Verifying Cyber-Physical Systems by Combining Software Model Checking with Hybrid Systems Reachability

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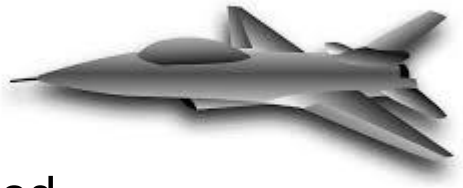
Motivation

Cyber-Physical System (CPSs) play safety-critical roles in day-to-day lives

- Avionics, automotive, healthcare, energy



High-level of assurance of safe and secure behavior desired

- As close to the executable as possible

Formal verification provides high confidence in principle, but

- **Issue1:** Application and controller algorithms analysed by different techniques – each with their own specialized tools
- **Issue2:** In practice plagued by scalability issues
- Can **compositional reasoning** address both issues?

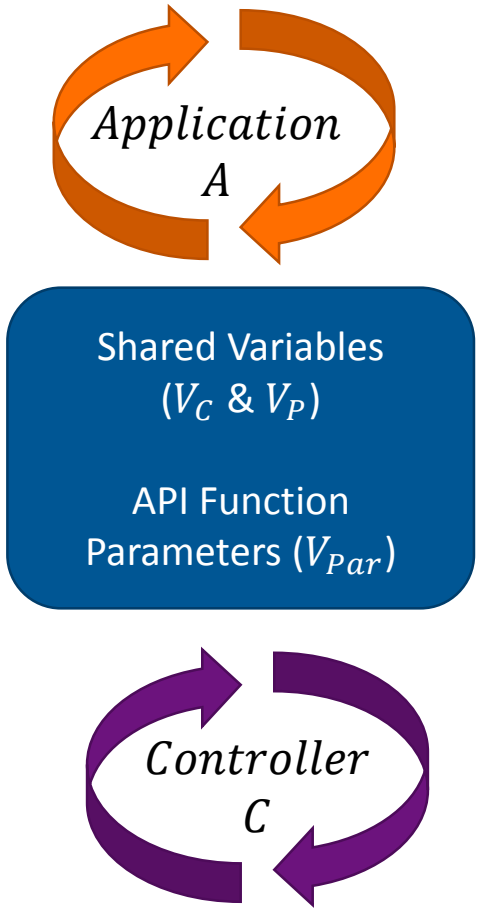
We present a compositional approach to verify CPS software

- Software model checking + hybrid system reachability
- Validated on a multi-agent collision avoidance protocol

