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# Control of Nonlinear Switched Systems Based on Validated Simulation

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## Abstract

We present an algorithm of control synthesis for nonlinear switched systems, based on an existing procedure of state-space bisection and made available for nonlinear systems with the help of validated simulation. The use of validated simulation also permits to take bounded perturbations and varying parameters into account. It is particularly interesting for safety critical applications, such as in aeronautical, military or medical fields. The whole approach is entirely guaranteed and the induced controllers are *correct-by-design*.

*Key words:* Nonlinear control systems, reachability, formal methods, numerical simulation, control system synthesis

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## 1 Introduction

We focus here on switched control systems, a class of hybrid systems recently used with success in various domains such as automotive industry and power electronics. These systems are merely described by piecewise dynamics, periodically sampled with a given period. At each period, the system is in one and only one mode, decided by a control rule [14,23]. Moreover, the considered systems can switch between any two modes instantaneously. This simplification can be easily by-passed by the addition of intermediate fictitious modes.

In this paper, we consider that these modes are represented by nonlinear ODEs. In order to compute the control of a switched system, we do need the solution of differential equations. In the general case, differential equations can not be integrated formally, and a numerical in-

tegration scheme is used to approximate the state of the system. With the objective of computing a guaranteed control, we base our approach on validated simulation (also called “reachability analysis”). The *guaranteed* or *validated* solution of ODEs using interval arithmetic is mainly based on two kinds of methods based on: i) Taylor series [29,30,24,11] ii) Runge-Kutta schemes [7,15,6,2]. The former is the oldest method used in interval analysis community because the expression of the bound of a Taylor series is simple to obtain. Nevertheless, the family of Runge-Kutta methods is very important in the field of numerical analysis. Indeed, Runge-Kutta methods have several interesting stability properties which make them suitable for an important class of problems. Our tool [1] implements Runge-Kutta based methods which prove their efficiency at low order for short simulation (fixed by sampling period of controller).

In the methods of symbolic analysis and control of hybrid systems, the way of representing sets of state values and computing reachable sets for systems defined by autonomous ordinary differential equations (ODEs), is fundamental (see, e.g., [16,4]). Many tools using, eg. linearization or hybridization of these dynamics are now available (e.g., Spacex [13], Flow\* [8], iSAT-ODE [12]). An interesting approach appeared recently, based on the propagation of reachable sets using guaranteed

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Runge-Kutta methods with adaptive step size control (see [6,19]). An originality of the present work is to use such guaranteed integration methods in the framework of switched systems. This notion of guarantee of the results is very interesting, because we are mainly interested into critical domain, such as aeronautical, military and medical ones. Other symbolic approaches for control synthesis of switched systems include the construction of a discrete abstraction of the original system on a grid of the state space. This can be done by computing symbolic models that are approximately bisimilar [17] or approximately alternatingly similar [34] to the original system. Another recent symbolic approach relies on feedback refinement relations [31]. We compare our work with the last two approaches, which are the closest related methods since the associated tools (respectively PESSOA [26] and SCOTS [32]) are used to perform control synthesis on switched systems without any stability assumptions, such as the present method.

The paper is divided as follows. In Section 2, we introduce some preliminaries on switched systems and some notation used in the following. In Section 3, the guaranteed integration of nonlinear ODEs is presented. In Section 4, we present the main algorithm of state-space bisection used for control synthesis. In Section 5, the whole approach is tested on three examples of the literature. We give some performance tests and compare our approach with the state-of-the-art tools in section 6. We conclude in section 7.

## 2 Switched systems

Let us consider the nonlinear switched system

$$\dot{x}(t) = f_{\sigma(t)}(x(t), d(t)) \quad (1)$$

defined for all  $t \geq 0$ , where  $x(t) \in \mathbb{R}^n$  is the state of the system,  $\sigma(\cdot) : \mathbb{R}^+ \rightarrow U$  is the switching rule, and  $d(t) \in \mathbb{R}^m$  is a bounded perturbation. The finite set  $U = \{1, \dots, N\}$  is the set of switching modes of the system. We focus on sampled switched systems: given a sampling period  $\tau > 0$ , switchings will occur at times  $\tau, 2\tau, \dots$ . The switching rule  $\sigma(\cdot)$  is thus piecewise constant, we will consider that  $\sigma(\cdot)$  is constant on the time interval  $[(k-1)\tau, k\tau)$  for  $k \geq 1$ . We call “*pattern*” a finite sequence of modes  $\pi = (i_1, i_2, \dots, i_k) \in U^k$ . With such a control input, and under a given perturbation  $d$ , we will denote by  $\mathbf{x}(t; t_0, x_0, d, \pi)$  the solution at time  $t$  of the system

$$\begin{aligned} \dot{x}(t) &= f_{\sigma(t)}(x(t), d(t)), \\ x(t_0) &= x_0, \\ \forall j \in \{1, \dots, k\}, \sigma(t) &= i_j \in U \text{ for } t \in [(j-1)\tau, j\tau). \end{aligned} \quad (2)$$

We address the problem of synthesizing a state-dependent switching rule  $\tilde{\sigma}(x)$  for (2) in order to verify some properties. The problem is formalized as follows:

**Problem 1 (Control Synthesis Problem)** *Let us consider a sampled switched system (2). Given three sets  $R, S$ , and  $B$ , with  $R \cup B \subset S$  and  $R \cap B = \emptyset$ , find a rule  $\tilde{\sigma}(x)$  such that, for any  $x(0) \in R$*

- $\tau$ -stability<sup>1</sup> :  $x(t)$  returns in  $R$  infinitely often, at some multiples of sampling time  $\tau$ .
- safety:  $x(t)$  always stays in  $S \setminus B$ .

