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Pre-orders for Reasoning about Input-to-State Stability Properties of Hybrid Systems

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ABSTRACT

In this paper, we investigate pre-orders for reasoning about input-to-state stability properties of hybrid systems. We define the notions of *uniformly continuous input simulations* and *bisimulations*, which extend the notions in previous work to include inputs. We show that uniformly continuous input bisimulations preserve incremental input-to-state stability of hybrid systems, and thus provide a basis for constructing abstractions for verification. We show that Lyapunov function based input-to-state stability analysis can be cast in our framework as constructing a simpler one-dimensional system, using a uniformly continuous input simulation, which is input-to-state stable, and thus, inferring the input-to-state stability of the original system.

1. INTRODUCTION

Input-to-state stability is an important property of systems when studying robustness of systems with respect to input. It captures the notion that small changes in the input of a system result in only small changes to the behavior of the system. In this paper, we investigate pre-orders for reasoning about input-to-state stability properties of hybrid systems.

With the increasing complexity of hybrid systems in today's applications, it is essential to develop automated methods for verification. One of the main challenges to this grand agenda has been the scalability of the verification methods. It has been proven more often than not that one has to rely on some notion of abstraction to reduce the enormous state space of the systems which is difficult to handle directly. Our work here is geared towards developing a formal framework for carrying out approximation based analysis of input-to-state stability properties of hybrid systems. At the crux of developing such methods lies understanding what relations between a system and its approximation preserve properties of interest. Hence, we study pre-orders on systems which preserving input-to-state stability.

Current techniques for proving stability of systems is based on establishing the existence of Lyapunov functions. Automation of these techniques for stability analysis essentially depends on automating the search for the Lyapunov functions. While the exact characterization of the existence and form of Lyapunov functions are know in the purely continuous case, for linear and certain classes of non-linear systems, the same is not true even for the linear case in the hybrid setting [15, 3]. This work is aimed towards developing an abstraction refinement framework for the analysis of stability properties. The task is challenging even for the case of linear hybrid systems. Establishing pre-orders which preserve stability properties is a first step towards constructing simpler systems for the verification of stability properties.

Approximation based analysis relies on being able to construct abstractions or "simplifications" of a system efficiently, which can then be verified easily. The notions of *simulation* and *bisimulation*, introduced in the context of concurrent processes [18], to study equivalences between processes, have been the basis for designing abstraction and minimization techniques for analysis of a variety of discrete-time properties [17]. Properties expressible in temporal and modal logics, such as, Linear-time Temporal Logic, Computation Tree Logic and μ-calculus are known to be invariant under bisimulation, in that, if two systems are known to be bisimilar, then either both of them satisfy the property or none of them satisfy the property. Hence, one can reduce the analysis of a system to that of a simpler system which is bisimilar. Similarly, the weaker notion of simulation preserves the property in one direction, that is, if a system $\mathcal{A}$ is simulated by a system $\mathcal{B}$ and $\mathcal{B}$ satisfies the property, then $\mathcal{A}$ satisfies the property. Properties in a safe fragment of the above logics are preserved by simulation in the above sense.

Even in the hybrid setting, bisimulations have been used to design algorithms for analysis of various classes of systems. Some of these classes include *Timed automata* [1], *O-minimal hybrid automata* [16, 4] and *STORMED hybrid systems* [22]. More recently, approximate notions of simulation and bisimulation have been proposed [9, 8] and used in the analysis of reachability and safety properties [10, 20].

However, when one turns to the analysis of stability properties, it has been shown that bisimulations do not suffice. In particular, it was shown in [6] that Lyapunov stability with respect to a set of equilibrium points is not preserved by bisimulations. Hence, additional continuity constraints were imposed on the bisimulation relation to achieve invari-

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ance under Lyapunov stability. In [19], it was shown that for stability with respect to a set of *trajectories*, the continuity constraints imposed by [6] do not suffice to preserve stability. Hence, the notion of uniformly continuous bisimulation was introduced, and Lyapunov and asymptotic stability of trajectories were shown to be invariant under this notion. In this paper, we extend these results to the case with inputs.

We study two properties with respect to inputs, namely, input-to-state stability and incremental input-to-state stability. Input-to-state stability refers to the stability of the system with respect to the origin under small perturbations to the input, where as, incremental input-to-state stability generalizes it to any reference trajectory. The extension of the results in [19] to the case of inputs has been challenging due to the lack of a definition of incremental input-to-state stability similar to the previous definition. So, we first provide a characterization of incremental input-to-state stability defined in [2] in an "ϵ-δ" form, and use that to provide a definition of incremental input-to-state stability for hybrid systems. A slight deviation is our definition is the notion of distance between executions, for which we use the notion of graphical distance introduced in [11]. However, our results are not sensitive to the particular choice of the definition of distance. We introduce the notion of *uniformly continuous input simulations* and *bisimulations*, which extend the classical notion of bisimulations for systems with input, and the uniform continuity constraints introduced in [19]. We show that incremental input-to-state stability is invariant under uniformly continuous input bisimulation, and obtain that input-to-state stability is invariant under uniformly continuous input bisimulations as a corollary. Next, we argue that uniformity conditions on both input and state are essential for preserving the properties, that is, continuity alone does not suffice.

Finally, we examine whether the notion introduced is a reasonable pre-order for reasoning about input-to-state stability properties. In particular, we ask whether we can hope to construct simpler systems which are related to the original system by uniformly continuous input simulations and bisimulations, and show that the simplification is input-to-state stable. First, we present some examples which illustrate the approximation based analysis of the stability of system with respect to input. Next, we show that the classical Lyapunov based approach for proving input-to-state stability can be considered as a concrete method for constructing simplifications which are uniformly continuously input similar to the original system. More precisely, we show that Lyapunov function based analysis of input-to-state stability can be cast as constructing simpler one-dimensional systems which are input-to-state stable, where the Lyapunov function serves as a uniformly continuous input simulation between the original system and the one-dimensional system.

2. PRELIMINARIES

Notation.

Let $\mathbb{R}$ and $\mathbb{R}^+$ denote the set of reals and non-negative reals, respectively. Let $\mathbb{R}_\infty$ denote the set $\mathbb{R}^+ \cup \{\infty\}$, where ∞ denotes the largest element of $\mathbb{R}_\infty$, that is, $x < \infty$ for all $x \in \mathbb{R}^+$. Also, for all $x \in \mathbb{R}_\infty$, $x + \infty = \infty$. Let $\mathbb{N}$ denote the set of all natural numbers $\{0, 1, 2, \cdots\}$, and let $[n]$ denote the first n natural numbers, that is, $[n] = \{0, 1, 2, \cdots, n-1\}$. Let $PreInt$ denote the set consisting of all closed intervals of the form $[0, T]$, where $T \in \mathbb{R}^+$, and the infinite interval $[0, \infty)$. Given an $x \in \mathbb{R}^n$, we use $|x|$ to denote the Euclidean norm of x. And, given a function $f : A \to \mathbb{R}^m$, we use $\|f\|_\infty$ to denote $\sup_{a \in A} |f(a)|$.

Functions and Relations.

Given a function F, let $Dom(F)$ denote the domain of F. Given a function $F : A \to B$ and a set $A' \subseteq A$, $F(A')$ denotes the set $\{F(a) \,|\, a \in A'\}$. Given a binary relation $R \subseteq A \times B$, R^{-1} denotes the set $\{(x, y) \,|\, (y, x) \in R\}$. For a binary relation R, we will interchangeably use "$(x, y) \in R$" and "$R(x, y)$" to denote that $(x, y) \in R$.

Sequences.

A sequence σ is a function whose domain is either $[n]$ for some $n \in \mathbb{N}$ or the set of natural numbers $\mathbb{N}$. We denote the set of all domains of sequences as $SeqDom$. Length of a sequence σ, denoted $|\sigma|$, is n if $Dom(\sigma) = [n]$ or ∞ otherwise. Given a sequence $\sigma : \mathbb{N} \to \mathbb{R}$ and an element r of $\mathbb{R}_\infty$ we use $\sum_{i=0}^{\infty} \sigma(i) = r$ to denote the standard limit condition $\lim_{N \to \infty} \sum_{i=0}^{N} \sigma(i) = r$.