CPS Model Of Computation

System composed of application A and controller C

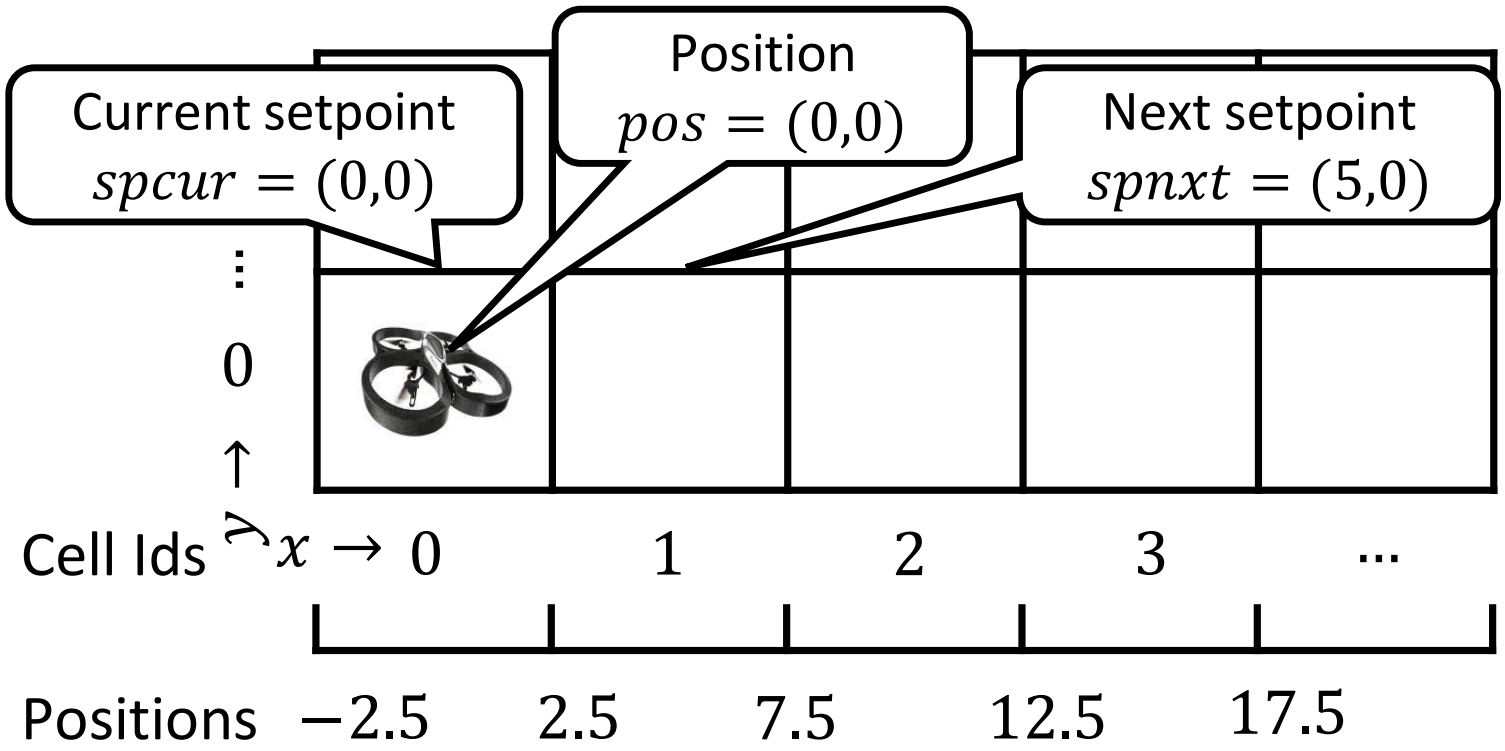
- Execute concurrently : $S = A \parallel C$
- Communicate via shared variables
  - Cyber variables V_C written by A and read by C
  - Physical variables V_P written by C and read by A
- Accessed by A via API functions
- Application A available as source code
- Controller C available as a hybrid automaton
  - C = controller + plant (from control theory perspective)



Want to verify that S satisfies a safety property (something bad never happens)

- Formally, $S \models \Phi$ where Φ is an invariant expressing the safety property of interest

Example: 2D Quadcopter Movement



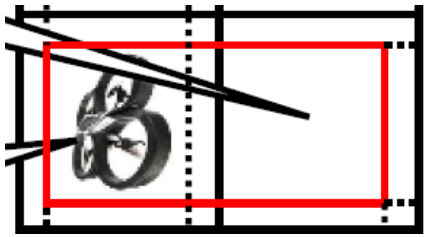
Example: Target Property

$$\Phi_{hover} \equiv |pos - spcur| \leq (1.5, 1.5)$$

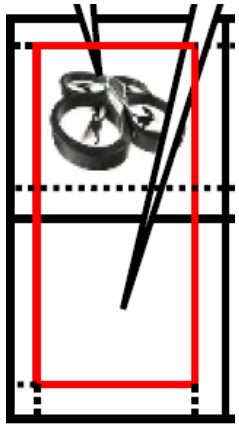
$$(\Phi_{hover} \wedge spnxt = spcur)$$

$$\vee$$

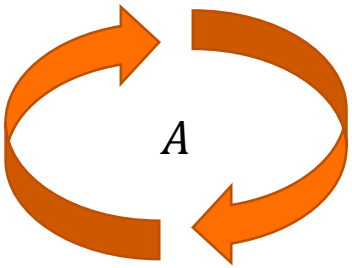
$$(\Phi_{move} \wedge (|spnxt - spcur| = (5,0) \vee |spnxt - spcur| = (0,5)))$$



$$\begin{aligned}\Phi_{move} \equiv\ & min(spcur_x, spnxt_x) - 1.5 \leq pos_x \\ & \leq max(spcur_x, spnxt_x) + 1.5 \\ \wedge\ & min(spcur_y, spnxt_y) - 1.5 \leq pos_y \\ & \leq max(spcur_y, spnxt_y) + 1.5\end{aligned}$$