Under the above-mentioned notation, we propose a procedure which solves this problem by constructing a law  $\tilde{\sigma}(x)$ , such that for all  $x_0 \in R$ , and under the unknown bounded perturbation  $d$ , there exists  $\pi = \tilde{\sigma}(x_0) \in U^k$  for some  $k$  such that:

$$\begin{cases} \mathbf{x}(t_0 + k\tau; t_0, x_0, d, \pi) \in R \\ \forall t \in [t_0, t_0 + k\tau], \mathbf{x}(t; t_0, x_0, d, \pi) \in S \\ \forall t \in [t_0, t_0 + k\tau], \mathbf{x}(t; t_0, x_0, d, \pi) \notin B \end{cases}$$

Such a law permits to perform an infinite-time state-dependent control. The synthesis algorithm is described in Section 4 and involves guaranteed set based integration presented in the next section, the main underlying tool is interval analysis [29]. To tackle this problem, we introduce some definitions. In the following, we will often use the notation  $[x] \in \mathbb{IR}$  (the set of intervals with real bounds) where  $[x] = [\underline{x}, \bar{x}] = \{x \in \mathbb{R} \mid \underline{x} \leq x \leq \bar{x}\}$  denotes an interval. By an abuse of notation  $[x]$  will also denote a vector of intervals, *i.e.*, a Cartesian product of intervals, a.k.a. a *box*. In the following, the sets  $R, S$  and  $B$  are given under the form of boxes.

### Definition 1 (Initial Value Problem (IVP))

*Consider an ODE with a given initial condition*

$$\dot{x}(t) = f(t, x(t), d(t)) \quad \text{with } x(0) \in X_0, d(t) \in [d], \quad (3)$$

*with  $f : \mathbb{R}^+ \times \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n$  assumed to be continuous in  $t$  and  $d$  and globally Lipschitz in  $x$ . We assume that parameters  $d$  are bounded (used to represent a perturbation, a modeling error, an uncertainty on measurement, ...). An IVP consists in finding a function  $x(t)$  described by the ODE (3) for all  $d(t)$  lying in  $[d]$  and for all the initial conditions in  $X_0$ .*

**Definition 2** *Let  $X \subset \mathbb{R}^n$  be a box of the state space. Let  $\pi = (i_1, i_2, \dots, i_k) \in U^k$ . The successor set of  $X$  via  $\pi$ , denoted by  $\text{Post}_\pi(X)$ , is the (over-approximation of the) image of  $X$  induced by application of the pattern  $\pi$ ,*

<sup>1</sup> This definition of stability is different from the stability in the Lyapunov sense.

i.e., the solution at time  $t = k\tau$  of

$$\begin{aligned} \dot{x}(t) &= f_{\sigma(t)}(x(t), d(t)), \\ x(0) &= x_0 \in X, \\ \forall t \geq 0, \quad d(t) &\in [d], \\ \forall j \in \{1, \dots, k\}, \quad \sigma(t) &= i_j \in U \text{ for } t \in [(j-1)\tau, j\tau]. \end{aligned} \quad (4)$$

**Definition 3** Let  $X \subset \mathbb{R}^n$  be a box of the state space. Let  $\pi = (i_1, i_2, \dots, i_k) \in U^k$ . We denote by  $\text{Tube}_\pi(X)$  the union of boxes covering the trajectories of IVP (4), which construction is detailed in Section 3.

### 3 Validated simulation

In this section, we describe our approach for validated simulation based on Runge-Kutta methods [6,2].

A numerical integration method computes a sequence of approximations  $(t_n, x_n)$  of the solution  $x(t; x_0)$  of the IVP defined in Equation (3) such that  $x_n \approx x(t_n; x_{n-1})$ . The simplest method is Euler's method in which  $t_{n+1} = t_n + h$  for some step-size  $h$  and  $x_{n+1} = x_n + h \times f(t_n, x_n, d)$ ; so the derivative of  $x$  at time  $t_n$ ,  $f(t_n, x_n, d)$ , is used as an approximation of the derivative on the whole time interval to perform a linear interpolation. This method is very simple and fast, but requires small step-sizes. More advanced methods coming from the Runge-Kutta family use a few intermediate computations to improve the approximation of the derivative. The general form of an explicit  $s$ -stage Runge-Kutta formula, that is using  $s$  evaluations of  $f$ , is

$$\begin{aligned} x_{n+1} &= x_n + h \sum_{i=1}^s b_i k_i, \\ k_1 &= f(t_n, x_n, d), \\ k_i &= f\left(t_n + c_i h, x_n + h \sum_{j=1}^{i-1} a_{ij} k_j, d\right), \quad i = 2, 3, \dots, s. \end{aligned} \quad (5)$$

The coefficients  $c_i$ ,  $a_{ij}$  and  $b_i$  fully characterize the method. To make Runge-Kutta validated, the challenging question is how to compute a bound on the distance between the true solution and the numerical solution, defined by  $x(t_n; x_{n-1}) - x_n$ . This distance is associated to the *local truncation error* (LTE) of the numerical method.

To bound the LTE, we rely on *order condition* [18] respected by all Runge-Kutta methods. This condition states that a method of this family is of order  $p$  iff the  $p+1$  first coefficients of the Taylor expansion of the solution and the Taylor expansion of the numerical methods are equal. In consequence, LTE is proportional to the Lagrange remainders of Taylor expansions. Formally, LTE

is defined by (see [6]):

$$\begin{aligned} x(t_n; x_{n-1}) - x_n &= \\ &= \frac{h^{p+1}}{(p+1)!} \left( f^{(p)}(\xi, x(\xi; x_{n-1}), d) - \frac{d^{p+1}\phi}{dt^{p+1}}(\eta) \right) \\ &\quad \xi \in ]t_n, t_{n+1}[ \text{ and } \eta \in ]t_n, t_{n+1}[. \end{aligned} \quad (6)$$

The function  $f^{(n)}$  stands for the  $n$ -th derivative of function  $f$  w.r.t. time  $t$  that is  $\frac{d^n f}{dt^n}$  and  $h = t_{n+1} - t_n$  is the step-size. The function  $\phi : \mathbb{R} \rightarrow \mathbb{R}^n$  is defined by  $\phi(t) = x_n + h \sum_{i=1}^s b_i k_i(t)$  where  $k_i(t)$  are defined as Equation (5).

