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Introduction

C2E2 is a tool for verifying time-bounded invariant properties of hybrid automata models. It supports models with nonlinear dynamics, discrete transitions, and sets of initial states. The invariant properties have to be specified by conjunctions of linear inequalities. Internally, C2E2 implements the simulation-based verification algorithms described in the sequence of publications Fan et al. [2016], Fan and Mitra [2015], Duggirala et al. [2013a, 2014], Sukumar and Mitra [2011]. The new version of C2E2 uses an on-the-fly discrepancy computation algorithm Fan and Mitra [2015] to automatically generate neighborhoods that conservatively contain all the behaviors of neighboring trajectories. In a nutshell, C2E2 parses and transforms the hybrid automata model to a mathematical representation, it generates faithful numerical simulations of this model using a validated numerical simulator, it then bloats these simulations using on-the-fly discrepancy computation to construct over-approximations of the bounded time reachable set, and it iteratively refines these over-approximations to prove the invariant or announce candidate counterexamples.

C2E2 has a GUI for loading and editing of hybrid automata models and properties in an internal HyXML format, launching the verifier, and for plotting 2D sections of the reach set computed by the verifier.

Please contact us at c2e2help@gmail.com and let us know about your experiences using C2E2. Previous versions of C2E2 allowed for the editing of Stateflow™ models and readily supported numerical simulators like VNODE-LP Nedialkov [2006]. Some of these features are getting depreciated because of numerical instability, lack of support, etc. Let us know if you are interested in these features.
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Installation

To install C2E2, you may either download and run the installation files, or download and virtual machine with the most recent version of C2E2 installed.

Example .hyxml files are included and located in the examples folder.

3.1 Download and install latest C2E2

Ubuntu 16.04, 64-bit is currently the only supported operating system. If you are using a different OS, we recommend that you download the virtual machine instead.

- Download the latest distribution of C2E2 distribution from: http://publish.illinois.edu/c2e2-tool/download/.
- Unzip the files in a local directory, say ~/c2e2/.
  tar -xvzf c2e2-2.0.0.tar.gz -C ~/c2e2/
- Navigate to that directory and run installRequirements.sh with superuser privileges. This should install all the packages needed and may take a while.
  cd ~/C2E2/
  sudo ./installRequirements.sh
- Launch the GUI for loading, editing, and verifying models.
  ./runc2e2
- If any of the above steps fail then you can try to install the packaged listed in the file installRequirements separately.

3.2 Install the Virtual Machine
The virtual machine can be downloaded from http://publish.illinois.edu/c2e2-tool/download/. Oracle VM VirtualBox was used to create and test the Open Virtual Appliance (.ova).
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**Key Improvements in Version 2.0**

One of our main focuses for C2E2 version 2.0 was to improve the usability of our software. Previously, editing models had to be done in the .hyxml files outside of C2E2. To fix this, we made two significant updates to our GUI:

- Models are now editable directly from the GUI on the *Model* tab.
- The new *Editor* tab allows you to edit the HyXML directly without closing C2E2

In addition, the *Plot* tab has been updated to improve usability and flexibility:

- The plotter now creates an interactive HTML.
- Any data file generated by C2E2 can be loaded into the plotter at any time.
5

Getting Started

In this chapter, we give a quick tour of some features of C2E2 using one of the examples that are distributed as part of the package.

5.1 Opening a Model

In the C2E2 folder, type the command `./runC2E2` to launch C2E2 and you should be able to see the front end of the tool as Figure 5.1. Once C2E2 is launched, go ahead and open one of the examples from the File menu (or use Ctrl + O). All examples are stored in the examples folder inside C2E2 folder. For this tutorial, we will use the model of an adaptive cruise control system (see the example webpage 1) which is stored as TotalMotion40s.hyxml. For the description of other examples, please refer to the examples webpage 2.

Upon opening the file, the C2E2 window should look similar to Figure 5.2. The left hand side of this window is the hybrid automaton model tree and the right hand side is the requirements sidebar.

5.2 Model Tree

When a model is opened, the HyXML is parsed and the result is displayed in the expandable model tree. Automata are at the base, followed by Variables, Modes, and Transitions. Modes can further be expanded to display Flows and Invariants. Every item on the tree can be expanded to view details by clicking on the arrow to the left. As you can see, our example in Figure 5.2 has five variables sx, vx, ax, sy, vy and omega. In addition, we have seven separate modes with six transitions between them.

