f^1 \cdot 1 \cdot 1^0 \cdot 12 \cdot 3^0 \cdot 13 \cdot 5^0 g \\ 1 \cdot 2903 & 18 \cdot 10^{-2} & f^1 \cdot 1 \cdot 2^0 \cdot 12 \cdot 4^0 \cdot 13 \cdot 6^0 g \\ 1 & 18 \cdot 10^{-2} & = 14 \cdot 7^0 \\ \dots & \dots & \dots \\ 1 \cdot 7321 & 18 \cdot 10^{-2} & = 14 \cdot 8^0 \end{pmatrix}, \quad (20d)$$

6.3 Networked platoon of vehicles

We consider a model of a networked platoon of vehicles adapted from [24]. The model describes the dynamics of a platoon of four vehicles where the inter-vehicle distances, relative speeds, and accelerations of the vehicles constitute a 9-dimensional state of the system. The system has a 3-dimensional feedback input acceleration applied on each of the three follower vehicles. The acceleration of the leading vehicle is uncertain and lies in the interval $\geq 9, 1\% m \cdot s^2$. However, in this paper, we shift the dynamics to the equilibrium point to be consistent with the analysis in this paper. Then the disturbance input lies in the range $\geq 5, 5\% m \cdot s^2$. The matrices corresponding to the system dynamics are given in Figure 2. The safe set is the set of states where the inter-vehicle distances are greater than a threshold so that collision is avoided. The corresponding matrix T and vector of offsets d specifying the half-space representation of the safe set are given in Figure 2. The lower bound ϵ on the sampling time period is 0.005 second.

6.4 Results

For all the three models, we successfully find a scale factor s that solves the constrained convex optimization in (14). This ensures that $\mathcal{C} = \text{Re} \{ Z^{-1} G, 0, s^{\circ} \}$ satisfies the conditions (6b,6c) in Lemma 3.3. The inclusion of \mathcal{C} inside the safe set for the underwater vehicle example is depicted in Figure 1. Next, we compute the sequences β and η satisfying the conditions (4a-4b) in Lemma 3.3. The increasing sequences are plotted with respect to their indices in Figures 3, 4. Based on the sequences and the set \mathcal{C} , we can derive a scheduling function according to Theorem 5.2. The offline computation time for finding the set \mathcal{C} and sequences β, η , and upper bound on arithmetic complexity of computing the scheduling function based on Theorem 19 are given in Table 2. We evaluate the scheduling function for 100000 randomly sampled points in the joint state space of state and feedback input. Then we plot the scheduling function δ versus the inclusion scaling function $\chi^{-1} z^{\circ}$. These plots are given in Figure 5. We then ran the algorithm in [15] to verify the sampling period bounds for all the 100000 samples and recorded the computation times on the same computing system. We observed a speed gain of 80–170 times in evaluating online our scheduling function as compared to the step-by-step reachability analysis method of [15]. This means that our algorithm is efficient in terms of speed for scheduling a self-triggered controller. The time of evaluating the scheduling function is also negligible since, for 100000 samples, the time of evaluation on the M1 Mac processor is less than a fraction of a second. This is shown in Table 3.

7 RELATED WORK

The major focus of designing self-triggered control has been to ensure the stability of the closed-loop system. The initial works on self-triggered control focused on input-to-state stability for linear systems [19, 20, 25]. They dealt with linear plant and linear controller, and derived the self-triggered control law by exploiting the closed-form expressions of the trajectories of the closed-loop system. Wang and Lemmon addressed the problem of designing linear self-triggered control law for linear systems with the goal of enforcing a desired level of L_2 gain on the closed-loop system [31, 32]. The design of a self-triggered control scheme for nonlinear systems to ensure input-to-state stability was addressed in [5]. Several papers (e.g. [8, 12, 18]) have shown that self-triggered control can reduce the computation load of model predictive control while ensuring the guarantee on the asymptotic stability of the closed loop systems.

Compared to stability, the design of self-triggered control ensuring safety has received limited attention in the literature. The safety aspect of self-triggered control was first considered in [10], where the authors presented a self-triggered control scheme for a nonlinear system with the goal of keeping the closed-loop system within a compact set. Recently, Yang et al. [34] propose a self-triggered control mechanism based on a combination of the Control Lyapunov Function and the Control Barrier Function. Their control mechanism ensures that the trajectory of the closed-loop system never violates the safety condition captured in a positive invariant set. In another recent work, Kooi et al. solve the safe self-triggered control problem for a constrained control system represented as a control differential inclusions with a continuous-time feedback

law [21]. Their technique relies on the availability of a barrier function ensuring the forward invariance property with a degree of robustness against input perturbation. The major limitation of the above-mentioned works is that they overapproximate the rate of change of the system to compute the schedule in real time. However, such an overapproximation can be conservative in the sense that it can reduce the possible range of the sampling time period. On the other hand, our paper precomputes the reachable sets without overapproximating the rate of state change.