The challenge to make Runge-Kutta integration schemes safe w.r.t. the true solution of IVP is then to compute a bound of the result of Equation (6). In other words we have to bound the value of  $f^{(p)}(\xi, x(\xi; x_{n-1}), d)$  and the value of  $\frac{d^{p+1}\phi}{dt^{p+1}}(\eta)$ . The latter expression is straightforward to bound because the function  $\phi$  only depends on the value of the step-size  $h$ , and so does its  $(p+1)$ -th derivative. The bound is then obtain using the affine arithmetic [10,3].

However, the expression  $f^{(p)}(\xi, x(\xi; x_{n-1}), d)$  is not so easy to bound as it requires to evaluate  $f$  for a particular value of the IVP solution  $x(\xi; x_{n-1})$  at an unknown time  $\xi \in ]t_n, t_{n+1}[$ . The solution used is the same as the one found in [30,7] and it requires to bound the solution of IVP on the interval  $[t_n, t_{n+1}]$ . This bound is usually computed using the Banach's fixpoint theorem applied with the Picard-Lindelöf operator, see [30]. This operator is used to compute an enclosure of the solution  $[\tilde{x}]$  of IVP over a time interval  $[t_n, t_{n+1}]$ , that is for all  $t \in [t_n, t_{n+1}]$ ,  $x(t; x_{n-1}) \in [\tilde{x}]$ . We can hence bound  $f^{(p)}$  substituting  $x(\xi; x_{n-1})$  by  $[\tilde{x}]$ .

For a given pattern of switched modes  $\pi = (i_1, \dots, i_k) \in U^k$  of length  $k$ , we are able to compute, for  $j \in \{1, \dots, k\}$ , the enclosures:

- $[x_j] \ni x(t_j)$ ;
- $[\tilde{x}_j] \ni x(t)$ , for  $t \in [(j-1)\tau, j\tau]$ .

with respect to the system of IVPs:

$$\left\{ \begin{array}{l} \dot{x}(t) = f_{\sigma(t)}(t, x(t), d(t)), \\ x(t_0 = 0) \in [x_0], d(t) \in [d], \\ \sigma(t) = i_1, \forall t \in [0, t_1], t_1 = \tau \\ \quad \vdots \\ \dot{x}(t) = f_{\sigma(t)}(t, x(t), d(t)), \\ x(t_{k-1}) \in [x_{k-1}], d(t) \in [d], \\ \sigma(t) = i_k, \forall t \in [t_{k-1}, t_k], t_k = k\tau \end{array} \right.$$

Thereby, the enclosure  $Post_\pi([x_0])$  is included in  $[x_k]$  and  $Tube_\pi([x_0])$  is included in  $\bigcup_{j=1,\dots,k} [\tilde{x}_j]$ . This applies for all initial states in  $[x_0]$  and all disturbances  $d(t) \in [d]$ . A view of enclosures computed by the validated simulation for one solution obtained for Example 5.2 is shown in Figure 1.

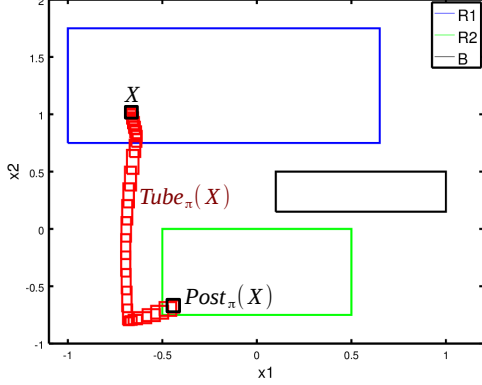


Fig. 1. Functions  $Post_\pi(X)$  and  $Tube_\pi(X)$  for the initial box  $X = [-0.69, -0.64] \times [1, 1.06]$ , with a pattern  $\pi = (1, 3, 0)$ .

## 4 The state-space bisection algorithm

### 4.1 Principle of the algorithm

We describe here the algorithm solving the control synthesis problem (see Problem 1, Section 2). Given the input boxes  $R, S, B$ , and given two positive integers  $K$  and  $D$ , the algorithm provides, when it succeeds, a decomposition  $\Delta$  of  $R$  of the form  $\{V_i, \pi_i\}_{i \in I}$ , with the properties:

$$\bigcup_{i \in I} V_i = R,$$

$$\forall i \in I, Post_{\pi_i}(V_i) \subseteq R,$$

$$\forall i \in I, Tube_{\pi_i}(V_i) \subseteq S,$$

$$\forall i \in I, Tube_{\pi_i}(V_i) \cap B = \emptyset.$$

The sub-boxes  $\{V_i\}_{i \in I}$  are obtained by repeated bisection. At first, function *Decomposition* calls sub-function *Find\_Pattern* which looks for a pattern  $\pi$  of length at most  $K$  such that  $Post_\pi(R) \subseteq R$ ,  $Tube_\pi(R) \subseteq S$  and  $Tube_\pi(R) \cap B = \emptyset$ . If such a pattern  $\pi$  is found, then a uniform control over  $R$  is found (see Figure 2(a)). Otherwise,  $R$  is divided into two sub-boxes  $V_1, V_2$ , by bisecting  $R$  w.r.t. its longest dimension. Patterns are then searched to control these sub-boxes (see Figure 2(b)). If for each  $V_i$ , function *Find\_Pattern* manages to get a pattern  $\pi_i$  of length at most  $K$  verifying  $Post_{\pi_i}(V_i) \subseteq R$ ,  $Tube_{\pi_i}(V_i) \subseteq S$  and  $Tube_{\pi_i}(V_i) \cap B = \emptyset$ , then it is done. If, for some  $V_j$ , no such pattern is found, the procedure is recursively applied to  $V_j$ . It ends with success when every sub-box of  $R$  has a pattern verifying the latter

conditions, or fails when the maximal degree of decomposition  $D$  is reached. The algorithmic form of functions *Decomposition* and *Find\_Pattern* is given in Figures 3 (cf. 4 and in [14,20] for the linear case).