In version 2.0, you can now also edit the model directly from the model tree by right-clicking the item you wish to edit, or by selecting it
and using the options under the Build menu. We will go over this in more detail in the next chapter.

Figure 5.2: Left: Model parse tree. Right: Verification pane.

5.3 Requirements Sidebar

The lower part of the sidebar shows a list of requirements (properties) for the hybrid automaton that can be verified. The top part of the sidebar shows the detailed parameters of the highlighted requirement. Each requirement is a bounded time safety property.

- **Name**
  Each requirement (property) to be checked is given a name. This name is used to name output files containing the reachtubes.

- **Time Horizon**
  The time bound for simulation and verification.

- **Time Step**
  The time step-size used for simulation and verification. If adaptive step size is used for simulation (see below) then this value is ignored.

- **K Value**
  The coordinate transformation step $K$ for nonlinear models has been set to 2000 by default at the top right corner of the verification pane. This value is important since the inappropriate $K$ value will influence the final result. The user can change the $K$ value to see different outputs.
• **Simulator**
  Current version of C2E2 supports Odeint constant time step simulator and Odeint adaptive time step simulator. Previously, CAPD simulator was also supported, but no longer is in the current version. Please contact us if you wish to use the CAPD simulator. The default simulator is Odeint constant time step simulator, and it is been compiled when you opening the model. You can change the simulator by selecting different simulator from the simulator drop down menu as shown in Figure 5.3.

• **Refinement**
  When the initial set needs refinement, C2E2 provides different refinement strategies. The default refinement strategy will refine the dimensions within the unsafe set for four times, then iteratively refine the dimension with the largest uncertainty size. C2E2 also supports user defined strategy, which can be found at Section 5.5.2. To select the strategy, please use the drop down menu on GUI as shown in Figure 5.4.

• **Initial set**
  A linear predicate on the variables to specify the initial set or starting states on the Initial set textbox. Currently, the syntax for specifying the initial set is as follows:

• **Unsafe set**

  At the bottom of the requirement sidebar is the requirement list. This is where you can add, edit, copy properties and launch the verifier or simulator. Currently C2E2 verifies bounded time linear invariant properties from linear bounded initial sets. Such properties are specified by the time bound \( T \), the initial set and the unsafe set. The Time horizon parameter listed at the top of the verification pane is the time bound. Currently C2E2 requires both the initial and the unsafe sets to be described by a conjunction of linear inequalities involving the model variables. The models in the Examples folder have already has a couple of sample properties.

---

### 5.4 Creating a New Property

Here we will walk you through the steps involved in creating a new property like in Figure 5.5.

1. Click New in the property pane. This opens an empty new Property box on the Right panel in the middle for editing.
2. Enter a name for the property at the top, say VxB1, in the first textbox.

3. Enter a linear predicate on the variables to specify the initial set or the starting states in the Initial set textbox. Currently, the syntax for specifying the initial set is as follows:
   \[(\text{mode-name}):((\text{linear-inequality} \&\&)+)\].
   For example, for the above model:
   \[\text{SlowDown: } sx>=-15.0 \&\& sx<=-14.95 \&\& vx>=3.25 \&\& vx<=3.3 \&\& ax==0 \&\& vy==0 \&\& omega==0 \&\& sy==0\]
   is a valid expression for specifying the set of initial states.

4. Enter the unsafe set in the Unsafe set textbox. Currently, the syntax for specifying the unsafe set is a \&\&-separated sequence of linear inequalities:
   \[vx<=2.1\]

5. Press Add.

If all the expressions are syntactically acceptable then there will be little green checks next to the textboxes and you will be able to save the property. Otherwise there will be a cross next to the textbox. Both the unsafe set and the initial set should be described by a collection of linear inequalities and in addition the initial set should be bounded.

Once the property is added the name of the property appears in the property pane. You may add several properties in the same way. You may also make copies of existing properties to save yourself some typing and edit them. The added properties can be saved with the model. See section ??.

5.5 Verifying

Once you have created a model and added a property (see Section 5.3) you can launch the verification engine by selecting the property and then clicking the Verify button.

C2E2 is sound which means that you can trust the Safe/Unsafe answer proclaimed by it. In principle, C2E2 is also complete for robust properties Duggirala et al. [2013a]. That is, if the model satisfies the property robustly3, and if the numerical precision supported by the algorithm is adequate then C2E2 should terminate with a Safe/Unsafe proclamation. In practice, the time it takes to verify is sensitive to the time horizon (T), the initial partition. You may want to first run the verification with small values of T and initial set with small size.