The approach in Findeisen [22] proposes to apply a set-based reachability analysis online for discrete-time systems. The proposed reachability analysis can be accurate and compute larger bounds on the sampling period. However, the computation time will significantly increase such that real-time constraints may be violated. In Yulon et al. [14], evaluating a safe scheduling function requires solving a mixed integer linear program. But the computational complexity of mixed integer programming can be very high compared to a simple matrix multiplication followed by binary search in our algorithm (19). In Hashimoto et al. [16], a graph search algorithm is proposed for scheduling the sampling time so that safety constraints are satisfied. But this approach requires discretization of the state space, which can be intractable in real-time for higher dimensional systems.

Although previous approaches on self-triggered controller synthesis perform offline computation of invariant sets (or invariant functions) [10, 14, 16, 22, 34], they do not precompute offline the sets reachable in between sampling times from a given point, which are also required for online scheduling. An important difference of the approach in this paper is that apart from the invariant, additional sets reachable in between sampling times from a point are also precomputed offline and represented in a parametrized way where the parameters depend on the point.

8 CONCLUSION

We presented a self-triggered control scheme for uncertain continuous-time linear systems. Our control mechanism relies on precomputed reachable sets of the closed-loop system, which ensures negligible online computation required for deciding the next trigger time without being too conservative. Our experimental results on standard higher dimensional control benchmarks and the computational complexity analysis establish the feasibility and scalability of our proposed method. In our future work, we plan to extend our technique to nonlinear hybrid systems.

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A APPENDIX

LEMMA A.1. Let \mathbf{z} be a joint trajectory of \mathcal{L} where $\{t_\beta^0\}_{\beta=0}^1$ is the sequence of sampling times and $\mathbf{v} : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}^n$ is the associated disturbance trajectory. Then $\forall t \geq t_\beta^0, \forall \tau \in [t_\beta^0, t_{\beta+1}^0)$,

$$\mathbf{z}^1(t) = \exp^1 A_2^1 t - t_\beta^0 \mathbf{z}^1(t_\beta^0) + \int_{t_\beta^0}^t \exp^1 A_2^1 t - \tau \mathbf{v}^1(\tau) d\tau$$

$$2 \exp^1 A_2^1 t - t_\beta^0 \mathbf{z}^1(t_\beta^0) + \int_{t_\beta^0}^t \exp^1 A_2^1 t - \tau \mathbf{v}^1(\tau) d\tau \quad (21a)$$

$$\mathbf{z}^1(t_{\beta+1}^0) = A_A \exp^1 A_2^1 t_{\beta+1}^0 - t_\beta^0 \mathbf{z}^1(t_\beta^0) + \int_{t_\beta^0}^{t_{\beta+1}^0} \exp^1 A_2^1 t_{\beta+1}^0 - \tau \mathbf{v}^1(\tau) d\tau$$

$$2 A_A \exp^1 A_2^1 t_{\beta+1}^0 - t_\beta^0 \mathbf{z}^1(t_\beta^0) + \int_{t_\beta^0}^{t_{\beta+1}^0} \exp^1 A_2^1 t_{\beta+1}^0 - \tau \mathbf{v}^1(\tau) d\tau \quad (21b)$$

PROOF. For all times $t \geq t_\beta^0$, the joint trajectory \mathbf{z} evolves according to the differential equation

$$\dot{\mathbf{z}}^1(t) = A_2 \mathbf{z}^1(t) + \mathbf{v}^1(t) \quad (22)$$

As the state of the system is a continuous function at all times, while the feedback input trajectory is a continuous function between any two sampling times because there is no reset, we get that at any $t \in [t_\beta^0, t_{\beta+1}^0)$, $\mathbf{z}^1(t)$ is the solution to the above differential equation (22), and this solution is given in (21a). Next, at time t_β^0 , the joint state gets reset as follows: $\mathbf{z}^1(t_\beta^0) = A_A \lim_{g \rightarrow 0} \mathbf{z}^1(t_{\beta-1}^0) =$

$$A_A \exp^1 A_2^1 t_\beta^0 - t_{\beta-1}^0 \mathbf{z}^1(t_{\beta-1}^0) + \int_{t_{\beta-1}^0}^{t_\beta^0} \exp^1 A_2^1 t_\beta^0 - \tau \mathbf{v}^1(\tau) d\tau$$

The following lemma allows us to represent reachable sets as uniformly scaled convex sets containing the origin. This result will be used later to prove the main Lemma 3.3 (Lemma A.3).