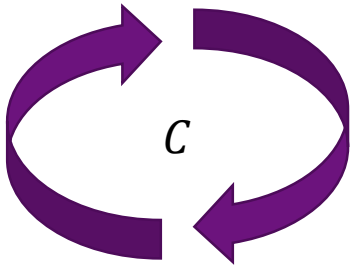


Example: 2D Quadcopter Movement



Shared Variables
Cyber: $spcur, spnxt$
Physical: pos

API Function Parameters
x, y



Periodically invokes API functions $update\_setpoint(x, y)$ and $has\_arrived()$ that update $spcur$ and $spnxt$ to interact with the controller.

Continuously executes a control algorithm to move/hover the platform based on values of $spcur$ and $spnxt$. Updates pos.

Verification Approach

No existing tools to verify (source code + hybrid automata)

- But each domain has its own specialized tools: software model checkers and hybrid reachability checkers
- Developing such a tool that combines the statespace A and C in a brute-force way will not scale

Insight: application and controller make assumptions about each other to achieve overall safe behavior

Approach:

- Use “contract automaton” to express inter-dependency between A and C
- Separately verify that A and C implement desired behavior under the assumption that the other party does so as well
- Use an “assume-guarantee” style proof rule to show the $A \parallel C \vDash \Phi$

Benefits of Verification Approach

Use "contract automaton" to express inter-dependency between A and C

- Explicit formal understanding between teams developing A and C

Separately verify that A and C implement desired behavior under the assumption that the other party does so as well

- Compositional ⇒ more scalable
- Use domain-specific tools ⇒ build on progress in each area

Use an "assume-guarantee" style proof rule to show the $A \parallel C \vDash \Phi$

- Proof-rule formally proven to be sound ⇒ amortized proof cost
- Other variants can be developed to manage tradeoff between completeness and verification complexity

Example: Assumptions between A and C

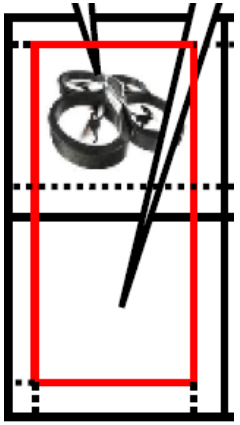
(C1) The application always calls $update\_setpoint(x, y)$, with arguments that satisfy the condition $|(x, y) - spcur| = (5, 0) \vee |(x, y) - spcur| = (0, 5)$.

(C2) Once the application calls $update\_setpoint(x, y)$, it can keep calling $has\_arrived()$ until it gets a return value of TRUE; once $has\_arrived()$ returns TRUE, the application can only then start to call $update\_setpoint(x, y)$ again.