3 Robustness: the requirement that the actual reachable set of the model does not skim the boundary of the unsafe set.
The reachable set over-approximation computed by C2E2 is stored in the `/work-dir/<Requirement name>`. You can also check the log file at `/work-dir/log` to check the progress of the verification. Once the verification is done, the result (Safe/Unsafe/Unknown) will show up at the Result column (as in Figure 5.6). Note that if you see verification result as Unknown, it is because of the following reason:

1. The system is neither robustly safe nor robustly unsafe Duggirala et al. [2013a].

2. Reachable set computed bloats up and thus the number of refinements needed is too large. Please go back and check the model dynamic and properties, or simulate first to see whether the system trajectories bloats up.

### 5.5.1 Simulation

C2E2 also allows users to generate pure simulation traces from initial sets. Once you have created a model and added a property (see Section 5.3) you can launch the simulation engine by selecting the property and then clicking the `Simulate` button. C2E2 will select several states from initial set and generate simulation traces from those initial states. Note the Safe/Unsafe result shown in this case only stands for the safety of the simulation traces instead of all the reachable states from the initial set.

### 5.5.2 User defined refinement strategy

C2E2 supports user defined refinement strategy (see Section 5.1). You can select USER DEFINE STRATEGY from the drop down menu as shown in Figure 5.4. In this case, you need to write down your strategy in a file named `refineorder.txt` and store it in the `/work-dir` folder. The file should be look like Figure 5.7. In each line, you should write down the index of the variables, the order of which is the same as the variables that are shown in the front end GUI. That is, "2" means the second variable shown in the Variables list in the front end. Indexes that are larger than the dimension of system will be ignored automatically. C2E2 will refine the initial set according to the order written in `refineorder.txt` iteratively. For example, if use the refinement strategy as in Figure 5.7, the dimension corresponding to the second variable will be refined three times, then the dimension corresponding to the first variable will be refined once, then go back to the first line of `refineorder.txt` if the verification process has not terminated.

![Figure 5.6: One or more properties can be selected by checking the boxes to the left of the property name. The Verify button launches the verification engine to verify one property at a time.](image)

![Figure 5.7: The user defined refine strategy file](image)
5.5.3 Change Verified Properties

Once a property is verified the status of the property will change to Verified, and the result Safe/Unsafe/Unknown will appear next to it. C2E2 will also create a new plot on the Plot Tab for each verified property with the name ⟨property name⟩ plot (see Section 9). Once the result has shown up, if you change any of the parameters associated with the property, say the initial set or unsafe set, then the status of the property will change to Verified*. This (*) indicates that the property and parameters verified is outdated and you can launch the verifier again.
6

Model (HyXML) Creation and Editing

- The new text editor tab, brief overview of xml. refer to details given at the end of the manual. Screen shot of editor tab.
- The graphical editing process. Variables, automata, transitions. Discuss all the dialog boxes. Screenshots. The error checks.
- Properties. New, copy, error checks.

6.1 Editing in the GUI

C2E2 version 2.0 allows editing directly in the GUI. To edit any item in the model tree, simply right-click it or use the Model menu in the menu bar.

6.1.1 Automata

Automata are not edited as a whole, but rather they are edited by adding, editing, and removing the variables, modes, and transitions in the automaton. The automaton name can be edited through the Automaton dialog. Similarly, when adding a new automaton, the name can be set in the same Automaton dialog.

To add an automaton, right-click the model tree on an automaton name or in a blank area and select Add Automaton. You can also add an automaton through the menu bar, Model -> Automaton -> Add Automaton. To edit an automaton, the same procedures can be followed, however an automaton must be selected.

6.1.2 Variables

Variables are added, edited, and deleted through the Variable dialog box. The Variable dialog can be accessed through right-clicking the...
model tree on the Variable heading or on the variables themselves. It can also be accessed through the menu bar, Model -> Variables -> Edit Variables. If you have two or more automata in the model, one of them must be selected.

Variables can be set as thin by selecting the check box next to their name. Variable type can be Real or Integer; variable scope can be Local, Input, or Output. To delete a variable, erase its name and leave the field blank, then press Confirm.