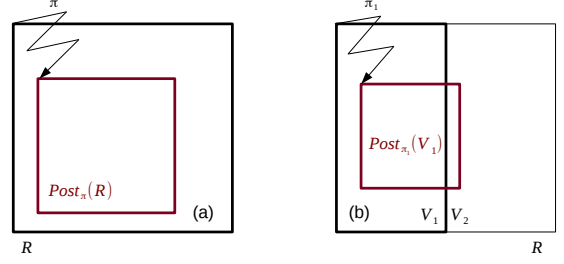


Fig. 2. Principle of the bisection method.

Having defined the control synthesis method, we now introduce the main result of this paper, stated as follows:

**Proposition 1** *The algorithm of Figure 3 with input  $(R, R, S, B, D, K)$  outputs, when it successfully terminates, a decomposition  $\{V_i, \pi_i\}_{i \in I}$  of  $R$  which solves Problem 1.*

**Proof 1** *Let  $x_0 = x(t_0 = 0)$  be an initial condition belonging to  $R$ . If the decomposition has terminated successfully, we have  $\bigcup_{i \in I} V_i = R$ , and  $x_0$  thus belongs to  $V_{i_0}$  for some  $i_0 \in I$ . We can thus apply the pattern  $\pi_{i_0}$  associated to  $V_{i_0}$ . Let us denote by  $k_0$  the length of  $\pi_{i_0}$ . We have:*

- $\mathbf{x}(k_0\tau; 0, x_0, d, \pi_{i_0}) \in R$
- $\forall t \in [0, k_0\tau], \mathbf{x}(t; 0, x_0, d, \pi_{i_0}) \in S$
- $\forall t \in [0, k_0\tau], \mathbf{x}(t; 0, x_0, d, \pi_{i_0}) \notin B$

*Let  $x_1 = \mathbf{x}(k_0\tau; 0, x_0, d, \pi_{i_0}) \in R$  be the state reached after application of  $\pi_{i_0}$  and let  $t_1 = k_0\tau$ . State  $x_1$  belongs to  $R$ , it thus belongs to  $V_{i_1}$  for some  $i_1 \in I$ , and we can apply the associated pattern  $\pi_{i_1}$  of length  $k_1$ , leading to:*

- $\mathbf{x}(t_1 + k_1\tau; t_1, x_1, d, \pi_{i_1}) \in R$
- $\forall t \in [t_1, t_1 + k_1\tau], \mathbf{x}(t; t_1, x_1, d, \pi_{i_1}) \in S$
- $\forall t \in [t_1, t_1 + k_1\tau], \mathbf{x}(t; t_1, x_1, d, \pi_{i_1}) \notin B$

*We can then iterate this procedure from the new state  $x_2 = \mathbf{x}(t_1 + k_1\tau; t_1, x_1, d, \pi_{i_1}) \in R$ . This can be repeated infinitely, yielding a sequence of points belonging to  $R$   $x_0, x_1, x_2, \dots$  attained at times  $t_0, t_1, t_2, \dots$ , at which the patterns  $\pi_{i_0}, \pi_{i_1}, \pi_{i_2}, \dots$  are applied.*

*We furthermore have that all the trajectories stay in  $S$  and never cross  $B$ :  $\forall t \in \mathbb{R}^+, \exists k \geq 0, t \in [t_k, t_{k+1}]$  and  $\forall t \in [t_k, t_{k+1}], \mathbf{x}(t; t_k, x_k, d, \pi_{i_k}) \in S, \mathbf{x}(t; t_k, x_k, d, \pi_{i_k}) \notin B$ . The trajectories thus return infinitely often in  $R$ , while always staying in  $S$  and never crossing  $B$ .*

**Remark 1** *Note that it is possible to perform reachability from a set  $R_1$  to another set  $R_2$  by computing*

**Function:**  $Decomposition(W, R, S, B, D, K)$

**Input:** A box  $W$ , a box  $R$ , a box  $S$ , a box  $B$ , a degree  $D$  of bisection, a length  $K$  of input pattern

**Output:**  $\langle \{(V_i, \pi_i)\}_i, True \rangle$  or  $\langle -, False \rangle$

```

 $(\pi, b) := Find\_Pattern(W, R, S, B, K)$ 
if  $b = True$  then
  return  $\langle \{(W, Pat)\}, True \rangle$ 
else
  if  $D = 0$  then
    return  $\langle -, False \rangle$ 
  else
    Divide equally  $W$  into  $(W_1, W_2)$ 
    for  $i = 1, 2$  do
       $(\Delta_i, b_i) := Decomposition(W_i, R, S, B, D - 1, K)$ 
    end for
    return  $(\bigcup_{i=1,2} \Delta_i, \bigwedge_{i=1,2} b_i)$ 
  end if
end if

```

Fig. 3. Algorithmic form of Function  $Decomposition$ .

**Function:**  $Find\_Pattern(W, R, S, B, K)$

**Input:** A box  $W$ , a box  $R$ , a box  $S$ , a box  $B$ , a length  $K$  of input pattern

**Output:**  $\langle \pi, True \rangle$  or  $\langle -, False \rangle$

```

for  $i = 1 \dots K$  do
   $\Pi :=$  set of input patterns of length  $i$ 
  while  $\Pi$  is non empty do
    Select  $\pi$  in  $\Pi$ 
     $\Pi := \Pi \setminus \{\pi\}$ 
    if  $Post_\pi(W) \subseteq R$  and  $Tube_\pi(W) \subseteq S$ 
    and  $Tube_\pi(W) \cap B = \emptyset$  then
      return  $\langle \pi, True \rangle$ 
    end if
  end while
end for
return  $\langle -, False \rangle$ 

```

Fig. 4. Algorithmic form of Function  $Find\_Pattern$ .

$Decomposition(R_1, R_2, S, B, D, K)$ . The set  $R_1$  is thus decomposed with the objective to send its sub-boxes into  $R_2$ , i.e. for a sub-box  $V$  of  $R_1$ , patterns  $\pi$  are searched with the objective  $Post_\pi(V) \subseteq R_2$  (see Example 5.2).

#### 4.2 The research of patterns

We propose here an improvement of the function  $Find\_Pattern$  given in [9,14,20], which is a naive testing of all the patterns of growing length (up to  $K$ ).