LEMMA A.2. Let \mathcal{C} be a convex set such that $0 \in \mathcal{C}$. Let us consider that there exists a function $\chi_{\min} : \mathbb{R}^n \rightarrow \mathbb{R}$ such that

$$\forall z \in \mathbb{R}^n, \chi_{\min}(z) = \min_{a \in \mathcal{C}} \|z - a\| \quad (23a)$$

Let us consider that there exist finite real valued sequences $\{\beta_j\}_{j=0}^m$ and $\{\eta_j\}_{j=0}^m$ satisfying $\forall j \in \{1, \dots, m\}$,

$$\beta_0 = 1, \eta_0 = 0, \beta_{j+1} = \beta_j, \eta_{j+1} = \eta_j \quad (23b)$$

$$\exp^1 A_2 \tau^0 \beta_j, \tau^0 \eta_j \quad (23c)$$

Let us consider a joint trajectory $z \in \text{Trj}^1 L^\circ$ for which $t_{\beta=1}^0$ is the set of feedback sampling times. Then the following are true $\forall z \in Z, t \in \mathbb{T}, t_{\beta=1}^0$.

$$z^1 t_{\beta=1}^0 \in S \quad (24a)$$

$$A_A \exp^{-1} A_2 \epsilon^0 \beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad A_A^{-1} \epsilon^0.$$

$$z^1 t^0 \in \beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad (24b)$$

PROOF. As $t_{\beta=1}^0 \in t_{\beta=1}^0$ as assumed in (1a), we derive the following using (21b) to prove (24a).

$$z^1 t_{\beta=1}^0 \in A_A \exp^{-1} A_2 \epsilon^0 z^1 t_{\beta=1}^0 \in \epsilon^0 \quad A_A^{-1} \epsilon^0$$

$$A_A \exp^{-1} A_2 \epsilon^0 \exp^{-1} A_2^1 t_{\beta=1}^0 t_{\beta=1}^0 \epsilon^0 z^1 t_{\beta=1}^0 \in t_{\beta=1}^0 t_{\beta=1}^0 \epsilon^0$$

$$A_A^{-1} \epsilon^0$$

% by (23c) and because S is convex set and $0 \in S$

$$A_A \exp^{-1} A_2 \epsilon^0 \beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad A_A^{-1} \epsilon^0$$

We next derive the following using (21a) to prove (24b).

$$z^1 t^0 \in \exp^{-1} A_2^1 t_{\beta=1}^0 z^1 t_{\beta=1}^0 \in t_{\beta=1}^0 t_{\beta=1}^0$$

% by (23c) and because S is convex set containing 0

$$\beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon}.$$

LEMMA A.3. Let us consider a set $S \subseteq \mathbb{R}^{\geq 0}$, called safe set and another set $I \subseteq \mathbb{R}^{\geq 0}$, called initial set. Let us consider that there exist a convex set $R \subseteq \mathbb{R}^{\geq 0}$, called sampling time invariant, a function $\chi : R \rightarrow \mathbb{R}^{\geq 0}$, called inclusion scaling function, and finite increasing sequences of positive real numbers β_j $_{j=0}^{\infty}$ and η_j $_{j=0}^{\infty}$ such that (23b,23c) and the following are true.

$$0 \in S, \forall z \in R, z \in \chi^1 z^0, \quad (25a)$$

$$A_A \exp^{-1} A_2 \epsilon^0 \in A_A^{-1} \epsilon^0, \quad (25b)$$

$$I \subseteq S, \beta_1 \succ \eta_1^0 \in S \quad (25c)$$

Let us consider that the number of arithmetic operations involved in evaluating $\chi^1 z^0$ for all $z \in R$ is less than N_j . Let us define a scheduling function $\delta : R \rightarrow \mathbb{R}^{\geq 0}$:

$$\text{Inds}^1 z^0 = j \in \{1, \dots, M\} \mid \chi^1 z^0 \beta_j \succ \eta_j - 1, \quad (25d)$$

$$\text{if } \text{Inds}^1 z^0 < j, \text{ then } \delta^1 z^0 = \max \text{Inds}^1 z^0 \epsilon \quad (25e)$$

$$\text{otherwise } \delta^1 z^0 = \epsilon \quad (25f)$$

Then the following are true.

$$\text{h1i } R \subseteq S, \forall z \in R, z \in S.$$

$$\text{h2i } \text{Number of arithmetic operations for computing the value of } \delta^1 z^0 \text{ for all } z \in R \text{ is not greater than } N_j \cdot 2 \log_2 M^0 + 1.$$

PROOF. Proof of h1i: We prove this by induction. Let us consider a joint trajectory $z \in \text{Trj}^1 L^\circ$ where $t_{\beta=0}^0$ is the sequence of feedback sampling times. As we assumed that a function χ exists where $\forall z \in R, z \in \chi^1 z^0$, so the function χ_{\min} exists where

$\forall z \in R, \chi_{\min}^1 z^0 = \min \{a \in \mathbb{R}^{\geq 0} \mid z \in a \chi^1 z^0\}$. Moreover, we have $\forall z \in R, \chi_{\min}^1 z^0 \leq \chi^1 z^0$.