6.1.3 Modes

Modes are added, edited, and deleted through the Mode dialog box. The dialog box is accessed through right-clicking the model tree on the Mode heading or the modes themselves. It can also be accessed through the menu bar, Model -> Modes -> Add Mode or Edit Mode or Delete Mode.

When adding modes, if you have more than one automaton in your model, one of the automata must be selected - this can be done by right-clicking within the correct automaton, or by having anything in the correct automaton selected when navigating through the menu bar. When editing or deleting modes, the correct mode must be selected.

To set the mode as the initial mode, make sure the corresponding box is selected. Add a new Flow or Invariant, click "Add Row" below the appropriate heading. To delete a Flow or Invariant, clear out the equation and leave the filed blank when confirming the dialog. As you can see in Figure 6.3, the ID field is disabled. IDs are used internally and do not need to be edited by the user - they are displayed because they can be set when editing the HyXML directly.

6.1.4 Transitions

Transitions are added, edited, and deleted through the Transition dialog box. The dialog box is accessed through right-clicking the model tree on the Transition heading or the transitions themselves. It can also be accessed through the menu bar, Model -> Transition -> Add Transition or Edit Transition or Delete Transition.

When adding transition, if you have more than one automaton in your model, one of the automata must be selected - this can be done by right-clicking within the correct automaton, or by having anything in the correct automaton selected when navigating through the menu bar. When editing or deleting transitions, the correct transition must be selected.

Transitions do not have names, but rather are defined by their source and destination modes. The source and destination are set by
the drop-down menus, which contain all of the modes currently in the automaton. Currently, C2E2 supports a single guard per transition, so if you include multiple guards, you need to create multiple transitions. Multiple actions are supported, and they can be added by clicking the Add Row button.

### 6.2 HyXML Format

In this section, we’ll review the basics of the HyXML file format. HyXMMML files can be edited directly in C2E2 on the Editor tab.

#### 6.2.1 Header

The first few lines of are very familiar to the XML format.

```xml
<?xml version='1.0' encoding='utf-8'?>
<!DOCTYPE hyxml>
<hyxml type="Model">
```

#### 6.2.2 Automaton

The first thing we add to our model is an automaton. To add an automaton, use an automaton element, and set its name with the name attribute. All of our Variables, Modes, and Transitions for this automaton will lie between the opening and closing automaton tags.

```
<automaton name="default_automaton">
</automaton>
```
6.2.3 Variables

Next, we add variables to our automaton. To add a variable, use a variable element, and set its name, scope, and type attributes.

```xml
<variable name="sx" scope="LOCAL_DATA" type="Real"/>
```

6.2.4 Modes

Adding mode requires three different elements. The mode element creates the mode and has attributes id, initial, and name. Within an automaton, only one mode can be the initial mode, and mode IDs must be unique.

After adding the opening mode tag, flows and invariants need to be added with the dai and invariant elements, respectively. The dai and invariant elements both have the same single attribute, equation.

```xml
<mode id="0" initial="True" name="SlowDown">
  <dai equation="vx_dot" = 0.1*ax"/>
  <invariant equation="sx + 10 \lt; 0"/>
</mode>
```

6.2.5 Transitions

Transitions are similar to modes in the HyXML. First, a transition element must be added. Guards and actions are then added with the guard and action elements, respectively. The transition element has three attributes, source, destination, and id. The guard and action element both have the same single attribute, equation.

```xml
<transition source="0" destination="1" id="1">
  <guard equation="sx + 10 \gt; 0">
  </transition>
```
7
Composition, Parsing, and Analysis

In this chapter, we describe in more detail the key operations on hybrid automata that can be performed by C2E2. The input a .hyxml file generally contains (i) A list of component hybrid automata $A_1, \ldots, A_k$, (ii) the definition of (one or more) composed hybrid automaton $A$, (iii) a list of safety requirements (See Section ??). The C2E2 workflow has the following steps: (i) The component automata $A_1, \ldots, A_k$ are composed according to the definition of the composed automaton $A$ to generate the complete (internal) representation of $A$. (ii) The automaton model $A$ is parsed. This generates internal files used for simulation and verification. (iii) Once parsed successfully, $A$ can be either simulated or verified against the requirements. (iv) Simulations draw random initial states and generate simulation traces and checks for safety of those traces. (v) Verification uses the algorithm presented in ?? to check the safety property of the given model. In the rest of this chapter, we mention some of the key aspects of these four steps. For details on the mathematical model used here and the algorithms, we refer the reader to Duggirala et al. [2014], ?.

