Appendix

F Source Code - List of Contents

This document explains which figures, tables et cetera in the doctoral thesis *Safety Verification of Real-Time Control Systems with Flexible Timing – M. Gaukler, 2023* correspond to which source and output files in the `output.tar.gz` archive.

The archive contains the following:

- a README.md file with an overview of how to run the program
- the source code
- the output files, so you don't have to run the code yourself.

The archive can be downloaded at https://doi.org/10.5281/zenodo.6373637 or created by running `./make_full_archive.sh` according to the `README.md` instructions.

If you are looking for the hybrid-automaton system model as a SpaceEx XML file, skip to Appendix F.7.

The output includes raw plot images as produced by the tools. In contrast, the images shown in the thesis have been postprocessed to adjust colors, make the axis clearly visible and repair missing filling of outlines.

F.1 Problem Statement (Chapter 3)

Figure 11: Timing Simulation The simulation reuses the simulation infrastructure of direct reachability analysis, which is explained later.

Command	See Appendix F.2
Output folder	`output/reachability_arch19/demo/`
Plot images	0 %: `D3_0_ONLY_SIMULATION___quadrotor_attitude_three_axis_large_jitter_3.png`
	10, 20, 40 %: `D3_10_...`, `D3_20_...`, `D3_40_...`

Figure 15: Bouncing Ball Simulation The plot data is created with MATLAB R2018b from the Simulink model `notes/simulink_bouncingBall.slx`.

F.2 Direct Reachability Analysis (Section 4.2.10)

Figure 26: Reachability analysis and simulation The computation can be started according to `README.md`. Output files are already contained in the archive, as noted earlier.

Command	`./run_experiments_docker.sh arch19`
Main source file	`src/qronos/reachability/experiments/arch19.py`
Output folder	`output/reachability_arch19/`

The output folder contents are grouped into several sub-folders, such as `solved_with_spaceex/stable`. The names of these subfolders are historical and were left unchanged for consistency with the older publication Gaukler and Ulbrich, 2019. Every system is sorted into one of these subfolders. The following files are created, where `XX` denotes the system, such as `A1_1` for example A1.

- Randomized simulation (first column of Figure 26):
  - Input for HyST to generate the PySim file:
    `XX__for_pysim__..spaceex.xml`, ….`cfg`
  - Plotted image:
    `XX__for_pysim__..spaceex.xml_pysim_plot_xp1_over_t.png`
- Reachable set over time: (Second column of Figure 26)
  - Input for HyST to generate the SpaceEx file:
    `XX__reachability_with_time_.spaceex.xml`, ….`cfg`
  - The processing with HyST/SpaceEx is described later.
  - Plotted image:
    `XX__reachability_with_time_.spaceex.xml__`↵
    `spaceex_plot_xp1_over_t.png`
- Reachable set on infinite time horizon (Mark ✓/ ✗ in Figure 26):
  - System definition in SpaceEx format: `XX.spaceex.xml`, ….`cfg`
    This system model can be used as a benchmark for other reachability tools.
  - The system definition is preprocessed by HyST and sent to SpaceEx. The preprocessing by HyST is not strictly necessary but merely a result of the HybridPy toolchain.

- The result (success or not) is stored in `results.tex` in the column "SpaceEx".

To avoid errors on certain CPUs, the GMP library version 10.2 included in SpaceEx was replaced with a newer version 10.3.2. Compared to the unmodified version used in Gaukler and Ulbrich, 2019, no significant deviation of the results was found.

F.3 LIS Derivations

Theorem 5.1.4: Splitting The numerical experiment for Theorem 5.1.4 is given in `src/qronos/lis/test_lis.py`, function `test_Ak_delta_to_nominal`.

Remark 5.1.18: Extremal P-ellipsoidal Norm Symbolic and numeric computations for the example are given as a MATLAB R2018b script in `notes/matlab_counterexample_for_existence_of_extreme_P.m`.

F.4 LIS Results

The values of Table 1, except for the "Reach" column, are generated by the following command:

Command	`./run_experiments_docker.sh ifac20`
Main source file	`src/qronos/lis/experiments/timing_stability_ifac20.py`
Output file	`output/lis_stability_ifac20/results.tex`

Results are printed to the commandline and saved in the log file `logfile.txt`. There is no separate result file. No plots are generated.

The reachability result ("Reach" column) is computed separately as described in Appendix F.2. The value (success or not) is stored in the `SpaceEx` column of `output/reachability_arch19/results.tex`.

The run-time measurements in Table 1 are taken from the publication Gaukler, Roppenecker, et al., 2020. The output file in the archive has slightly different times since it was re-created later. The reason for the re-creation is to ensure that the output consistently matches the code.

The implementation of interval arithmetic uses a modified version of *mpmath*. Unfortunately, the maintainers of this software are very busy, so it was not possible to merge all the modifications into the main *mpmath* codebase. The GIT repository corresponding to the modified *mpmath* can be found at https://github.com/maxgaukler/mpmath/tree/current, branch "current".

F.5 Continuization

The continuization experiment of Figure 35 corresponds to the following files:

Command	`./run_experiments_docker.sh cont`
Main source file	`src/qronos/reachability/experiments/continuization.py`
Output folder	`output/continuization_arch20/output_continuization`
Left plot	`XX__reachability_with_time_.spaceex.xml__spaceex_plot_xp1_over_t.png`
Center plot	`XX__for_pysim__.spaceex.xml_pysim_plot_xp1_over_t.png`
Right plot	`XX__for_pysim__.spaceex.xml_pysim_plot_xd1_over_t.png`
Rows	Replace `XX` with `C4_orig`, `C4_continuized`, `C5_orig`, `C5_continuized`.
HA file	Hybrid automaton in SpaceEx format: Original: `C4_orig.spaceex.xml`, `C5_orig`... Continuized: `C4_continuized.spaceex.xml`, `C5_continuized`...

F.6 Dynamic Resource Management (Section 7.5)

The simulation experiment from Section 7.5 and its output can be found at the following location:

Command	`./run_experiments_docker.sh abs`
Main source file	`src/qronos/lis/experiments/abstraction_timing.py`
Output folder	`output/abstractions/`
Output files	`XX.pdf`: PDF plot `XX/plot.tex` LaTeX source code for plotting `XX/....tsv`: raw data

In these file names, `XX` refers to the corresponding figure:

Figure	Filename
Figure 38	`abstraction-timing-nominal_case__perfect_timing__no_skips`
Figure 39	`abstraction-timing-skips__fixed__short`, `abstraction-timing-skips_fixed_long`
Figure 40	`abstraction-timing-skips__low_probability`
Figure 41	`abstraction-timing-skips__high_probability`, `abstraction-timing-skips__high_probability__ASSUMING_BETTER_ABSTRACTION__UNPROVEN__`
Figure 43	`abstraction-timing-timing_forced_max`
Figure 44	`abstraction-timing-timing_deviation__low_variance`, `abstraction-timing-timing_deviation__medium_variance`

F.7 Example systems (Appendix A)

Definition of the Example Systems The example systems are defined in the source code at `src/qronos/examples.py`. As detailed in Appendix F.2, the hybrid automata are output in SpaceEx format at `output/reachability_arch19/.../XX.spaceex.xml`, where `XX` refers to the specific example. For instance, example A1 can be found at `code/template/output/solved_with_spaceex/stable/A1_1.spaceex.xml`.

Figure 45: Nominal Case of Example C The plot is generated with MATLAB/Simulink R2018b from the files in `notes/example-c-nominal-case/`.