Extended Metric Space.

An *extended metric space* is a pair (M, d) where M is a set and $d : M \times M \to \mathbb{R}_\infty$ is a distance function such that for all m_1, m_2 and m_3, the following hold: (Identity of indiscernibles) $d(m_1, m_2) = 0$ if and only if $m_1 = m_2$, (Symmetry) $d(m_1, m_2) = d(m_2, m_1)$, and (Triangle inequality) $d(m_1, m_3) \leq d(m_1, m_2) + d(m_2, m_3)$. When the metric on M is clear we will simply refer to M as a metric space.

We define an open ball of radius ϵ around a point x to be the set of all points which are within a distance ϵ from x. Formally, an *open ball* is a set of the form $B_\epsilon(x) = \{y \in M \,|\, d(x, y) < \epsilon\}$. An *open set* is a subset of M which is a union of open balls. Given a set $X \subseteq M$, a *neighborhood* of X is an open set in M which contains X. Given a subset X of M, an ϵ-neighborhood of X is the set $B_\epsilon(X) = \bigcup_{x \in X} B_\epsilon(x)$. A subset X of M is *compact* if for every collection of open sets $\{U_\alpha\}_{\alpha \in A}$ such that $X \subseteq \bigcup_{\alpha \in A} U_\alpha$, there is a finite subset J of A such that $X \subseteq \bigcup_{i \in J} U_i$.

Set Valued Functions.

We consider set valued functions and define continuity of these functions. We choose not to treat set valued functions as single valued functions whose co-domain is a power set, since as argued in [13], it leads to strong notions of continuity, which are not satisfied by many functions. A *set valued function* $F : A \rightsquigarrow B$ is a function which maps every element of A to a set of elements in B. Given a set $A' \subseteq A$, $F(A')$ will denote the set $\bigcup_{a \in A'} F(a)$. Given a binary relation $R \subseteq A \times B$, we use R also to denote the set valued function $R : A \rightsquigarrow B$ given by $R(x) = \{y \,|\, (x, y) \in R\}$. Further, $F^{-1} : B \rightsquigarrow A$ will denote the set valued function which maps $b \in B$ to the set $\{a \in A \,|\, b \in F(a)\}$.

Continuity of Set Valued Functions.

Let $F : A \rightsquigarrow B$ be a set valued function, where A and B are extended metric spaces. We define upper semi-continuity of F which is a generalization of the "ϵ, δ - definition" of continuity for single valued functions [13]. The function $F : A \rightsquigarrow B$ is said to be *upper semi-continuous* at $a \in Dom(F)$

if and only if

$$\forall \epsilon > 0, \exists \delta > 0 \,\text{such that}\, F(B_\delta(a)) \subseteq B_\epsilon(F(a)).$$

If F is upper semi-continuous at every $a \in Dom(F)$ we simply say that F is upper semi-continuous. Next we define a "uniform" version of the above definition, where, analogous to the case of single valued functions, corresponding to an ϵ, there exists a δ which works for every point in the domain.

Definition. A function $F : A \rightsquigarrow B$ is said to be *uniformly continuous* if and only if

$$\forall \epsilon > 0, \exists \delta > 0 \,\text{such that}$$

$$\forall a \in Dom(A), F(B_\delta(a)) \subseteq B_\epsilon(F(a)).$$

Given an $\epsilon > 0$, we call a $\delta > 0$ satisfying the above condition, a *uniformity constant of* F corresponding to ϵ. We refer to uniform upper semi-continuity as just uniform continuity, because it turns out that the two notions of upper and lower semi-continuity coincide with the addition of uniformity condition, i.e., uniform upper semi-continuity is equivalent to uniform lower semi-continuity. Next, we state some properties about upper semi-continuous and uniformly continuous functions.

PROPOSITION 1. *Let $F : A \rightsquigarrow B$ be a set-valued upper semi-continuous function. Then:*

- *F^{-1} is also an upper semi-continuous function.*
- *If A is compact, then F is also uniformly continuous.*

Class $\mathcal{K}$, L, $\mathcal{K}_\infty$ and $\mathcal{KL}$ functions.

A continuous function $\alpha : [0, a) \to [0, \infty)$ is said to belong to *class* $\mathcal{K}$ if it is strictly increasing and $\alpha(0) = 0$. A continuous function $\alpha : [0, \infty) \to [0, \infty)$ is said to belong to *class* $\mathcal{K}_\infty$ if α is a class $\mathcal{K}$ function and $\alpha(r) \to \infty$ as $r \to \infty$. A continuous function $\varphi : [0, \infty) \to [0, \infty)$ is said to be of *class* L if it is monotonically decreasing and $\lim_{s\to\infty} \varphi(s) = 0$. A continuous function $\beta : [0, a) \times [0, \infty) \to [0, \infty)$ is a *class* $\mathcal{KL}$ function if it is a class $\mathcal{K}$ function with respect to the first argument and class L with respect to the second argument, that is, for a fixed s, $\beta(r, s)$ is a class $\mathcal{K}$ function and for a fixed r, $\beta(r, s)$ is a class L function.

3. HYBRID SYSTEMS WITH INPUT

In this section, we present a general formalism for representing hybrid systems with inputs, called *hybrid input transition systems*. Hybrid systems are systems exhibiting mixed discrete-continuous behaviors. We represent the continuous behavior using a pair of input and state *trajectories* which capture the values of input and state over an interval of time; and represent the discrete behavior using *transitions* which capture instantaneous changes to the state due to impulse inputs. We will not concern ourselves with the exact representation of the models, see, for example, the hybrid automaton model [12]. However, our abstract model captures the behaviors arising from a hybrid automaton model.

3.1 Trajectories

A *trajectory* τ over a set A is a function $\tau : I \to A$, where $I \in PreInt$. We denote the set of all trajectories over A as $Traj(A)$. Let us define a function $Size : Traj(A) \to \mathbb{R}_\infty$ which assigns a size to the trajectories. For $\tau \in Traj(A)$, $Size(\tau) = T$ if $Dom(\tau) = [0, T]$ and $Size(\tau) = \infty$ if $Dom(\tau) = [0, \infty)$.

Relating trajectories.

Given a relation $R \subseteq A_1 \times A_2$ and trajectories $\mathbf{a}_1 \in Traj(A_1)$ and $\mathbf{a}_2 \in Traj(A_2)$, we say that $\mathbf{a}_1$ and $\mathbf{a}_2$ are related by R, denoted $R(\mathbf{a}_1, \mathbf{a}_2)$ if $Dom(\mathbf{a}_1) = Dom(\mathbf{a}_2)$ and for every $t \in Dom(\mathbf{a}_1)$, $R(\mathbf{a}_1(t), \mathbf{a}_2(t))$. We use $R(\mathbf{a}_1)$ to denote the set $\{\mathbf{a}_2 \,|\, R(\mathbf{a}_1, \mathbf{a}_2)\}$.

Input-State Trajectories.

An input-state trajectory specifies the state evolution on an input signal. Let us fix an *input space* U and a *state space* S. An *input-state trajectory* over a pair (U, S) is a pair of trajectories $(\mathbf{u}, \mathbf{s})$ from $Traj(U) \times Traj(S)$ such that $Dom(\mathbf{u}) = Dom(\mathbf{s})$. We call $\mathbf{u}$ an *input trajectory* and $\mathbf{s}$ a *state trajectory*. We will use $ISTraj(U, S)$ to denote the set of all input-state trajectories over (U, S).

Size, First, Last, States, Inputs of Input-State Trajectories.

We extend $Size$ to input-state trajectories in the natural way, namely, $Size(\mathbf{u}, \mathbf{s}) = Size(\mathbf{u}) = Size(\mathbf{s})$. We use $First((\mathbf{u}, \mathbf{s}))$ to denote the initial state, that is, $\mathbf{s}(0)$, and $Last((\mathbf{u}, \mathbf{s}))$ to denote the last state, that is, $\mathbf{s}(Size(\mathbf{s}))$, if $Size(\mathbf{s})$ is not ∞, and is not defined otherwise. Given a state trajectory $\mathbf{s}$, we use $States(\mathbf{s})$ to denote the set of states occurring in $\mathbf{s}$, namely, $\{\mathbf{s}(t) \,|\, t \in Dom(\mathbf{s})\}$. Also, for a input-state trajectory we use $States((\mathbf{u}, \mathbf{s}))$ to denote $States(\mathbf{s})$. Similarly, for an input trajectory $\mathbf{u}$, we use $Inputs(\mathbf{u})$ to denote the set of inputs occurring in $\mathbf{u}$, namely, $\{\mathbf{u}(t) \,|\, t \in Dom(\mathbf{u})\}$.