7.1 Composing

It convenient to define a complex model in terms of its components. The composition operation for hybrid automaton defines a bigger (more complex) hybrid automaton $A$ in terms of a pair of component automata $A_1$ and $A_2$. This binary operation can be applied repeatedly to compose a finite set of automata.

A hybrid automaton $A$ in C2E2 is defined by the following followings:

(i) $L$: A finite set of modes or locations.

(ii) $X, I, Y$: Finite pair-wise disjoint sets of state (local), input, and output variables. State variables are called LOCAL in HyXML.
We will denote the set of valuations for these variables by $val(X), val(Y), val(U)$, etc.

(iii) $D \subseteq L \times L$: A discrete transition graph. For each edge in the graph $(\ell, \ell') \in D$, two functions are specified. First, $\text{guard}(\ell, \ell') : val(X) \rightarrow B$ is a transition precondition, and $\text{reset}(\ell, \ell') : val(X) \rightarrow val(X)$ is a (linear) reset function.

(iv) $\{f_\ell\}$: Differential equations describing the evolution of $X \cup Y$ (with $U$ as input) for each mode $\ell \in L$.

When discussing several automata $A, A_1, A_2$, etc., we will use subscripts $X_A, X_1, X_2, and L_A, L_1, L_2, etc.$ to disambiguate components coming from different automata.

For the composition of a pair of hybrid automata $A_1$ and $A_2$ to be well-defined, they must be compatible. That is, the following conditions must be met:

- $(X_1 \cup Y_1) \cap (X_2 \cap Y_2) = \emptyset$,
- $U_1 \subseteq Y_2$ and $U_2 \subseteq Y_1$

In the current implementation of C2E2, $A_1$ and $A_2$ can only interact through shared variables, and not through shared transitions.

For a pair of compatible automata $A_1$ and $A_2$ the Compose operation of C2E2, constructs the composed automaton $A$ (as defined below). Once this composed model is saved, a new HyXML file with the composed automaton is saved.

(i) $L_A = L_1 \times L_2$,
(ii) $X_A = X_1 \cup X_2, Y_A = Y_1 \cup Y_2, U_A = \emptyset$.
(iii) $[((\ell_1, \ell_2), (\ell'_1, \ell'_2)) \in D_A \text{ iff } (\ell_1, \ell'_1) \in D_1 \text{ and } \ell_2 = \ell'_2, \text{ or } (\ell_2, \ell'_2) \in D_2 \text{ and } \ell_1 = \ell'_1$.
(iv) $\{f_{\ell_1, \ell_2}; f_{\ell_2, \ell_2}\}$ for each mode $(\ell_1, \ell_2) \in L_A$, the differential equations for $X_A = X_1 \cup X_2 \cup Y_1 \cup Y_2$, are derived by simply concatenating the differential equations for $(X_1 \cup Y_1)$ in mode $\ell_1$ with those for $(X_2 \cup Y_2)$ in mode $\ell_2$. The differential equations for each mode of $A$ are derived from those of the component modes.

7.2 Parsing

Before any simulation or verification can happen, the system must first be parsed. When parsing, we perform a variety of checks to
make sure the system is capable of being simulated and verified. In
the following sections we enumerate these checks (see Section 6.1 for
details about the HyXML format).

7.2.1 Variables

• Local variables must all be distinct from all other variables in the
model
• Output variables must be distinct from all local variables
• Output variables must be distinct from all other output variables
• Input variables must be distinct from all local variables
• Input variables must be distinct from other input variables within
the same automaton
• Every input variable must have a matching output variable in a
different automaton

7.2.2 Mode

Mode names and mode IDs must be unique within an automaton.
Note that mode IDs can only be changed through editing the HyXML
directly.

7.2.3 Flows

• Expressions must be standard mathematical expressions and use
standard mathematical operators
• Expression contains only one symbol on the left-hand side
• Output variables on right-hand side must not end with _dot
• Local variables on left-hand side must end with _dot
• Input variables must not be used on the left-hand side

7.2.4 Invariants

• Expressions must be standard mathematical expressions and use
standard mathematical operators.

7.2.5 Transition Guards

• Expressions must be standard mathematical expressions with
standard mathematical operators.
• Expressions must be separated by "&&".
7.2.6 Transition Actions

- Expressions must be standard mathematical expressions with standard mathematical operators.
- Expressions must be separated by "&&".