Let us consider that for some $i \in \mathbb{Z}^+$ we have $z^1 t_{\beta=1}^0 \in S$. Then we shall prove that

$$z^1 t_{\beta=1}^0 \in S, \forall z \in \mathbb{T}, t_{\beta=1}^0 \in \mathbb{T}^0 \subseteq S. \quad (26a)$$

Let us consider two cases, (i) $\text{Inds}^1 z^1 t_{\beta=1}^0 < i$, (ii) $\text{Inds}^1 z^1 t_{\beta=1}^0 = i$.

In the first case, by (25e) and as $\chi_{\min} \leq \chi$, we get

$$\beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon}$$

$$\beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad (26b)$$

$$= \beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad (26c)$$

$$\beta^1 \max \text{Inds}^1 t^0 \in \mathbb{T}^0 \chi^1 z^1 t_{\beta=1}^0 \succ \eta^1 \max \text{Inds}^1 t^0 \in \mathbb{T}^0 \quad (26d)$$

% As V and I are increasing sequences

$$\beta^1 \max \text{Inds}^1 t^0 \chi^1 z^1 t_{\beta=1}^0 \succ \eta^1 \max \text{Inds}^1 t^0 \in \mathbb{T}^0, \quad \text{% by (25e),} \quad (26e)$$

Similarly we can derive:

$$\beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad \beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon}$$

$$1 = \beta_0 \succ \eta_0 \quad \beta_1 \succ \eta_1. \quad (26f)$$

In the second case, we have $t_{\beta=1}^0 \in t_{\beta=1}^0 \delta^1 z^0 = \epsilon$. Also, $t_{\beta=1}^0 \in t_{\beta=1}^0 \epsilon$ because ϵ is the minimum sampling time period for the self-triggered system L . Therefore, $t_{\beta=1}^0 \in t_{\beta=1}^0 \epsilon$. So we have, $\frac{t_{i-1} t_i \epsilon}{n} = 0$ and $\frac{t_{i-1} t_i \epsilon}{n} = \frac{t_{i-1} t_i \epsilon}{n} = 1$. So, we get

$$\beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} = \beta_0 \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta_0$$

% as $z^1 t_{\beta=1}^0 \in S$, so $j_{\min}^1 z^1 t_{\beta=1}^0 = 1$

$$= 1 \quad \chi_{<\beta=}^1 z^1 t_{\beta=1}^0 = 0 = \chi_{<\beta=}^1 z^1 t_{\beta=1}^0 = 1, \quad (26g)$$

$$\beta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta^1 \frac{t_{i-1} t_i \epsilon}{\epsilon} \quad \text{% As } \mathcal{C} \subseteq \mathcal{C}_i \subseteq \mathcal{C}_{i-1} \subseteq \mathcal{C}_i = n^0 \quad (26h)$$

$$\beta_1 \chi_{\min}^1 z^1 t_{\beta=1}^0 \succ \eta_1$$

% as $z^1 t_{\beta=1}^0 \in S$, so $j_{\min}^1 z^1 t_{\beta=1}^0 = 1$

$$\beta_1 \succ \eta_1 \quad (26i)$$

Then by (24a, 26e,26g), we get,

$$z^1 t_{\beta=1}^0 \in A_A \exp^{-1} A_2 \epsilon^0 \in A_A^{-1} \epsilon^0. \quad \text{% by (25b)} \quad (26j)$$

Similarly, by (24b, 26f,26i), we get $z^1 t^0 \in \beta_1 \succ \eta_1^0 \in S$ (by (25c)). So, we have proved (26a).

Then by induction we get that if $I \subseteq S$, then h1i is true. As $I \subseteq S$ by (25c), we get h1i.

Proof of h2i: The arithmetic operations involved in evaluating $\delta^1 z^0$ consist of computing the value of the function $\chi^1 z^0$ and then computing the maximum of $\text{Inds}^1 z^0$. The number of arithmetic operations involved in computing $\chi^1 z^0$ is given to be upper bounded by N_j . On the other hand, we evaluate the maximum value of $\text{Inds}^1 z^0$ using binary search and this complexity in logarithmic in M . We thus get the upper bound given in the above lemma for the arithmetic complexity of evaluating $\delta^1 z^0$.