3.2 Transitions

A transition specifies the instantaneous change in a state resulting from an impulse input. A *transition* over a pair (U, S) is an element of $U \times (S \times S)$. A transition $(u, (s_1, s_2))$ denotes the fact that if an input impulse u is applied to the system in state s_1, then the system state changes to s_2. We will represent a transition $(u, (s_1, s_2))$ as $s_1 \xrightarrow{u} s_2$. We denote the set of all transition over a pair (U, S) as $Trans(U, S)$.

Size, First, Last, States, Inputs of Transitions.

We define $Size$ of a transition $(u, (s_1, s_2))$ to be 0. As before, given $\tau = (u, (s_1, s_2))$, we use $First(\tau)$ and $Last(\tau)$ to denote the state of the system before and after the transition, namely, $First(\tau) = s_1$ and $Last(\tau) = s_2$. Also, $First((s_1, s_2)) = s_1$ and $Last((s_1, s_2)) = s_2$. Similarly, $States((s_1, s_2)) = States((u, (s_1, s_2))) = \{s_1, s_2\}$. And, $Inputs(u) = \{u\}$, for an input u.

3.3 Hybrid Input Transition Systems

We can now define a hybrid input transition system as consisting of sets of input-state trajectories and transitions.

Definition. A *hybrid input transition system* (*HITS*) $\mathcal{H}$ is a tuple (S, U, Σ, Δ), where S is a set of states, U is a set of inputs, $\Sigma \subseteq Trans(U, S)$ is a set of transitions and $\Delta \subseteq ISTraj(U, S)$ is a set of input-state trajectories.

We will just use hybrid system or hybrid transition system to refer to the above entity. Next, we define an execution of a hybrid transition system, which is a behavior of the system.

An execution is a finite or infinite sequence of trajectories and transitions which have matching end-points.

Definition. An *execution* of a hybrid input transition system $\mathcal{H}$ is a sequence $\sigma : M \to \Sigma \cup \Delta$, where $M \in SeqDom$, such that for each $0 \leq i < |\sigma| - 1$, $Last(\sigma(i)) = First(\sigma(i+1))$. Let $Exec(\mathcal{H})$ denote the set of all executions of $\mathcal{H}$.

We can view an execution as a pair consisting of an input signal and state signal. Let $\sigma \in Exec(\mathcal{H})$. Then for each $i \in Dom(\sigma)$, $\sigma(i) = (\mathbf{u}_i, \mathbf{s}_i)$, where either $(\mathbf{u}_i, \mathbf{s}_i)$ is an input-state trajectory or a transition. Let σ^u and σ^s be sequences whose domain is the same as σ such that $\sigma^u(i) = \mathbf{u}_i$ and $\sigma^s(i) = \mathbf{s}_i$. Then we also use (σ^u, σ^s) to denote the execution σ.

Given a set of executions $\mathcal{T}$ and an input signal σ^u, we use $\mathcal{T}|_{\sigma^u}$ to denote the set of all executions in $\mathcal{T}$ whose state signals can result from application of the input signal σ^u. Formally, $\mathcal{T}|_{\sigma^u} = \{\sigma^s \,|\, (\sigma^u, \sigma^s) \in \mathcal{T}\}$.

First, Last, States, Inputs of Executions.

We extend *first* and *last* to executions and state signals in the natural way, that is, the *first* of the first element in the sequence and the *last* of the last element if the sequence is finite. Formally, for an execution or a state signal σ, $First(\sigma) = First(\sigma(0))$ and $Last(\sigma)$ is defined only if $Dom(\sigma) = [n]$ for some $n \in \mathbb{N}$ and is equal to $Last(\sigma(n))$. Similarly, $States(\sigma) = \bigcup_{i \in Dom(\sigma)} States(\sigma(i))$. Also, for an input signal σ^u, $Inputs(\sigma^u) = \bigcup_{i \in Dom(\sigma^u)} Inputs(\sigma^u(i))$. The functions are extended to sets of trajectories, state signals and executions in a natural manner. Let $States(\mathcal{H})$ denote $States(\Sigma) \cup States(\Delta)$ and $Inputs(\mathcal{H})$ denote $Inputs(\Sigma) \cup Inputs(\Delta)$.

Graph of an execution.

In order to define distance between executions, we interpret the input and state signals as sets called the graphs which have information about the linear ordering between the states and inputs at various times. The set corresponding to a state signal σ^s consists of triples (t, i, x) such that x is a state that is reached after time t has elapsed along the execution, and i is the number of discrete transitions that have taken place before time t. Similarly, the set corresponding to an input signal σ^u consists of triples (t, i, u) such that the input u was applied at time t, and the number of impulse inputs applied before time t is i.

Definition. For an input or state signal σ and $j \in Dom(\sigma)$, let $T_j = \sum_{k=0}^{j-1} Size(\sigma(k))$ and $K_j = |\{k \,|\, k < j,\ \sigma(k)$ is not a trajectory$\}|$. The *graph* of the signal σ, denoted $gr(\sigma)$, is the set of all triples (i, t, x) such that there exists $j \in Dom(\sigma)$ satisfying the following:

- $t \in [T_j, T_j + Size(\sigma(j))]]$.
- If $\sigma(j)$ is a trajectory, then $i = K_j$ and $x = \sigma(j)(t - T_j)$.
- If $\sigma(j)$ is not a trajectory, then
  - if σ is a state signal and $\sigma(j) = (x_1, x_2)$, then either $i = K_j$ and $x = x_1$, or $i = K_j + 1$ and $x = x_2$.
  - if σ is an input signal and $\sigma(i) = u$, then $i = K_j$ and $x = u$.

3.4 Metric Hybrid Input Transition System

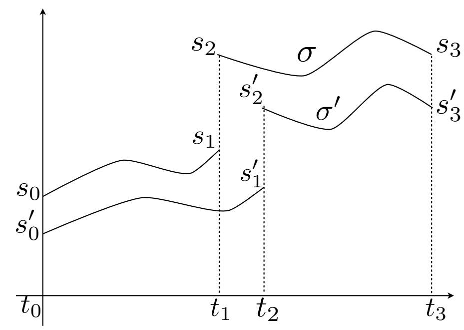

Figure 1: Graphical Distance between Executions.

In order to reason about stability of a system, one needs a notion of distance between behaviors of the system. Hence, we extend the definition of the hybrid system with a metric on the states and inputs which can then be extended to distance between signals and executions.

A metric hybrid input transition system is a hybrid input transition system whose state and input spaces are equipped with a metric. A *metric hybrid input transition system* (*MHS*) is a pair $(\mathcal{H}, d^s, d^u)$ where $\mathcal{H} = (S, U, \Sigma, \Delta)$ is a hybrid input transition system, and (S, d^s) and (U, d^u) are extended metric spaces. The metric d^s on the state space can be lifted to state signals executions and d^u to input signals, which will then be used to define input-to-state stability notions. Before defining this extension, recall that given an extended metric space (M, d), the *Hausdorff distance* between $A, B \subseteq M$, also denoted $d(A, B)$, is given by the maximum of

$$\{\sup_{p \in A} \inf_{q \in B} d(p, q), \sup_{p \in B} \inf_{q \in A} d(p, q)\}.$$

We extend d to triples used in the definition of graphs. *Definition.* For $(t_1, i_1, x_1), (t_2, i_2, x_2) \in \mathbb{R}^+ \times \mathbb{N} \times M$, let

$$d((t_1, i_1, x_1), (t_2, i_2, x_2)) = \max\{|t_1 - t_2|, |i_1 - i_2|, d(x_1, x_2)\}.$$

Now we can define the distance between state signals and input signals.