Compatibility checks. This happens here or in compose?
List of error messages and their interpretations.

7.3 Simulation

When the Simulate button is clicked, C2E2 transforms the input hybrid automaton model and generates faithful numerical simulations of this model. The type of simulator used can be chosen by the user. The most robust simulator is ODEInt from the Boost library. Other validated numerical simulators like VNODE-LP Nedialkov [2006] and CAPD are also supported but because of numerical instability issues, using these simulators may require some extra work in the latest version of C2E2.

Roughly, the simulation procedure works as follows. A sequence of initial states are drawn randomly from the specified starting set. From each of these initial states, a simulation in the current mode is generated using the C++ simulator function. This function is compiled when the HyXML file is parsed. Once the simulation in the current mode is computed, the result is checked to see if any guards are hit. If any of the guards are hit, the simulation is truncated, the initial state in the next mode is computed using the reset function, and the simulation is continued in the new mode for the remaining time. If none of the guards are hit, the simulation is complete. This procedure is repeated for all the initial state. If any of the simulations hit the specified “unsafe set”, then the result unsafe is returned, otherwise the result “safe” is returned. Of course, “safe” does not mean that all behaviors from the starting set are safe. The simulation output is stored in a text file in the working directory.

7.4 Verification

There are several papers describing the C2E2 verification algorithms Fan and Mitra [2015], Fan et al. [2016], Duggirala et al. [2013b], Fan et al. [2016], Duggirala et al. [2014] and therefore we are not going to repeat them here. For linear systems a global discrepancy function is used, while for nonlinear systems the local discrepancy
computation presented in Fan and Mitra [2015], Fan et al. [2018a] is implemented. The reach tubes computed for verification are stored in a textfile in the working directory.

You may want to look at some of the applications of C2E2 in verification of cyber-physical systems: Toyota’s Powertrain control system Duggirala et al. [2015], NASA landing alarm system Duggirala et al. [2014], Complex transistor models Fan et al. [2018b], model of cardiac pacemaker Huang et al. [2014, 2015], and autonomous spacecraft maneuvers Chan and Mitra [2017]. Several other examples are reported in the ARCH competition of 2018 Althoff et al. [2018]. We will be happy to hear about your applications; send email to c2e2help@gmail.com.
C2E2 version 2.0 comes with a completely overhauled plotter. On the new Plot tab, you can plot any data set you choose, and the result will be an interactive HTML plot that you can use to focus in on certain parts of your data.

The Plot tab has two main components - the plot pane, where small images on the plots are displayed, and the plot sidebar, where plots can be created and edited.

8.1 Creating and Editing Plots

To create a plot, the first thing you need to do is select the data source. To do this, select on the button next to the Source field (labeled "...") , and choose which file to load - the data files generated by C2E2 are stored in the /work-dir/output/ directory. As mentioned, this can be any data source generated by C2E2, it does not have to be
related to the model you currently have open in the Model and Editor tabs. Next, fill out the Filename and Plot Name fields.

- **Filename**
  This represents the filename used to store the various plots generated by the plotter. Two files will be generated using this name, `filename.html` and `filename.png`. The PNG file is the preview image displayed done the plot pane, and the HTML file in the interactive plot.

- **Plot Name**
  This the title as it will be displayed on your plot.

- **Source**
  This is the data source used to create the plot. The data source used must be a properly-formatted file generated by C2E2 when running a simulation or verification. These files will be stored in the `/work-dir/output/` directory and be named after the requirement that created them.

If you recently simulated or verified a requirement, you may notice that you have this field, as well as plot name and file name, already filled out. This is because C2E2 automatically creates a new plot with the fields defaulted in when a requirement is simulated or verified.

Next, you need to choose which variables will appear on the vertical axis, and which will appear on the horizontal axis. You can only select one variable to be on the horizontal axis, and you must choose at least one variable to be on the vertical axis.

Finally, click on the Plot button. Once the plotting is complete, you will see a preview appear on the plot pane. You can double-click on this image to open the interactive HTML plot in your default browser.

### 8.2 Multiple Plots

Multiple plots can be added by using the New and Copy buttons, and they will be displayed in the Plot List on the Plot Sidebar.

### 8.3 Requirements

The requirements (properties) that were used to create the source data file can be displayed by clicking on the `+` next to the Properties label.