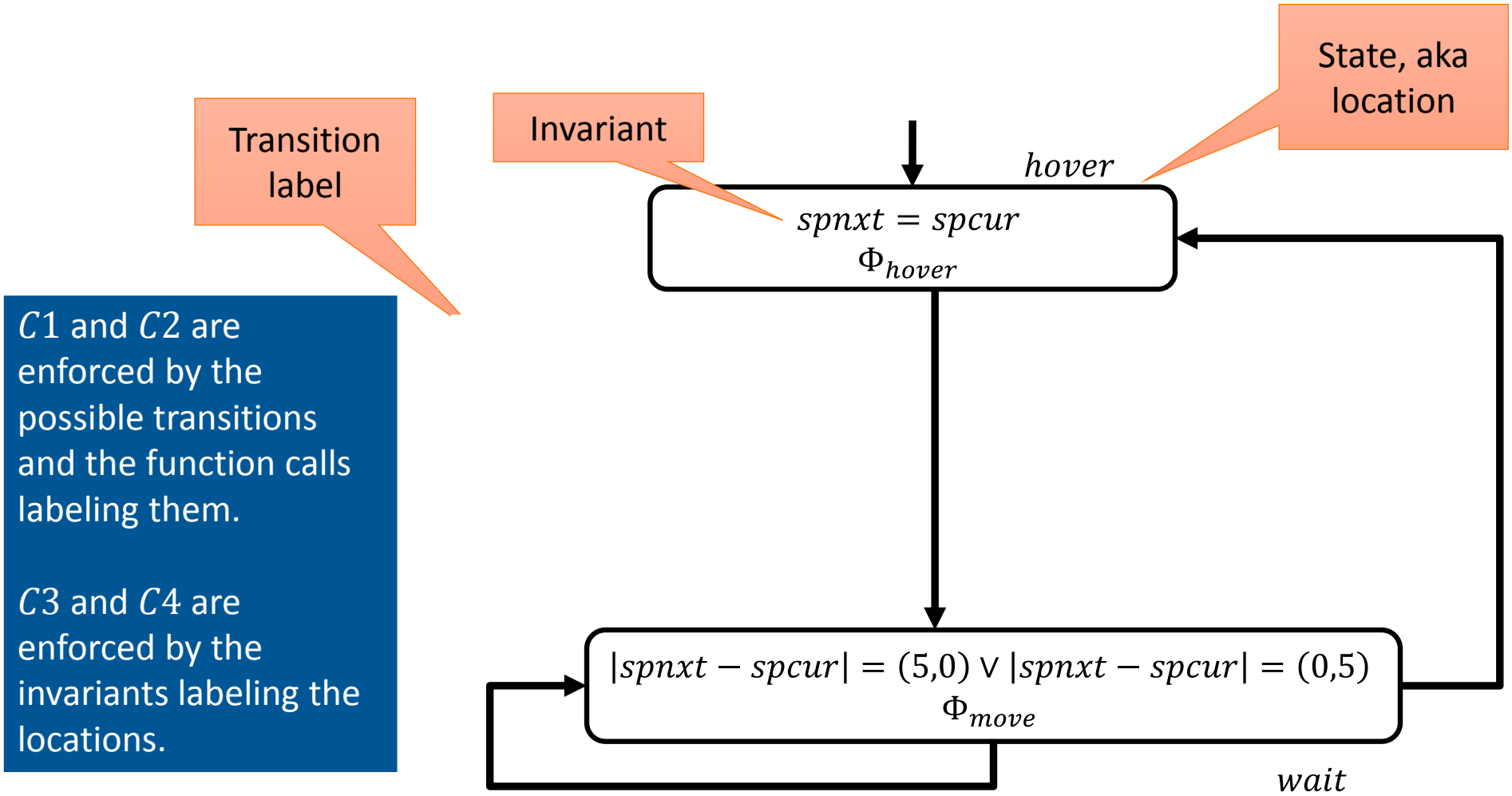
(C3) When the quadcopter is hovering (i.e., $spnxt = spcur$), the controller must maintain the following invariant: $\Phi_{hover} \equiv |pos - spcur| \leq (1.5, 1.5)$.

(C4) When the quadcopter is moving (i.e., $|spnxt - spcur| = (5, 0) \vee |spnxt - spcur| = (0, 5)$), the controller must maintain the following invariant:

$$\begin{aligned} \Phi_{move} \equiv\ & min(spcur_x, spnxt_x) - 1.5 \leq pos_x \\ & \leq max(spcur_x, spnxt_x) + 1.5 \\ \wedge\ & min(spcur_y, spnxt_y) - 1.5 \leq pos_y \\ & \leq max(spcur_y, spnxt_y) + 1.5 \end{aligned}$$