Definition. Let $(\mathcal{H}, d^s, d^u)$ be a metric hybrid input transition system with $\mathcal{H} = (S, U, \Sigma, \Delta)$. The *distance between state signals* σ_1^s, σ_2^s, denoted as $d^s(\sigma_1^s, \sigma_2^s)$, is defined to be the distance between their graphs, that is, $d^s(gr(\sigma_1^s), gr(\sigma_2^s))$, and the *distance between input signals* σ_1^u, σ_2^u, denoted $d^u(\sigma_1^u, \sigma_2^u)$, is defined as $d^u(gr(\sigma_1^u), gr(\sigma_2^u))$.

Distance between executions as defined above, called *graphical distance*, captures the notion that two executions are close if their states are close at approximately same times. The notion of graphical distance is borrowed from [11], where it has been argued that allowing a wiggle time is necessary when one considers hybrid executions. Graphical distance between two executions is illustrated in Figure 1. Note that the two executions σ and σ' are not close at all times t, for example, at a time $t \in (t_1, t_2)$, the states are very far. However, for every time t and corresponding state s of σ, there exists a time $t' \in [t - \epsilon, t + \epsilon]$ such that s is close to the state of σ' at time t'. For example, s_2 is close to s'_2 and times t_1 and t_2 are close.

In order to define convergence, we need the distance between suffixes of signals starting from some time T. Given a subset G of $\mathbb{R}^+ \times \mathbb{N} \times A$ and a $T \in \mathbb{R}^+$, let us denote by $G|_T$ the set $\{(t, i, x) \in G \mid t \geq T\}$. Given two signals σ_1, σ_2 and a $T \in \mathbb{R}^+$, we define $d(\sigma_1|_T, \sigma_2|_T)$ to be $d(gr(\sigma_1)|_T, gr(\sigma_2)|_T)$.

4. INCREMENTAL INPUT-TO-STATE STABILITY OF HYBRID INPUT TRANSITION SYSTEMS

In this section, we define a notion of incremental input-to-state stability of hybrid input transition systems. Our definition of input-to-state stability is motivated by the following definition of incremental input-to-state stability of [2]. Let $\mathcal{T}$ be a set of input-state trajectories over $(\mathbb{R}^m, \mathbb{R}^n)$ such that for each $\zeta \in \mathbb{R}^n$ and input trajectory $\mathbf{u}$, there exists a unique element $(\mathbf{u}, \mathbf{s}) \in \mathcal{T}$ with $First(\mathbf{s}) = \zeta$. Given ζ and $\mathbf{u}$, let us denote the unique trajectory $\mathbf{s}$ by $\mathbf{x}(\zeta, \mathbf{u})$. Then the definition of incremental input-to-state stability from [2] is as follows:

Definition.(δISS for input-state trajectories) The set of input-state trajectories $\mathcal{T}$ is said to be *incrementally input-to-state stable* if there exists a $\mathcal{KL}$ function β and a $\mathcal{K}_\infty$ function γ such that for any $t \geq 0$, any ζ_1, ζ_2 and any pair of input trajectories u_1, u_2, the following is true:

$$|\mathbf{x}(\zeta_1, \mathbf{u}_1)(t) - \mathbf{x}(\zeta_2, \mathbf{u}_2)(t)| \leq \beta(|\zeta_1 - \zeta_2|, t) + \gamma(\|\mathbf{u}_1 - \mathbf{u}_2\|_\infty).$$

The above definition forces the following properties of the system $\mathcal{T}$:

($C1$) The system is Lyapunov stable "uniformly" in the input. For every $\epsilon > 0$, there exists a $\delta > 0$, such that for every input trajectory $\mathbf{u}$, and for all initial states ζ_1, ζ_2, the following holds for every $t \geq 0$.

$$|\zeta_1 - \zeta_2| < \delta \Rightarrow |\mathbf{x}(\zeta_1, \mathbf{u})(t) - \mathbf{x}(\zeta_2, \mathbf{u})(t)| < \epsilon.$$

Note that δ depends only on ϵ, in particular, it is independent of the input trajectory $\mathbf{u}$.

($C2$) The system converges "uniformly" in the input. For every $\epsilon > 0$, there exists a $T \geq 0$, such that for every ζ_1, ζ_2 and input signal $\mathbf{u}$,

$$|\mathbf{x}(\zeta_1, \mathbf{u})(t) - \mathbf{x}(\zeta_2, \mathbf{u})(t)| < \epsilon, \forall t > T.$$

Note that T depends only on ϵ and is independent of $\mathbf{u}$.

($C3$) The system is input-to-state stable "uniformly" in the initial state. For every $\epsilon > 0$, there exists a $\delta > 0$ such that for all input signals $\mathbf{u}_1, \mathbf{u}_2$ and initial state ζ, the following holds for every $t \geq 0$:

$$\|\mathbf{u}_1 - \mathbf{u}_2\|_\infty < \delta \Rightarrow |\mathbf{x}(\zeta, \mathbf{u}_1)(t) - \mathbf{x}(\zeta, \mathbf{u}_2)(t)| < \epsilon.$$

Note the independence of δ with respect to ζ.

In fact, it is straightforward to check that the conditions $C1 - C3$ implies incremental input-to-state stability as given in the above definition.

Theorem 1. *A set of input-state trajectories $\mathcal{T}$ is δISS iff it satisfies Conditions $(C1) - (C3)$.*

Next, we formalize the definition of incremental input-to-state stability for hybrid input transition system using the above observation. A slight deviation is our definition of distance between trajectories, for which we use the graphical distance introduced in [11] for hybrid trajectories. However, the results in the paper are not sensitive to the particular definition of distance, in that, the results hold even when one considers the distance between two executions to be the supremum of the pointwise distance between states and inputs. We define $Valid(\mathcal{T}) = \{(\sigma^u, \zeta) \mid \exists \sigma^s, First(\sigma^s) = \zeta, (\sigma^u, \sigma^s) \in \mathcal{T}\}$. And $InSig(\mathcal{T}) = \{\sigma^u \mid \exists \sigma^s, (\sigma^u, \sigma^s) \in \mathcal{T}\}$.

Definition.(δISS for Hybrid Systems) Given a hybrid input transition system $\mathcal{H}$ and a set of executions $\mathcal{T} \subseteq Exec(\mathcal{H})$, we say that $\mathcal{H}$ is *incrementally input-to-state stable* (δISS) with respect to the set of executions $\mathcal{T}$, if the following hold:

($D1$) for every $\epsilon > 0$, there exists a $\delta > 0$, such that the following holds for every input signal σ^u:

$$\forall (\sigma^u, \sigma^s) \in Exec(\mathcal{H}), d^s(First(\sigma^s), First(\mathcal{T}|_{\sigma^u})) < \delta$$

$$\Rightarrow \exists (\sigma^u, \hat{\sigma}^s) \in \mathcal{T}, d^s(\sigma^s, \hat{\sigma}^s) < \epsilon$$

($D2$) there exists a $\delta > 0$ and a function $T : \mathbb{R}_{>0} \to \mathbb{R}_{>0}$ such that the following holds for every input signal σ^u:

$$\forall (\sigma^u, \sigma^s) \in Exec(\mathcal{H}), d^s(First(\sigma^s), First(\mathcal{T}|_{\sigma^u})) < \delta \Rightarrow$$

$$\exists (\sigma^u, \hat{\sigma}^s) \in \mathcal{T}, \forall \epsilon > 0, \forall t \geq T(\epsilon), d^s(\sigma^s|_t, \hat{\sigma}^s|_t) < \epsilon.$$

($D3$) for every $\epsilon > 0$, there exists a $\delta > 0$ such that for every input signal σ^u and state ζ with $(\sigma^u, \zeta) \in Valid(\mathcal{T})$, the following holds:

$$\forall \hat{\sigma}^u, [d^u(\sigma^u, \hat{\sigma}^u) < \delta \Rightarrow \forall (\hat{\sigma}^u, \hat{\sigma}^s) \in Exec(\mathcal{H}),$$

$$[First(\hat{\sigma}^s) = \zeta \Rightarrow \exists (\sigma^u, \sigma^s) \in \mathcal{T},$$

$$First(\sigma^s) = \zeta, d^s(\sigma^s, \hat{\sigma}^s) < \epsilon]]$$

5. INPUT (BI)-SIMULATIONS

In this section, we define the notion of pre-order under which, we will show in the next section, δISS is invariant. First, we define the notion of input (bi)-simulation, which is an extension of the classical notion of (bi)-simulation with inputs for hybrid input transition systems. Our definition is closely related to the definition of (bi)-simulation defined in [14].