![Figure 8.2: Requirements Display](image)
9

Building models for C2E2

In this chapter, we will discuss two example C2E2 models.

9.1 Example 1: Laub-Loomis

The first example mentioned is a continuous system with nonlinear dynamics. The example we used is the Laub-Loomis model. It is a model with seven variables. The dynamics of the model is given by:

\[
\begin{align*}
\dot{x}_1 &= 1.4x_3 - 0.9x_1 \\
\dot{x}_2 &= 2.5x_5 - 1.5x_2 \\
\dot{x}_3 &= 0.6x_7 - 0.8x_2x_3 \\
\dot{x}_4 &= 2 - 1.3x_3x_4 \\
\dot{x}_5 &= 0.7x_1 - x_4x_5 \\
\dot{x}_6 &= 0.3x_1 - 3.1x_6 \\
\dot{x}_7 &= 1.8x_6 - 1.5x_2x_7
\end{align*}
\]

In this example, we use initial set given by 
\( x_1(0) \in [1.1, 1.3], \)
\( x_2(0) \in [0.95, 1.15], x_3(0) \in [1.4, 1.6], x_4(0) \in [2.3, 2.5], x_5(0) \in [0.9, 1.1], x_6(0) \in [0, 0.2], x_7(0) \in [0.35, 0.55], \)
and the unsafe set is 
\( x_4 \leq 5. \) The model is running in time interval \( t \in [0, 20] \). The problem can be described as follows.

```xml
<hyxml type="Model">
  <automaton name="default_automaton">
     <!-- specify variables -->
     <variable name="x1" scope="LOCAL_DATA" type="Real" />
     <variable name="x2" scope="LOCAL_DATA" type="Real" />
     <variable name="x3" scope="LOCAL_DATA" type="Real" />
     <variable name="x4" scope="LOCAL_DATA" type="Real" />
     <variable name="x5" scope="LOCAL_DATA" type="Real" />
     <variable name="x6" scope="LOCAL_DATA" type="Real" />
     <variable name="x7" scope="LOCAL_DATA" type="Real" />
  </automaton>
</hyxml>
```
<!- specify modes -->

<mode id="0" initial="True" name="Model">
    <!- specify dynamic equations in mode -->
    <dai equation="x1_dot = 1.4*x3-0.9*x1" />
    <dai equation="x2_dot = 2.5*x5-1.5*x2" />
    <dai equation="x3_dot = 0.6*x7-0.8*x2*x3" />
    <dai equation="x4_dot = 2-1.3*x3*x4" />
    <dai equation="x5_dot = 0.7*x1-x4*x5" />
    <dai equation="x6_dot = 0.3*x1-3.1*x6" />
    <dai equation="x7_dot = 1.8*x6-1.5*x2*x7" />
</mode>

</automaton>

<composition automata="default_automaton"/>

<!- setup the initial set and unsafe set of the constraints -->

<property
    initialSet="Model:
        x1&ge;1.1 &amp;&amp; x1&le;1.3 &amp;&amp;
        x2&ge;0.95 &amp;&amp; x2&le;1.15 &amp;&amp;
        x3&ge;1.4 &amp;&amp; x3&le;1.6 &amp;&amp;
        x4&ge;2.3 &amp;&amp; x4&le;2.5 &amp;&amp;
        x5&ge;0.9 &amp;&amp; x5&le;1.1 &amp;&amp;
        x6&ge;0 &amp;&amp; x6&le;0.2 &amp;&amp;
        x7&ge;0.35 &amp;&amp; x7&le;0.55"
    name="large"
    unsafeSet="x4&ge;5">
    <!- specify the parameters for computation -->
    <parameters
        kvalue="50.0"
        timehorizon="20.0"
        timestep="0.05" />
</property>

</hyxml>

C2E2 is able to solve the model with time step 0.05 and k is set to be 50. The computed reachtube for variable $x_4$ is shown in Figure 9.1.

Figure 9.1: Plot for $x_4$ for example 1.
9.2 Example 2: Cell and Pacemaker

The second example mentioned is a hybrid system. The example we used is the FitzHugh-Nagumo (FHN) model. The model has 2 variables and 2 modes. The dynamic for each mode is give by hybrid automaton.