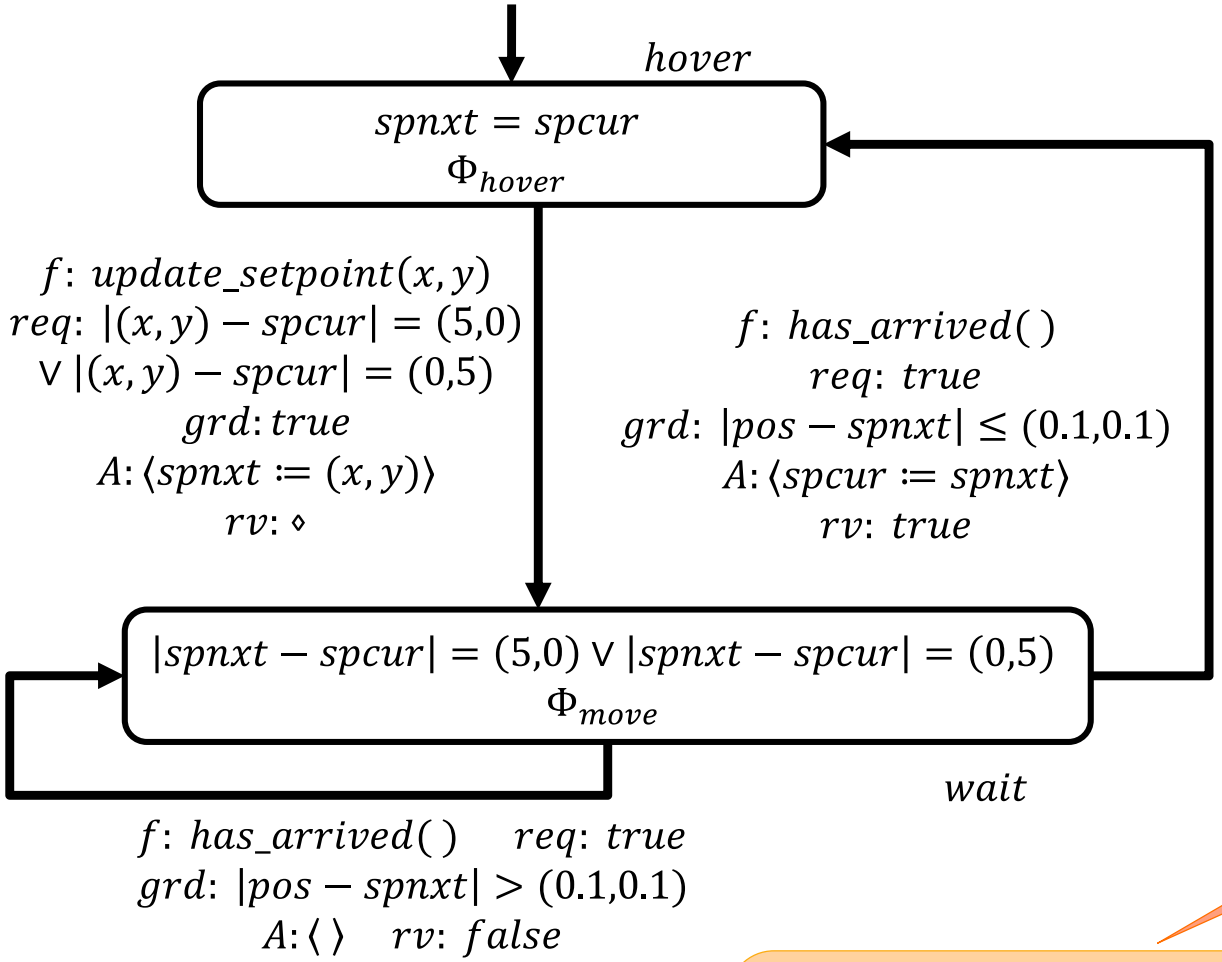
Example: Contract Automaton



$C1$ and $C2$ are enforced by the possible transitions and the function calls labeling them.

$C3$ and $C4$ are enforced by the invariants labeling the locations.