The improved function, denoted here by  $Find\_Pattern2$ ,

exploits heuristics to prune the search tree of patterns. The algorithmic form of  $Find\_Pattern2$  is given in Figure 5. It relies on a new data structure consisting of a list of triplets containing:

- An initial box  $V \subset \mathbb{R}^n$ ,
- A *current* box  $Post_\pi(V)$ , image of  $V$  by the pattern  $\pi$ ,
- The associated pattern  $\pi$ .

For any element  $e$  of a list of this type, we denote by  $e.Y_{init}$  the initial box,  $e.Y_{current}$  the *current* box, and by  $e.\Pi$  the associated pattern. We denote by  $e_{current} = takeHead(\mathcal{L})$  the element on top of a list  $\mathcal{L}$  (this element is removed from list  $\mathcal{L}$ ). The function  $putTail(\cdot, \mathcal{L})$  adds an element at the end of the list  $\mathcal{L}$ .

Let us suppose one wants to control a box  $X \subseteq R$ . The list  $\mathcal{L}$  of Figure 5 is used to store the intermediate computations leading to possible solutions (patterns sending  $X$  in  $R$  while never crossing  $B$  or  $\mathbb{R}^n \setminus S$ ). It is initialized as  $\mathcal{L} = \{(X, X, \emptyset)\}$ . First, a testing of all the control modes is performed (a set simulation starting from  $W$  during time  $\tau$  is computed for all the modes in  $U$ ). The first level of branches is thus tested exhaustively. If a branch leads to crossing  $B$  or  $\mathbb{R}^n \setminus S$ , the branch is cut. Otherwise, either a solution is found or an intermediate state is added to  $\mathcal{L}$ . The next level of branches (patterns of length 2) is then explored from branches that are not cut. And so on iteratively. At the end, either the tree is explored up to level  $K$  (avoiding the cut branches), or all the branches have been cut at lower levels. List  $\mathcal{L}$  is thus of the form  $\{(X, Post_{\pi_i}(X), \pi_i)\}_{i \in I_X}$ , where for each  $i \in I_X$  we have  $Post_{\pi_i}(X) \subseteq S$  and  $Tube_{\pi_i}(X) \cap B = \emptyset$ . Here,  $I_X$  is the set of indexes associated to the stored intermediate solutions,  $|I_X|$  is thus the number of stored intermediate solutions for the initial box  $X$ . The number of stored intermediate solutions grows as the search tree of patterns is explored, then decreases as solutions are validated, branches are cut, or the maximal level  $K$  is reached.

The storage of the intermediate solutions  $Post_{\pi_i}(X)$  allows to reuse the computations already performed. Even if the search tree of patterns is visited exhaustively, it already allows to obtain much better computation times than with Function  $Find\_Pattern$ .

A second list, denoted by  $Solution$  in Figure 5, is used to store the validated patterns associated to  $X$ , i.e. a list of patterns of the form  $\{\pi_j\}_{j \in I'_X}$ , where for each  $j \in I'_X$  we have  $Post_{\pi_j}(X) \subseteq R$ ,  $Tube_{\pi_j}(X) \cap B = \emptyset$  and  $Tube_{\pi_j}(X) \subseteq S$ . Here,  $I'_X$  is the set of indexes associated to the stored validated solutions,  $|I'_X|$  is thus the number of stored validated solutions for the initial box  $X$ . The number of stored validated solutions can only increase, and we hope that at least one solution is found, otherwise, the initial box  $X$  is split in two sub-boxes.

Note that several solutions can be returned by

*Find\_Pattern2*, further optimizations could thus be performed, such as returning the pattern minimizing a given cost function. In practice, and in the examples given below, we return the first validated pattern and stop the computation as soon as it is obtained (see commented line in Figure 5).

Compared to [14,20], this new function highly improves the computation times, even though the complexity of the two functions is theoretically the same, at most in  $O(N^K)$ . A comparison between functions *Find\_Pattern* and *Find\_Pattern2* is given in Section 6.

## 5 Experimentations

In this section, we apply our approach to different case studies taken from the literature. Our solver prototype is written in C++ and based on DynIBEX [1]. The computations times given in the following have been performed on a 2.80 GHz Intel Core i7-4810MQ CPU with 8 GB of memory. Note that our algorithm is mono-threaded so all the experimentation only uses one core to perform the computations. The results given in this section have been obtained with Function *Find\_Pattern2*.

### 5.1 A linear example: boost DC-DC converter

This linear example is taken from [5] and has already been treated with the state-space bisection method in a linear framework in [14].

The system is a boost DC-DC converter with one switching cell. There are two switching modes depending on the position of the switching cell. The dynamics is given by the equation  $\dot{x}(t) = A_{\sigma(t)}x(t) + B_{\sigma(t)}$  with  $\sigma(t) \in U = \{1, 2\}$ . The two modes are given by the matrices:

$$A_1 = \begin{pmatrix} -\frac{r_l}{x_l} & 0 \\ 0 & -\frac{1}{x_c} \frac{1}{r_0+r_c} \end{pmatrix} \quad B_1 = \begin{pmatrix} \frac{v_s}{x_l} \\ 0 \end{pmatrix}$$

$$A_2 = \begin{pmatrix} -\frac{1}{x_l} (r_l + \frac{r_0 r_c}{r_0+r_c}) & -\frac{1}{x_l} \frac{r_0}{r_0+r_c} \\ \frac{1}{x_c} \frac{r_0}{r_0+r_c} & -\frac{1}{x_c} \frac{r_0}{r_0+r_c} \end{pmatrix} \quad B_2 = \begin{pmatrix} \frac{v_s}{x_l} \\ 0 \end{pmatrix}$$

with  $x_c = 70$ ,  $x_l = 3$ ,  $r_c = 0.005$ ,  $r_l = 0.05$ ,  $r_0 = 1$ ,  $v_s = 1$ . The sampling period is  $\tau = 0.5$ . The parameters are exact and there is no perturbation. We want the state to return infinitely often to the region  $R$ , set here to  $[1.55, 2.15] \times [1.0, 1.4]$ , while never going out of the safety set  $S = [1.54, 2.16] \times [0.99, 1.41]$ .