Definition. Given two hybrid input transition systems $\mathcal{H}_1 = (S_1, U_1, \Sigma_1, \Delta_1)$ and $\mathcal{H}_2 = (S_2, U_2, \Sigma_2, \Delta_2)$, a pair of binary relations (R_1, R_2), where $R_1 \subseteq S_1 \times S_2$ and $R_2 \subseteq U_1 \times U_2$, is called an *input simulation relation* from $\mathcal{H}_1$ to $\mathcal{H}_2$ if, for every $(s_1, s_2) \in R_1$, the following hold:

- For every state s_1' and input u_1 such that $(u_1, (s_1, s_1')) \in \Sigma_1$, there exist a state s_2' and an input u_2 such that $R_1(s_1', s_2')$, $R_2(u_1, u_2)$ and $(u_2, (s_2, s_2')) \in \Sigma_2$.
- For every input-state trajectory $(\mathbf{u}_1, \mathbf{s}_1) \in \Delta_1$ such that $First(\mathbf{s}_1) = s_1$, there exists an input-state trajectory $(\mathbf{u}_2, \mathbf{s}_2) \in \Delta_2$ such that $First(\mathbf{s}_2) = s_2$, $\mathbf{s}_2 \in R_1(\mathbf{s}_1)$ and $\mathbf{u}_2 \in R_2(\mathbf{u}_1)$.

We denote the fact that (R_1, R_2) is an input simulation relation from $\mathcal{H}_1$ to $\mathcal{H}_2$ by $\mathcal{H}_1 \preceq_{(R_1,R_2)} \mathcal{H}_2$. Further, (R_1, R_2) is an *input bisimulation relation* between $\mathcal{H}_1$ and $\mathcal{H}_2$ if both (R_1, R_2) and (R_1^{-1}, R_2^{-1}) are input simulation relations, that is, $\mathcal{H}_1 \preceq_{(R_1,R_2)} \mathcal{H}_2$ and $\mathcal{H}_2 \preceq_{(R_1^{-1},R_2^{-1})} \mathcal{H}_1$.

Image of $\mathcal{H}$ under (R_1, R_2).

We define the image of a hybrid input transition system on a pair of relations . Given a hybrid input transition system $\mathcal{H} = (S, U, \Sigma, \Delta)$, and a pair (R_1, R_2), where $R_1 \subseteq S \times S'$ and $R_2 \subseteq U \times U'$, for some S' and U', we define $(R_1, R_2)(\mathcal{H})$ to be the hybrid input transition system $(S', U', \Sigma', \Delta')$, where:

- $\Sigma' = \{(u', (s'_1, s'_2)) \mid \exists (u, (s_1, s_2)) \in \Sigma, u' \in R_2(u), s'_1 \in R_2(s_1), s'_2 \in R_1(s_2)\}$.
- $\Delta' = \{(\mathbf{u}', \mathbf{s}') \mid \exists (\mathbf{u}, \mathbf{s}) \in \Delta, \mathbf{u}' \in R_2(\mathbf{u}), \mathbf{s}' \in R_1(\mathbf{s})\}$.

PROPOSITION 2. *Let $\mathcal{H} = (S, U, \Sigma, \Delta)$ be a hybrid input transition system, and $R_1 \subseteq S \times S'$ and $R_2 \subseteq U \times U'$, for some S' and U' such that $R_1(s)$ and $R_2(u)$ is not empty for any $s \in S$ and $u \in U$. Then (R_1, R_2) is an input simulation from $\mathcal{H}$ to $(R_1, R_2)(\mathcal{H})$.*

We will show later that input bisimulation does not preserve incremental input-to-state stability of systems. Hence, we strengthen the pre-order with uniform continuity conditions.

5.1 Uniformly Continuous Input (Bi)-Simulation

Let $(\mathcal{H}_1, d_1^s, d_1^u)$ and $(\mathcal{H}_2, d_2^s, d_2^u)$ be two metric input hybrid transition systems.

Definition. A pair (R_1, R_2) is a *uniformly continuous input simulation* from $\mathcal{H}_1$ to $\mathcal{H}_2$ if (R_1, R_2) is an input simulation from $\mathcal{H}_1$ to $\mathcal{H}_2$ and R_1, R_1^{-1}, R_2 and R_2^{-1} are uniformly continuous.

We denote the fact that (R_1, R_2) is a uniformly continuous input simulation from $\mathcal{H}_1$ to $\mathcal{H}_2$ by $\mathcal{H}_1 \preceq^C_{(R_1,R_2)} \mathcal{H}_2$, and $\mathcal{H}_1 \preceq^C \mathcal{H}_2$ to denote that there exists (R_1, R_2) such that $\mathcal{H}_1 \preceq^C_{(R_1,R_2)} \mathcal{H}_2$. Next, we show that uniformly continuous input simulations define a pre-order on systems.

THEOREM 2. *Let $(\mathcal{H}_i, d_i^s, d_i^u)$, for $1 \leq i \leq 3$, where $\mathcal{H}_i = (S_i, U_i, \Sigma_i, \Delta_i)$, be three metric hybrid transition systems. Then we have the following properties about $\preceq^C$:*

- *(Reflexivity) $\mathcal{H}_1 \preceq^C \mathcal{H}_1$.*
- *(Transitivity) If $\mathcal{H}_1 \preceq^C \mathcal{H}_2$ and $\mathcal{H}_2 \preceq^C \mathcal{H}_3$, then $\mathcal{H}_1 \preceq^C \mathcal{H}_3$,*

PROOF. (Sketch.) Reflexivity follows from the fact that $\mathcal{H}_1 \preceq_{(Id_1,Id_2)} \mathcal{H}_2$, where $Id_1 = \{(s, s) \mid s \in S\}$ and $Id_1 = \{(u, u) \mid u \in U\}$. Transitivity follows from the fact that $\mathcal{H}_1 \preceq^C_{(R_1,R_2)} \mathcal{H}_2$ and $\mathcal{H}_2 \preceq^C_{(R'_1,R'_2)} \mathcal{H}_3$, then $\mathcal{H}_1 \preceq^C_{(R'_1 \circ R_1, R'_2 \circ R_2)} \mathcal{H}_3$, where $A \circ B = \{(x, z) \mid \exists (x, y) \in A, (y, z) \in B\}$ (since composition of continuous relations is continuous). $\square$

5.2 Necessity of Uniformity

We will show that uniformity of R_1 and R_2 are both necessary.

To show that uniformity of R_1 is necessary, we borrow the example from [19]. We use the notation $x, \mathbf{u}, t \mapsto x'$ to indicate that the trajectory starting from x on the input signal $\mathbf{u}$ at time t has state x'. We will define two systems $\mathcal{H}_1$ and $\mathcal{H}_2$ both of which have state space $\mathbb{R}^2$ and input space 0. The unique input signal $\mathbf{u}$ of the systems in the constant 0 signal. The trajectories of both the systems start in the set $\{0\} \times [-1, 1]$, and the evolution of any state $(0, y)$ in the first system is given by $(0, y), \mathbf{u}, t \mapsto (t, e^{-t}y)$, and in the second system is given by $(0, y), \mathbf{u}, t \mapsto (t, y)$. Note that the first system is incrementally input-to-state stable with respect to the trajectory $(\mathbf{u}, \tau)$, where τ is the trajectory which starts at $(0, 0)$ and evolves as $(0, 0), \mathbf{u}, t \mapsto (t, 0)$. The second system is not incrementally input-to-state stable with respect to the same trajectory. However, defining R_1 to be $\{((x_1, y_1), (x_2, y_2)) \mid x_1 = x_2, y_1 = e^{-x_1}y_2\}$, and R_2 to be the identity map $\{(0, 0)\}$ gives an input bisimulation between the systems, where R_1 is continuous and R_2 is uniformly continuous. So, just continuity on R_1 does not suffice to preserve incremental input-to-state stability.