Contract Automaton Invariant = Target Property



Target Property

CA Invariant = disjunction of state invariants

$$(\Phi_{hover} \wedge spnxt = spcur) \vee (\Phi_{move} \wedge \begin{pmatrix} |spnxt - spcur| = (5,0) \vee \\ |spnxt - spcur| = (0,5) \end{pmatrix})$$

Assume-Guarantee Proof Rule

Premise1: Application A refines the contract automaton M (calls API functions in the right order and with proper arguments)

Premise2: Controller C refines the contract automaton M (keeps the physical state within required bounds)

THEOREM 1 (COMPOSITIONAL REFINEMENT).

$$\frac{A \preceq M \qquad C \preceq M}{A \parallel C \preceq M}$$

Conclusion: System satisfies all invariants of the contract automaton M = target safety property

$$(\Phi_{hover} \wedge spnxt = spcur) \vee (\Phi_{move} \wedge (|spnxt - spcur| = (5,0) \vee |spnxt - spcur| = (0,5)))$$

Discharging The Premises

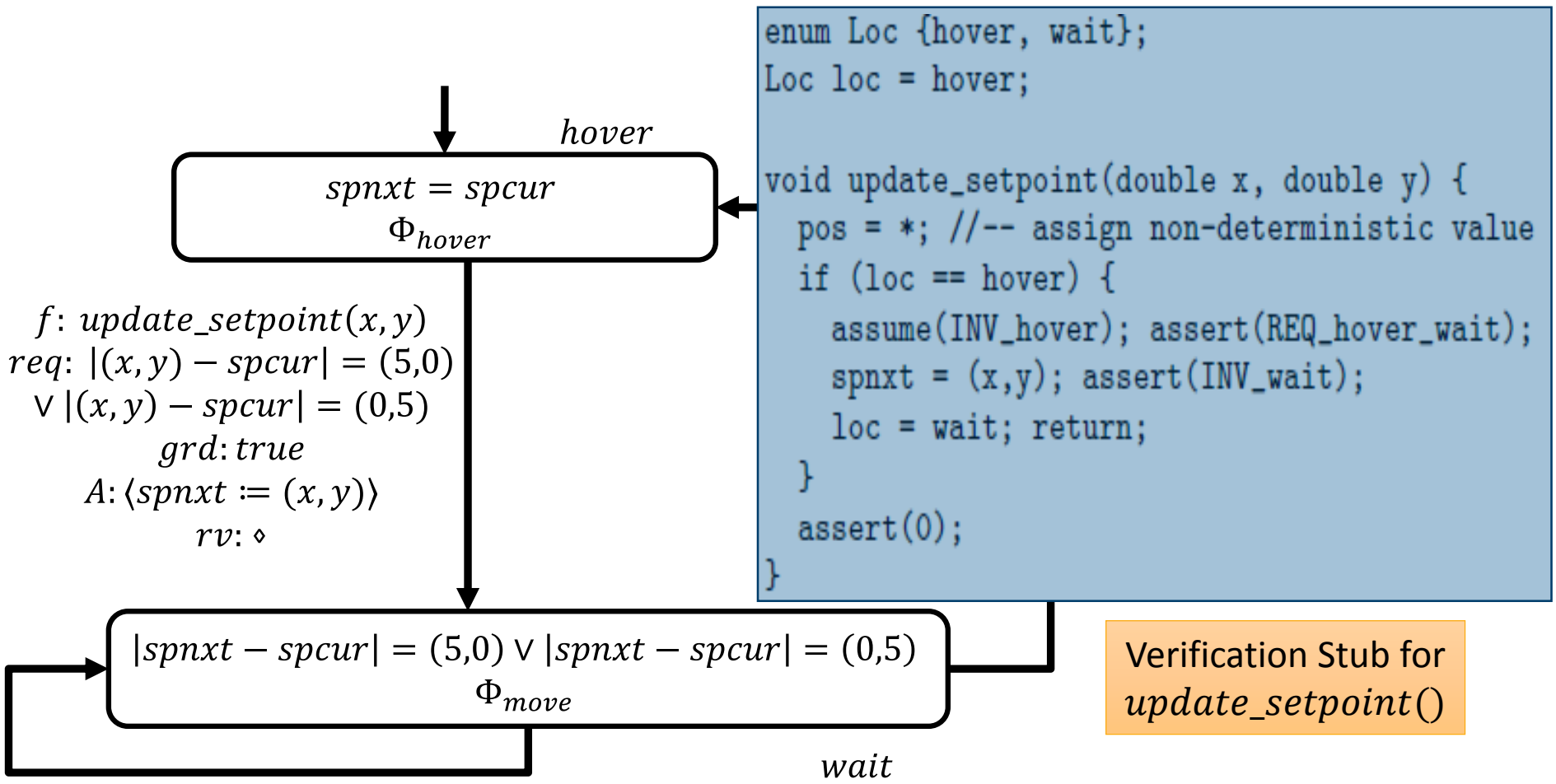
Premise1: Application A refines the contract automaton M (calls API functions in the right order and with proper arguments)