The decomposition was obtained in less than one second with a maximum length of pattern set to  $K = 6$  and

a maximum bisection depth of  $D = 3$ . A simulation is given in Figure 6.

### 5.2 A polynomial example

We consider the polynomial system taken from [25]:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -x_2 - 1.5x_1 - 0.5x_1^3 + u_1 + d_1 \\ x_1 + u_2 + d_2 \end{bmatrix}. \quad (7)$$

The control inputs are given by  $u = (u_1, u_2) = K_{\sigma(t)}(x_1, x_2)$ ,  $\sigma(t) \in U = \{1, 2, 3, 4\}$ , which correspond to four different state feedback controllers  $K_1(x) = (0, -x_2^2 + 2)$ ,  $K_2(x) = (0, -x_2)$ ,  $K_3(x) = (2, 10)$ ,  $K_4(x) = (-1.5, 10)$ . We thus have four switching modes. The disturbance  $d = (d_1, d_2)$  lies in  $[-0.005, 0.005] \times [-0.005, 0.005]$ . The objective is to visit infinitely often two zones  $R_1$  and  $R_2$ , without going out of a safety zone  $S$ , and while never crossing a forbidden zone  $B$ . Two decompositions are performed:

- a decomposition of  $R_1$  which returns  $\{(V_i, \pi_i)\}_{i \in I_1}$  with:
  - $\bigcup_{i \in I_1} V_i = R_1$ ,
  - $\forall i \in I_1, Post_{\pi_i}(V_i) \subseteq R_2$ ,
  - $\forall i \in I_1, Tube_{\pi_i}(V_i) \subseteq S$ ,
  - $\forall i \in I_1, Tube_{\pi_i}(V_i) \cap B = \emptyset$ .
- a decomposition of  $R_2$  which returns  $\{(V_i, \pi_i)\}_{i \in I_2}$  with:
  - $\bigcup_{i \in I_2} V_i = R_2$ ,
  - $\forall i \in I_2, Post_{\pi_i}(V_i) \subseteq R_1$ ,
  - $\forall i \in I_2, Tube_{\pi_i}(V_i) \subseteq S$ ,
  - $\forall i \in I_2, Tube_{\pi_i}(V_i) \cap B = \emptyset$ .

The input boxes are the following:

$$R_1 = [-0.5, 0.5] \times [-0.75, 0.0],$$

$$R_2 = [-1.0, 0.65] \times [0.75, 1.75],$$

$$S = [-2.0, 2.0] \times [-1.5, 3.0],$$

$$B = [0.1, 1.0] \times [0.15, 0.5].$$

The sampling period is set to  $\tau = 0.15$ . The decompositions were obtained in 2 minutes and 30 seconds with a maximum length of pattern set to  $K = 12$  and a maximum bisection depth of  $D = 5$ . A simulation is given in Figure 7 in which the disturbance  $d$  is chosen randomly in  $[-0.005, 0.005] \times [-0.005, 0.005]$  at every time step.

### 5.3 Building ventilation

We consider a building ventilation application adapted from [27]. The system is a four room apartment subject

**Function:**  $Find\_Pattern2(W, R, S, B, K)$

**Input:** A box  $W$ , a box  $R$ , a box  $S$ , a box  $B$ , a length  $K$  of input pattern

**Output:**  $\langle \pi, True \rangle$  or  $\langle -, False \rangle$

---

```

Solution = {∅}
L = {(W, W, ∅)}
while L ≠ ∅ do
  ecurrent = takeHead(L)
  for i ∈ U do
    if Posti(ecurrent.Ycurrent) ⊆ R and Tubei(ecurrent.Ycurrent) ∩ B = ∅ and
       Tubei(ecurrent.Ycurrent) ⊆ S then
      putTail(Solution, ecurrent.Π + i) /*can be replaced by: "return ⟨ecurrent.Π + i, True⟩" */
    else
      if Tubei(ecurrent.Ycurrent) ∩ B ≠ ∅ or Tubei(ecurrent.Ycurrent) ⊄ S then
        discard ecurrent
      end if
    else
      if Tubei(ecurrent.Ycurrent) ∩ B = ∅ and Tubei(ecurrent.Ycurrent) ⊆ S then

        if Length(Π) + 1 < K then
          putTail(L, (ecurrent.Yinit, Posti(ecurrent.Ycurrent), ecurrent.Π + i))
        end if
      end if
    end if
  end for
end while
return ⟨-, False⟩ if no solution is found, or ⟨π, True⟩, π being any pattern validated in Solution.

```

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Fig. 5. Algorithmic form of Function  $Find\_Pattern2$ .

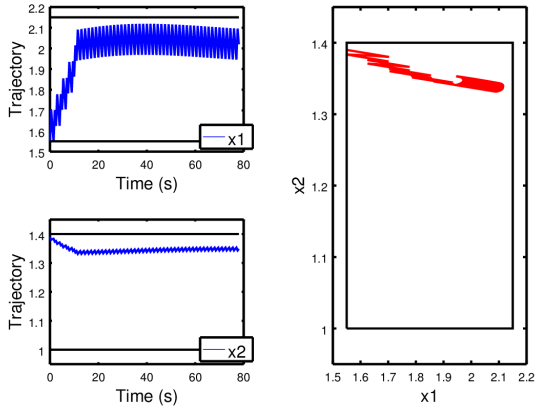


Fig. 6. Simulation from the initial condition  $(1.55, 1.4)$ . The box  $R$  is in plain black. The trajectory is plotted within time for the two state variables on the left, and in the state-space plane on the right.