To show the necessity of uniformity on the input space, that is, of R_2, we consider the following systems. The state-space as before is $\mathbb{R}^2$ and the input space is $\mathbb{R}$. The initial states are $\{0\} \times [-1, 1]$. The trajectories of the first system are given by $(0, y), \mathbf{u}, t \mapsto (t, e^{-t}y + \mathbf{u}(0)t)$ and the trajectories of the second system are given by $(0, y), \mathbf{u}, t \mapsto (t, e^{-t}y + e^{\mathbf{u}(0)}t)$. So, for a particular $\mathbf{u}$ both systems are asymptotically stable in a "uniform" manner. With respect to the reference signal $(\mathbf{u}, \tau)$ where $\mathbf{u}$ is any constant signal and τ is given by $(0, 0), \mathbf{u}, t \mapsto (t, \mathbf{u}(0)t)$, the first system is incrementally input to state stable. With respect to the reference signal $(\mathbf{u}, \tau)$ where $\mathbf{u}$ is any constant signal and τ is given by $(0, 0), \mathbf{u}, t \mapsto (t, e^{\mathbf{u}(0)t)})$, the second system is not incrementally input-to-state stable. However, defining R_1 to be the identity and $R_2 = \{(u_1, u_2) \mid u_1 = e^{u_2}\}$ defines an input bisimulation between the two systems. Here R_1 is uniformly continuous and R_2 is just continuous. This example shows that continuity of R_2 does not suffice to preserve incremental input-to-state stability.

6. INCREMENTAL INPUT-TO-STATE STABILITY PRESERVATION

In this section, we present the main result of the paper, namely, that incremental input-to-state stability is invariant under uniformly continuous input bisimulations.

We need a technical consistency condition between the input bisimulation relations and the reference executions.

Definition. A pair of relations (R_1, R_2), where $R_1 \subseteq S_1 \times S_2$ and $R_2 \subseteq U_1 \times U_2$, is said to be *semi-consistent* with respect to the sets of executions $\mathcal{T}_1$ and $\mathcal{T}_2$ over (S_1, U_1) and (S_2, U_2), respectively, if the following hold:

(A1) For every $(\sigma_1^u, \zeta_1) \in \mathit{Valid}(\mathcal{T}_1)$, there exists $(\sigma_2^u, \zeta_2) \in \mathit{Valid}(\mathcal{T}_2)$ such that $R_2(\sigma_1^u, \sigma_2^u)$ and $R_1(\zeta_1, \zeta_2)$.

(A2) For every $(\sigma_2^u, \sigma_2^s) \in \mathcal{T}_2$, for every $\sigma_1^u \in R_2^{-1}(\sigma_2^u)$ and $\zeta_1 \in R_2^{-1}(\mathit{First}(\sigma_2^s))$ such that $(\sigma_1^u, \zeta_1) \in \mathit{Valid}(\mathcal{T}_1)$, there exists σ_1^s with $\mathit{First}(\sigma_1^s) = \zeta_1$, $R_1(\sigma_1^s, \sigma_2^s)$ and $(\sigma_1^u, \sigma_1^s) \in \mathcal{T}_1$.

(A3) $R_2(u)$ is a singleton for every $u \in \mathit{Inputs}(\mathcal{T}_1)$.

(A4) $R_1^{-1}(s)$ is singleton for every $s \in \mathit{States}(\mathcal{T}_2)$.

(A5) For every σ_1^u, $R_1(\mathit{First}(\mathcal{T}_1|_{\sigma_1^u})) = \mathit{First}(\mathcal{T}_2|_{R_2(\sigma_1^u)})$.

(A6) There exists $\delta > 0$ such that for every $x \in B_\delta(\mathit{First}(\mathcal{T}_1))$, there exists a y such that $R_1(x, y)$.

(R_1, R_2) is said to be *consistent* with respect to $\mathcal{T}_1$ and $\mathcal{T}_2$ if both (R_1, R_2) and (R_1^{-1}, R_2^{-2}) are semi-consistent with respect to $\mathcal{T}_1$ and $\mathcal{T}_2$.

THEOREM 3. *Let* $(\mathcal{H}_1, d_1^s, d_1^u)$ *and* $(\mathcal{H}_2, d_2^s, d_2^u)$*, where* $\mathcal{H}_1 = (S_1, U_1, \Sigma_1, \Delta_1)$ *and* $\mathcal{H}_2 = (S_2, U_2, \Sigma_2, \Delta_2)$*, be two metric hybrid input transition systems, and let* $\mathcal{T}_1 \subseteq Exec(\mathcal{H}_1)$ *and* $\mathcal{T}_2 \subseteq Exec(\mathcal{H}_2)$ *be two sets of executions. Let* (R_1, R_2) *be a uniformly continuous input simulation from* $\mathcal{H}_1$ *to* $\mathcal{H}_2$*, and let* (R_1, R_2) *be semi-consistent with respect to* $\mathcal{T}_1$ *and* $\mathcal{T}_2$*. Then the following holds:*

If $\mathcal{H}_2$ is δISS with respect to $\mathcal{T}_2$, then $\mathcal{H}_1$ is δISS with respect to $\mathcal{T}_1$.

PROOF. Let us assume $\mathcal{H}_2$ is δISS with respect to $\mathcal{T}_2$. We need to show that $\mathcal{H}_1$ is δISS with respect to $\mathcal{T}_1$. We will show that $\mathcal{H}_1$ satisfies conditions $(D1) - (D3)$.

Proof of satisfaction of Condition $(D1)$ Let us fix an $\epsilon_1 > 0$. We need to find a $\delta_1 > 0$ such that Condition $(D1)$ holds in $\mathcal{H}_1$ and $\mathcal{T}_1$. Let ϵ_2 be the uniformity constant of R_1^{-1} corresponding to ϵ_1. Let δ_2 be the constant satisfying Condition $(D1)$ for $\mathcal{H}_2$ corresponding to ϵ_2. Set δ_1 to be the uniformity constant of R_2 corresponding to δ_2.

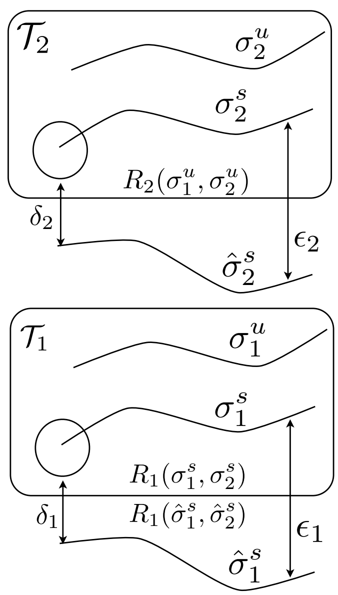

Figure 2: Illustration for Proof of Condition $(D1)$

Let us fix an input signal σ_1^u. Let $(\sigma_1^u, \sigma_1^s) \in Exec(\mathcal{H}_1)$ such that $d_1^s(First(\sigma_1^s), First(\mathcal{T}_1|_{\sigma_1^u}) < \delta_1$ (see Figure 2). We need to show that there exists a $\hat{\sigma}_1^s$, such that $(\sigma_1^u, \hat{\sigma}_1^s) \in \mathcal{T}_1$ and $d_1^s(\sigma_1^s, \hat{\sigma}_1^s) < \epsilon_1$.