- Reduced to software model checking, discharged via CBMC
- Manually supplied invariants and used CBMC to verify that they are inductive
- 1700 LOC, 2.9GHz, 16GB RAM, 3.5 seconds

Premise2: Controller C refines the contract automaton M (keeps the physical state within required bounds)

- Reduced to hybrid system reachability, discharged via SpaceEX
- Required continuous approximation and symmetry argument
- 2.3GHz, 16GB RAM, 33 seconds

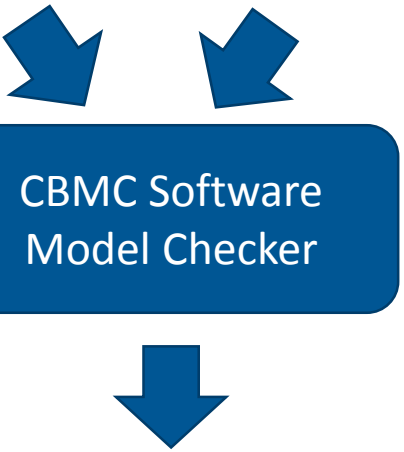
Discharging Premise 1



Discharging Premise 1

Verification Stubs for API functions

Application Source code that calls API functions



Verification Result

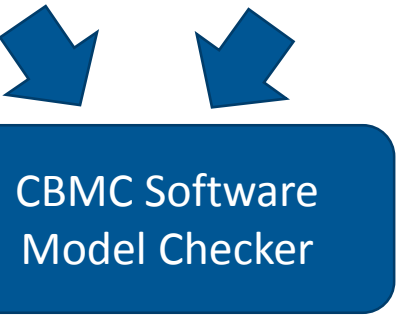
```
void A1() {
 for (int n=1;;++n) {
  update_setpoint(n,0);
  while(!has_arrived());
 }
}
```

SUCCESS

Discharging Premise 1

Verification Stubs for API functions

Application Source code that calls API functions



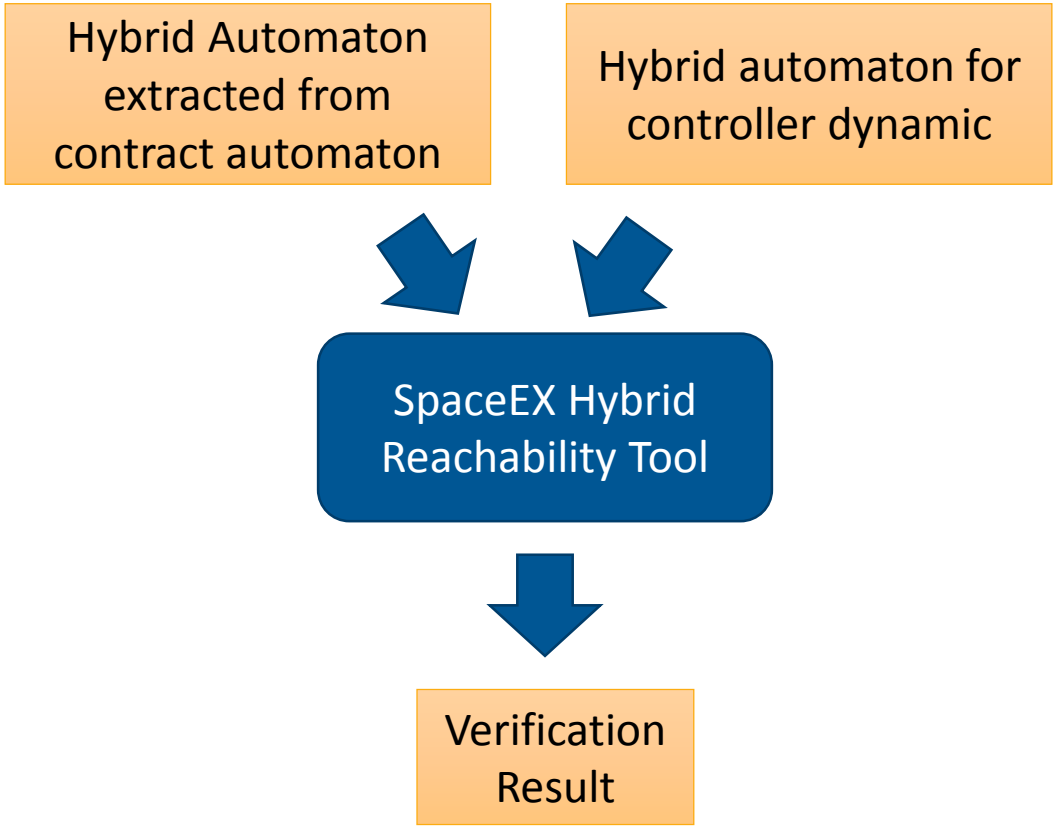
Verification Result

```
void A2() {
 for (int n=1;;++n) {
  update_setpoint(n,0);
  while(has_arrived());
 }
}
```