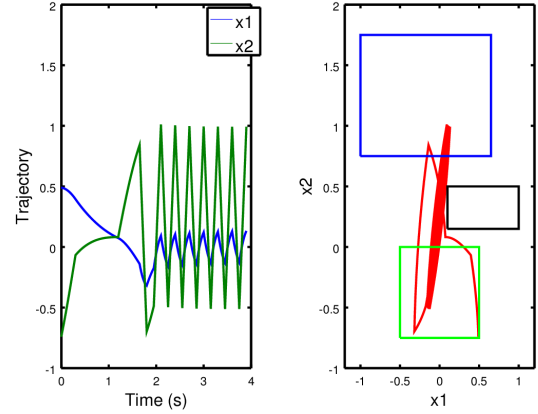


Fig. 7. Simulation from the initial condition  $(0.5, -0.75)$ . The trajectory is plotted within time on the left, and in the state space plane on the right. In the state space plane, the set  $R_1$  is in plain green,  $R_2$  in plain blue, and  $B$  in plain black.

ing equation:

$$\frac{dT_i}{dt} = \sum_{j \in \mathcal{N}^*} a_{ij}(T_j - T_i) + \delta_{s_i} b_i (T_{s_i}^4 - T_i^4) + c_i \max\left(0, \frac{V_i - V_i^*}{V_i - V_i^*}\right) (T_u - T_i). \quad (8)$$

to heat transfer between the rooms, with the external environment, with the underfloor, and with human beings. The dynamics of the system is given by the follow-



The state of the system is given by the temperatures in the rooms  $T_i$ , for  $i \in \mathcal{N} = \{1, \dots, 4\}$ . Room  $i$  is subject to heat exchange with different entities stated by the indexes  $\mathcal{N}^* = \{1, 2, 3, 4, u, o, c\}$ .

The heat transfer between the rooms is given by the coefficients  $a_{ij}$  for  $i, j \in \mathcal{N}^2$ , and the different perturbations are the following:

- The external environment: it has an effect on room  $i$  with the coefficient  $a_{io}$  and the outside temperature  $T_o$ , varying between  $27^\circ\text{C}$  and  $30^\circ\text{C}$ .
- The heat transfer through the ceiling: it has an effect on room  $i$  with the coefficient  $a_{ic}$  and the ceiling temperature  $T_c$ , varying between  $27^\circ\text{C}$  and  $30^\circ\text{C}$ .
- The heat transfer with the underfloor: it is given by the coefficient  $a_{iu}$  and the underfloor temperature  $T_u$ , set to  $17^\circ\text{C}$  ( $T_u$  is constant, regulated by a PID controller).
- The perturbation induced by the presence of humans: it is given in room  $i$  by the term  $\delta_{s_i} b_i (T_{s_i}^4 - T_i^4)$ , the parameter  $\delta_{s_i}$  is equal to 1 when someone is present in room  $i$ , 0 otherwise, and  $T_{s_i}$  is a given identified parameter.

The control  $V_i$ ,  $i \in \mathcal{N}$ , is applied through the term  $c_i \max(0, \frac{V_i - V_i^*}{V_i - V_i^*})(T_u - T_i)$ . A voltage  $V_i$  is applied to force ventilation from the underfloor to room  $i$ , and the command of an underfloor fan is subject to a dry friction. Because we work in a switched control framework,  $V_i$  can take only discrete values, which removes the problem of dealing with a “max” function in interval analysis. In the experiment,  $V_1$  and  $V_4$  can take the values 0V or 3.5V, and  $V_2$  and  $V_3$  can take the values 0V or 3V. This leads to a system of the form (1) with  $\sigma(t) \in U = \{1, \dots, 16\}$ , the 16 switching modes corresponding to the different possible combinations of voltages  $V_i$ . The sampling period is  $\tau = 10\text{s}$ .

The parameters  $T_{s_i}$ ,  $V_i^*$ ,  $\bar{V}_i$ ,  $a_{ij}$ ,  $b_i$ ,  $c_i$  are given in [27] and have been identified with a proper identification procedure detailed in [28]. Note that here we have neglected the term  $\sum_{j \in \mathcal{N}} \delta_{d_{ij}} c_{i,j} * h(T_j - T_i)$  of [27], representing the perturbation induced by the open or closed state of the doors between the rooms. Taking a “max” function into account with interval analysis is actually still a difficult task. However, this term could have been taken into account with a proper regularization (smoothing).

The decomposition was obtained in 4 minutes with a maximum length of pattern set to  $K = 2$  and a maximum bisection depth of  $D = 4$ . The perturbation due to human beings has been taken into account by setting the parameters  $\delta_{s_i}$  equal to the whole interval  $[0, 1]$  for the decomposition, and the imposed perturbation for the simulation is given Figure 8. The temperatures  $T_o$  and  $T_c$  have been set to the interval  $[27, 30]$  for the decomposition, and are set to  $30^\circ\text{C}$  for the simulation. A sim-

Table 1  
Comparison of *Find\_Pattern* and *Find\_Pattern2*.

Example	Computation time	
	<i>Find_Pattern</i>	<i>Find_Pattern2</i>
DC-DC Converter	1609 s	< 1 s
Polynomial example	Time Out	150 s
Building ventilation	272 s	228 s

ulation of the controller obtained with the state-space bisection procedure is given in Figure 9, where the control objective is to stabilize the temperature in  $[20, 22]^4$  while never going out of  $[19, 23]^4$ .

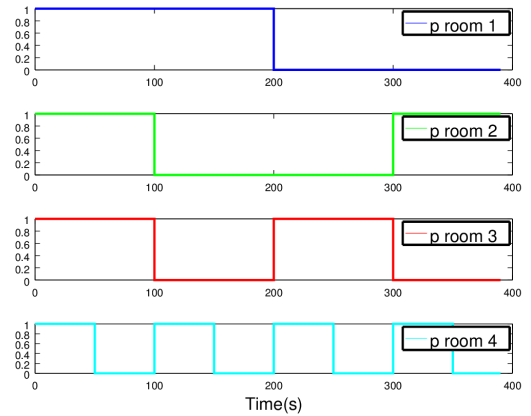


Fig. 8. Perturbation (presence of humans) imposed within time in the different rooms.

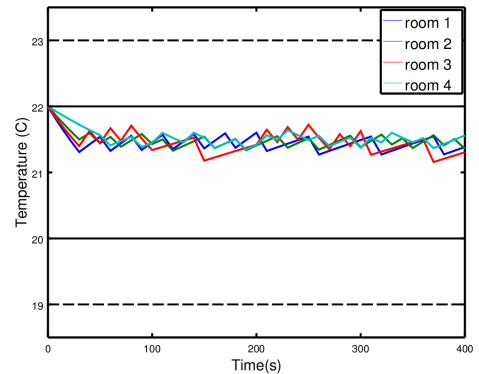


Fig. 9. Simulation from the initial condition  $(22, 22, 22, 22)$ . The objective set  $R$  is in plain black and the safety set  $S$  is in dotted black.