Note that Condition $(A1)$ also implies that there exists $\sigma_2^u \in InSig(\mathcal{T}_2)$ such that $R_2(\sigma_1^u, \sigma_2^u)$. Further, σ_2^u is unique because of Condition $(A3)$ on R_2. From Condition $(A6)$, there exists a ζ_2 such that $(First(\sigma_1^s), \zeta_2) \in R_1$. Therefore, from input simulation relation, there exists σ_2^s such that $(\sigma_2^u, \sigma_2^s) \in Exec(\mathcal{H}_2)$ and $R_1(\sigma_1^s, \sigma_2^s)$ (note that σ_2^u is the same as before, this follows from the uniqueness of σ_2^u). Since $d_1^s(First(\sigma_1^s), First(\mathcal{T}_1)\sigma_1^u) < \delta_1$, $d_2^s(R_1(First(\sigma_1^s)), R_1(First(\mathcal{T}_1)|_{\sigma_1^u})) < \delta_1$. From Condition $(A5)$, we have $d_2^s(R_1(First(\sigma_1^s)), First(\mathcal{T}_2|_{R_2(\sigma_1^u)})) < \delta_1$, or equivalently $d_2^s(R_1(First(\sigma_1^s)), First(\mathcal{T}_2|_{\sigma_2^u})) < \delta_1$. In particular, $d_2^s(First(\sigma_2^s), First(\mathcal{T}_2|_{\sigma_2^u})) < \delta_1$. From the δISS of $\mathcal{H}_2$ with respect to $\mathcal{T}_2$, we have that there exists $\hat{\sigma}_2^s$ such that $(\sigma_2^u, \hat{\sigma}_2^s) \in \mathcal{T}_2$ and $d_2^s(\sigma_2^s, \hat{\sigma}_2^s) < \epsilon_2$. Then from Condition $(A2)$, there exists $\hat{\sigma}_1^s$, such that $(\sigma_1^u, \hat{\sigma}_1^s) \in \mathcal{T}_1$, and $R_1(\hat{\sigma}_1^s, \hat{\sigma}_2^s)$. Now, $d_1^s(\sigma_1^s, \hat{\sigma}_1^s) < \epsilon_1$ since $R_1^{-1}(s)$ is a singleton for every $s \in States(\mathcal{T}_2)$ (from Condition $(A4)$).

Proof of satisfaction of Condition $(D2)$ Let $\delta_2 > 0$ and $T_2 : \mathbb{R}^+ \to \mathbb{R}^+$ be such that they satisfy Condition $(D2)$ for system $\mathcal{H}_2$ with respect to $\mathcal{T}_2$. Choose $\delta_1 > 0$ to be the uniformity constant of R_2 with respect to δ_2. Similarly, define $T_1 : \mathbb{R}^+ \to \mathbb{R}^+$ as follows: Given any $\epsilon_1 > 0$, set $T_1(\epsilon_1)$ to be equal to $T_2(\epsilon_2)$, where ϵ_2 is the uniformity constant of R_1^{-1} with respect to ϵ_1.

The proof essentially is the same as before, except that we need to show that $\forall \epsilon_1 > 0, \forall t \geq T_1(\epsilon_1), d_1^s(\sigma_1^s|_t, \hat{\sigma}_1^s|_t) < \epsilon_1$. Note that the above condition follows from the fact that now we have $\forall \epsilon_2 > 0, \forall t \geq T_2(\epsilon_2), d_2^s(\sigma_2^s|_t, \hat{\sigma}_2^s|_t) < \epsilon_2$. The required result follows from the definition of T_1.

Proof of satisfaction of Condition $(D3)$ Let us fix an $\epsilon_1 > 0$, we need to find a $\delta_1 > 0$ such that Condition $(D3)$ holds. Let ϵ_2 be the uniformity constant of R_1^{-1} corresponding to ϵ_1. Let δ_2 be the constant satisfying Condition $(D3)$ for $\mathcal{H}_2$ corresponding to ϵ_2. Set δ_1 to be the uniformity constant of R_2 corresponding to δ_2.

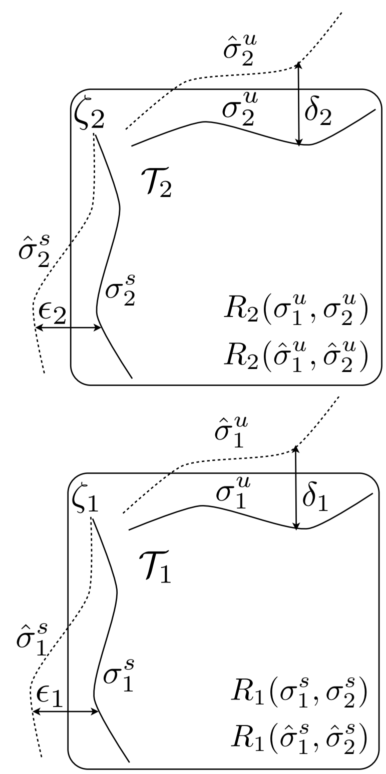

Figure 3: Illustration for Proof of Condition $(D3)$

Let us fix an input signal σ_1^u and state ζ_1 such that $(\sigma_1^u, \zeta_1) \in Valid(\mathcal{T}_1)$ (see Figure 3). Let $\hat{\sigma}_1^u$ be such that $d_1^u(\sigma_1^u, \hat{\sigma}_1^u) < \delta_1$ and let $(\hat{\sigma}_1^u, \hat{\sigma}_1^s) \in Exec(\mathcal{H}_1)$ with $First(\hat{\sigma}_1^s) = \zeta_1$. We need to show that there exists σ_1^s such that $First(\sigma_1^s) = \zeta_1$, $(\sigma_1^u, \sigma_1^s) \in \mathcal{T}_1$ and $d_1^s(\hat{\sigma}_1^s, \sigma_1^s) < \epsilon_1$.

From Condition $(A1)$ of semi-consistency, we have that there exists $(\sigma_2^u, \zeta_2) \in Valid(\mathcal{T}_2)$ such that $R_2(\sigma_1^u, \sigma_2^u)$ and $R_1(\zeta_1, \zeta_2)$. From the fact that (R_1, R_2) is an input simulation, and $R_1(\zeta_1, \zeta_2)$, we know that there exists $(\hat{\sigma}_2^u, \hat{\sigma}_2^s) \in Exec(\mathcal{H}_2)$ with $First(\hat{\sigma}_2^s) = \zeta_2$, $R_2(\hat{\sigma}_1^u, \hat{\sigma}_2^u)$ and $R_1(\hat{\sigma}_1^s, \hat{\sigma}_2^s)$.

Now, $d_1^u(\sigma_1^u, \hat{\sigma}_1^u) < \delta_1$ and $R_2(u)$ is a singleton for every $u \in Inputs(\mathcal{T}_1)$ (from Condition $(A3)$) implies that $d_2^u(\sigma_2^u, \hat{\sigma}_2^u) < \delta_2$. From the definition of δISS for $\mathcal{H}_2$, we know that there exists σ_2^s such that $(\sigma_2^u, \sigma_2^s) \in \mathcal{T}_2$ and $d_2^s(\sigma_2^s, \hat{\sigma}_2^s) < \epsilon_2$.

From Condition $(A2)$ of semi-consistency, there exists σ_1^s with $First(\sigma_1^s) = \zeta_1$, $R_1(\sigma_1^s, \sigma_2^s)$ and $(\sigma_1^u, \sigma_1^s) \in \mathcal{T}_1$. Note that $d_1^s(\sigma_1^s, \hat{\sigma}_1^s) < \epsilon_1$ since $d_2^s(\sigma_2^s, \hat{\sigma}_2^s) < \epsilon_2$, and $R_1^{-1}(s)$ is a singleton for every $s \in States(\mathcal{T}_2)$ (from Condition $(A4)$). □

Remark There have been various proposals for defining a metric on the set of executions, including the Skorokhod metric (see [7, 5] for more details), wherein, two executions are considered close if there exists a bijective, strictly order-preserving function between the time domains of the executions, such that the distance between a time point and its image under the function is small and the values of the corresponding states are small. However, we would like to point out here that our proof is not sensitive to the particular choice of distance metric.

THEOREM 4. *Let $(\mathcal{H}_1, d_1^s, d_2^u)$ and $(\mathcal{H}_2, d_2^s, d_2^u)$, where $\mathcal{H}_1 = (S_1, U_1, \Sigma_1, \Delta_1)$ and $\mathcal{H}_2 = (S_2, U_2, \Sigma_2, \Delta_2)$, be two metric hybrid input transition systems, and $\mathcal{T}_1 \subseteq Exec(\mathcal{H}_1)$ and $\mathcal{T}_2 \subseteq Exec(\mathcal{H}_2)$ be two sets of executions. Let (R_1, R_2) be a uniformly continuous input simulation from $\mathcal{H}_1$ to $\mathcal{H}_2$, and let (R_1, R_2) be consistent with respect to $\mathcal{T}_1$ and $\mathcal{T}_2$. Then the following holds:*

$\mathcal{H}_2$ is δISS with respect to $\mathcal{T}_2$ if and only if $\mathcal{H}_1$ is δISS with respect to $\mathcal{T}_1$.