In this example, we use initial set given by \( u(0) = 0 \) and \( v(0) = 0 \) and a variable \( t \) is introduced to track time spend in each mode. The model is running in time interval \( t \in [0, 40] \). The problem can be described as follows.

\[
\begin{align*}
\text{Stim On} & \\
\text{• Flow} & \\
\begin{cases}
\dot{u} = 1 - u^3 - 0.9y^2 - 0.9u - v \\
\dot{v} = u - 2v \\
t = 1
\end{cases} & \\
\text{• Invariant} & \\
t < 5
\end{align*}
\]

\[
\begin{align*}
\text{StimOff} & \\
\text{• Flow} & \\
\begin{cases}
\dot{u} = -u^3 - 0.9y^2 - 0.9u - v \\
\dot{v} = u - 2v \\
t = 1
\end{cases} & \\
\text{• Invariant} & \\
t < 5
\end{align*}
\]

\[
\begin{align*}
\text{Guard: } t \geq 5 & \\
\text{Action: } t = 0
\end{align*}
\]

\[
\begin{align*}
\text{Guard: } t \geq 20 & \\
\text{Action: } t = 0
\end{align*}
\]

<hyxml type="Model">
<automaton name="default_automaton">
<!-- specify variables -->
<variable name="t" scope="LOCAL_DATA" type="Real" />
<variable name="u" scope="LOCAL_DATA" type="Real" />
<variable name="v" scope="LOCAL_DATA" type="Real" />

<!-- specify modes -->
<mode id="0" initial="True" name="stimOn_cardiac">
  <dai equation="t_dot = 1" />
  <dai equation="u_dot = 1 - pow(u,3) - 0.9*pow(u,2) - 0.9*u - v" />
  <dai equation="v_dot = u - 2*v" />
  <!-- specify invariants -->
  <invariant equation="t&lt;5" />
</mode>

<mode id="1" initial="False" name="stimOff_cardiac">
  <dai equation="t_dot = 1" />
  <dai equation="u_dot = 0 - pow(u,3) - 0.9*pow(u,2) - 0.9*u - v" />
  <dai equation="v_dot = u - 2*v" />
  <!-- specify invariants -->
</mode>
</automaton>
</hyxml>
C2E2 is able to solve the model with time step 0.01 and k value 2000. The computed reachtube for variable v is shown in Figure 9.2

9.3 Intermediate Files

Several files are generated while verifying the model and some of them are worth mentioning.

jacobiantxt The jacobiantxt file contains the jacobian for the dynamic of the system. If the system have multiple modes, files with higher index will be generated and each file correspond to one mode of the system. Each file contain the number of variables,
the name of variables, the total number of entries in the jacobian
matrix and the matrix itself. These files are used in computing the
reach tube.

*simulator.cpp*  The *simulator.cpp* file is auto generated by the frontend.
It contains a simulator for the model for simulation engine odeint.
The file can be compiled to an independent executable *simu* which
is also located inside the work-dir folder. The simulator *simu* and
it’s corresponding configuration file *Config* (which is also located in
work-dir folder), can be executed and providing simulation result by
using command "./simu Config".

*SimuOutput*  The *SimuOutput* file contains the simulated result for
the model.

*reachtube.dat*  The *reachtube.dat* file contains the computed reach tube
for the model.
A

Required Libraries

The following is a complete list of packages needed for installing C2E2.

1. GNU Linear Programming Kit along with Python bindings, GLPK and PyGLPK (http://www.gnu.org/software/glpk/) (http://tfinley.net/software/pyglpk/)
2. GNU parser generator, Bison (http://www.gnu.org/software/bison/)
3. The Fast Lexical Analyzer, Flex (http://flex.sourceforge.net/)
4. Python (http://www.python.org/)
5. Python parsing libraries, Python-PLY (http://code.google.com/p/ply/)
6. GTK libraries for Python (http://www.pygtk.org/)
7. Plotting libraries for Python, Matplotlib (http://matplotlib.org/)
8. Packing configurations library (http://www.freedesktop.org/wiki/Software/pkg-config/)
9. GNU Autoconf (http://www.gnu.org/software/autoconf/)
13. Boost libraries (http://www.boost.org)
14. Python Numpy library (http://www.numpy.org/)
15. Python SciPy library (https://www.scipy.org/)
16. Python Pillow library (https://python-pillow.org/)
17. Python3 GnuPlot library (https://github.com/oblalex/gnuplot.py-py3k)
Bibliography


Chuchu Fan and Sayan Mitra. Bounded verification with on-the-fly discrepancy computation. 13th International Symposium on Automated