## 6 Performance tests

We present a comparison of the computation times obtained with functions *Find\_Pattern*, *Find\_Pattern2*, and with the state-of-the-art tools PESSOA [26] and SCOTS [32].

Table 2  
Comparison with state-of-the-art tools.

Example	Computation time		
	FP2	SCOTS	PESSOA
DC-DC Converter	< 1 s	43 s	760 s
Polynomial example	150 s	131 s	--
Unicycle [34,31]	3619 s	492 s	516 s

Table 1 shows a comparison of functions *Find\_Pattern* and *Find\_Pattern2*, which shows that the new version highly improves the computation times. We can note that the new version is all the more efficient as the length of the patterns increases, and as obstacles cut the research tree of patterns. This is why we observe significant improvements on the examples of the DC-DC converter and the polynomial example, and not on the building ventilation example, which only requires patterns of length 2, and presents no obstacle.

Table 2 shows of comparison of function *Find\_Pattern2* with state-of-the-art tools SCOTS and PESSOA. On the example of the DC-DC converter, our algorithm manages to control the whole state-space  $R = [1.55, 2.15] \times [1.0, 1.4]$  in less than one second, while SCOTS and PESSOA only control a part of  $R$ , and with greater computation times. Note that these computation times vary with the number of discretization points used in both, but even with a very fine discretization, we never managed to control the whole box  $R$ . For the polynomial example, we manage to control the whole boxes  $R_1$  and  $R_2$ , such as SCOTS and in a comparable amount of time. However, PESSOA does not support natively this kind of nonlinear systems. We compared our method on a last case study on which PESSOA and SCOTS perform well (see [34,31] for details of this case study, and see Appendix for a simulation obtained using our method). For this case study, we have not obtained as good computations times as they have. This comes from the fact that this example requires a high number of switched modes, long patterns, as well as a high number of boxes to tile the state-space. Note that for this case study we used an automated pre-tiling of the state-space permitting to decompose the reachability problem in a sequence of reachability problems. This is in fact the most difficult case of application of our method. This reveals that our method is more adapted when either the number of switched modes or the length of patterns is not high (though it can be handled at the cost of high computation times). Another advantage is that we do not require a homogeneous discretization of the state space. We can thus tile large parts of the state-space using only few boxes, and this often permits to consider much less symbolic states than with discretization methods, especially in high dimensions (see [22]).

## 7 Conclusion

We presented a method of control synthesis for nonlinear switched systems, based on a simple state-space bisection algorithm, and on validated simulation. The approach permits to deal with stability, reachability, safety and forbidden region constraints. Varying parameters and perturbations can be easily taken into account with interval analysis. The approach has been numerically validated on several examples taken from the literature, a linear one with constant parameters, and two nonlinear ones with varying perturbations. Our approach compares well with the state-of-the-art tools SCOTS and PESSOA.

We would like to point out that the exponential complexity of the algorithms presented here, which is inherent to guaranteed methods, is not prohibitive. Two approaches have indeed been developed to overcome this exponential complexity. A first approach is the use of compositionality, which permits to split the system in two (or more) sub-systems, and to perform control synthesis on these sub-systems of lower dimensions. This approach has been successfully applied in [22] to a system of dimension 11, and we are currently working on applying this approach to the more general context of contract-based design [33]. A second approach is the use of Model Order Reduction, which allows to approximate the full-order system (1) with a reduced-order system, of lower dimension, on which it is possible to perform control synthesis. The bounding of the trajectory errors between the full-order and the reduced-order systems can be taken into account, so that the induced controller is guaranteed. This approach, described in [21], has been successfully applied on (space-discretized) partial differential equations, leading to systems of ODEs of dimension up to 100000. The present work is a potential ground for the application of such methods to control of nonlinear partial differential equations, with the use of proper nonlinear model order reduction techniques.

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## 8 Appendix

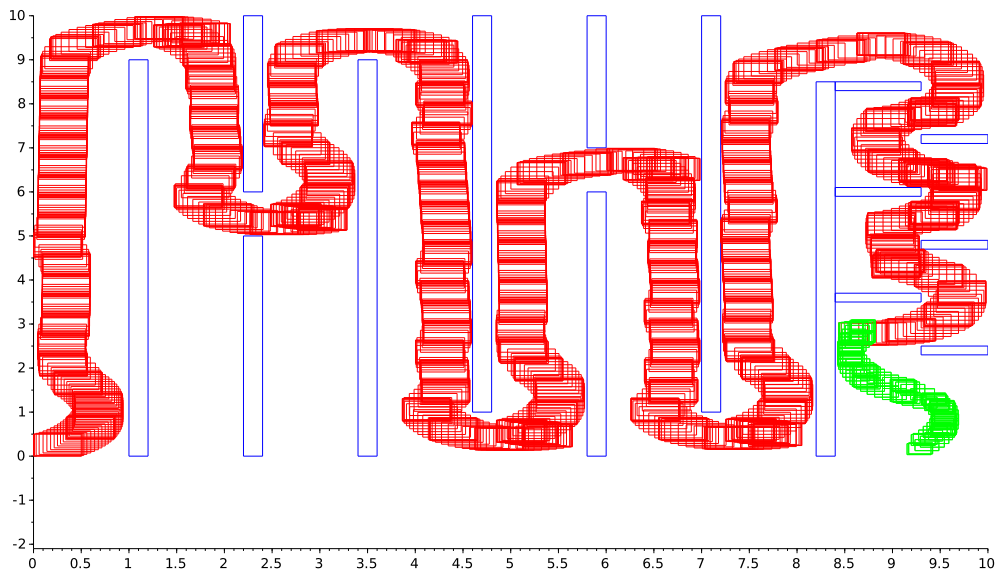


Fig. 10. Simulation of the unicycle example.