6.1 Modeling Input-to-State Stability of Continuous Dynamical Systems

We define input-to-state stability of dynamical systems and formulate it in our framework: Consider a continuous dynamical system

$$\dot{x} = f(x, u), \tag{1}$$

$$x \in X \subseteq \mathbb{R}^n, u \in U \subseteq \mathbb{R}^m, x_0 \in X_0 \subseteq X,$$

where $f : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n$ is locally Lipschitz in x and u, and X_0 and U are compact sets. We will assume that the input signal space D_u consists of functions $u : [0, \infty) \to U$ that are piecewise continuous, bounded functions of t for all $t \geq 0$.

We define the hybrid system corresponding to the System (1) to be the following: $\mathcal{H}_{f,X_0,X,U} = (X, U, \emptyset, \Delta)$, where Δ is the set of pairs $(\mathbf{u}, \mathbf{x})$, where $\mathbf{u}$ is in D_u, $\mathbf{x}(0) \in X_0$ and $\mathbf{x}$ is the solution of System (1) starting from $\mathbf{x}(0)$, that is, $\mathbf{u}, \mathbf{x}$ satisfy $\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t))$ for every $t \geq 0$. Let d^s and d^u be the standard Euclidean norms on $\mathbb{R}^n$ and $\mathbb{R}^m$, respectively.

The notion of input-to-state stability captures the notion of "bounded input-bounded state".

Definition. The System (1) is said to be *input-to-state stable* (*ISS*) if there exists a $\mathcal{KL}$ function β, a class $\mathcal{K}$ function γ such that

$$\|x(t)\| \leq \beta(\|x_0\|, t) + \gamma(\|u\|_\infty), \tag{2}$$

for all $t \geq 0, x_0 \in X_0$ and $u \in D_u$.

Let $\mathcal{T}_{0,0}$ be the set of trajectories with 0 input and 0 initial state, that is, $\mathcal{T}_{0,0} = \{(\mathbf{0}, \mathbf{0})\}$. It is easy to see that input-to-state stability of System (1) is equivalent to δISS of $\mathcal{H}_{f,X_0,X,U}$ with respect to $\mathcal{T}_{0,0}$.

PROPOSITION 3. *System (1) is input-to-state stable if and only if the system $\mathcal{H}_{f,X_0,X,U}$ is δISS with respect to $\mathcal{T}_{0,0}$.*

Hence, we can use Theorem 3 and Theorem 4 to also reason about input-to-state stability of systems.

7. APPLICATIONS OF THEOREM ??

First, we illustrate through an example of a linear system with inputs, how we can prove input-to-stability using our results.

7.1 A simple example

Consider a linear system with input, that is,

$$\dot{x} = f(x, u) = Ax + Bu, A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, \tag{3}$$

$$x \in X \subseteq \mathbb{R}^n, u \in U \subseteq \mathbb{R}^m, x_0 \in X_0 \subseteq X,$$

where, A is a Hurwitz matrix, and X_0 and U are compact sets.

Let P be a positive definite symmetric matrix satisfying $A^T P + PA = -Q$ for some positive definite matrix Q. Consider a function $R_1 : \mathbb{R}^n \to \mathbb{R}^+$ given by $R_1(x) = x^T Px$ and a function $R_2 : \mathbb{R}^m \to \mathbb{R}^+$ given by $R_2(u) = |u|$. Then, $\dot{R}_1(x) = \dot{x}^T Px + x^T P\dot{x} = x^T(A^T P + PA)x + u^T B^T Px + x^T PBu \leq -\lambda R_1(x) + \mu\|u\|_\infty$, where λ and μ are positive constants depending on P, Q and B.

Consider the one-dimensional system:

$$\dot{y} \leq -\lambda y + \mu\|v\|_\infty, y \geq 0. \tag{4}$$

Note that the solutions to the system satisfy $y(t) \leq e^{-\lambda t} y(0) + \mu/\lambda\|v\|_\infty$. This system is trivially input-to-state stable since it is in the form required by Inequality 2.

We will show that (R_1, R_2) is a uniformly continuous input simulation from System (3) to System (4). Input simulation follows from the fact that if $(\mathbf{x}, \mathbf{u})$ satisfies $\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + B\mathbf{u}(t)$ for all $t \geq 0$, then by construction, $(R_1(\mathbf{x}), R_2(\mathbf{u}))$ satisfies $\dot{R}_1(\mathbf{x}) \leq -\lambda R_1(\mathbf{x}) + \mu\|R_2(\mathbf{u})\|_\infty$. Also, when R_1 and R_2 are interpreted as relations or set valued functions, then R_1, R_1^{-1}, R_2 and R_2^{-1} are continuous. Further, since X_0 and U are compact, these functions are uniformly continuous over $States(\mathcal{H}_{f,X_0,X,U})$ and $Inputs(\mathcal{H}_{f,X_0,X,U})$. Note that the set of reference executions in both the systems is $\{(\mathbf{0}, \mathbf{0})\}$, where $\mathbf{0}$ is of appropriate dimension. It is easy to see the semi-consistency is trivially satisfied. Hence, from Theorem 3 System (3) is input-to-state stable.

7.2 Lyapunov Functions for Input-to-State Stability

Next we show that Lyapunov function based input-to-state stability can be cast as constructing simpler one dimensional systems, using uniformly continuous input simulations, which are input-to-state stable.

Let us consider System (1) and assume that the system $\dot{y} = f(y, 0)$ has a uniformly asymptotically stable equilibrium point at the origin.

Definition. A continuously differentiable function $V : X \to \mathbb{R}^+$ is said to be an *ISS* Lyapunov function for the System (1) if there exist class $\mathcal{K}_\infty$ functions $\alpha_1, \alpha_2, \alpha_3$ and $\mathcal{X}$ such that:

$$\alpha_1(\|x\|) \leq V(x(t)) \leq \alpha_2(\|x\|), \forall x \in X, t > 0 \tag{5}$$

$$\frac{\partial V(x)}{\partial x} f(x,u) \leq \alpha_3(\|x\|), \forall u \in D_u : \|x\| \geq \mathcal{X}(\|u\|). \quad (6)$$

THEOREM 5. *[21] (ISS Theorem) Let $V : X \to \mathbb{R}^+$ be an ISS Lyapunov function for the System (1). Then System (1) is input-to-state stable.*

Following theorem formulates Lyapunov analysis in our framework:

THEOREM 6. *Let V be an ISS Lyapunov function for System (1), and let $N : \mathbb{R}^n \to \mathbb{R}^+$ be the function $u \mapsto |u|$. Then:*

- $(V, N)(\mathcal{H}_{f,X_0,X,U})$ *input simulates* $\mathcal{H}_{f,X_0,X,U}$.
- V, V^{-1}, N *and* N^{-1} *are uniformly continuous over States*$(\mathcal{H})$ *and Inputs*$(\mathcal{H})$.
- (V, N) *is consistent with* $\mathcal{T}_{0,0}$ *and* $(V, N)(\mathcal{T}_{0,0})$.
- $(V, N)(\mathcal{H}_{f,X_0,X,U})$ *is δISS with respect to* $(V, N)(\mathcal{T}_{0,0})$.

Hence $\mathcal{H}_{f,X_0,X,U}$ *is δISS with respect to* $\mathcal{T}_{0,0}$.

Proof follows from Proposition 2 and Theorem 5.

8. CONCLUSIONS

In this paper, we investigated pre-orders for reasoning about input-to-state stability properties. We introduced the notion of uniformly continuous input simulations and bisimulations as pre-orders which preserve input-to-state stability of systems. We showed that the notion is a reasonable pre-order to consider by establishing Lyapunov function based analysis of input-to-state stability as a special case of our analysis framework.

In the future, we intend to develop concrete techniques for constructing abstractions based on uniformly continuous input simulations and bisimulations. Our broad goal is to develop an abstraction refinement technique for analysis of stability properties.

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