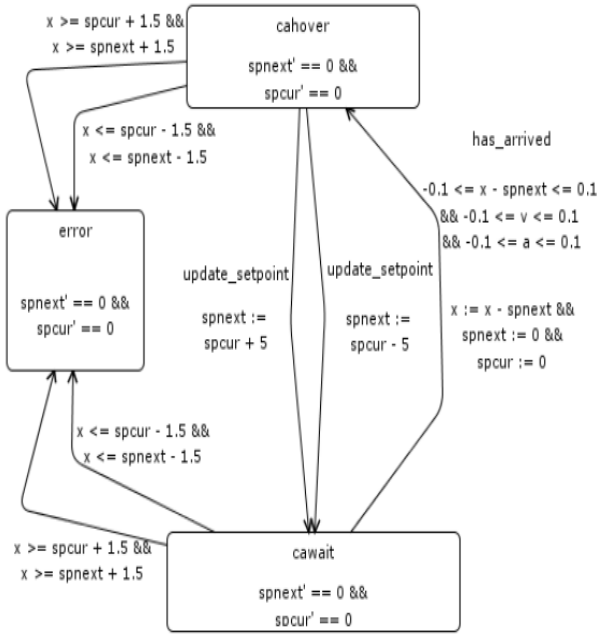
FAILURE

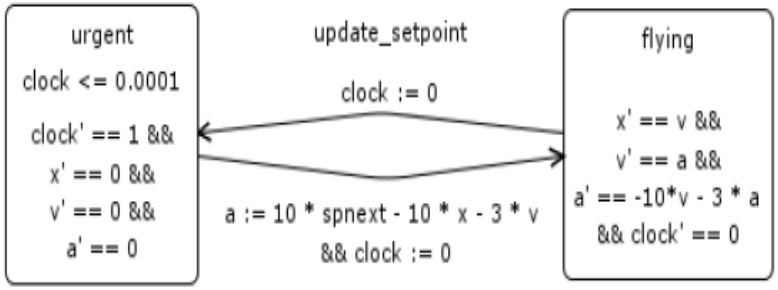
More details in paper

Discharging Premise 2



Discharging Premise 2





SpaceEX Hybrid Reachability Tool

Success

Used symmetry to reduce statespace (dimensions, time horizon)

More details in paper

Verifying Distributed Collision Avoidance

We implemented a system with 10 quadcopters moving on the 2D grid using a DSL called DMPL that supports synchronous model of computation

Verified two properties of this distributed system using software model checking

- Property 1. Distinct quadcopters have disjoint $cellcur$ and $cellnext$ values
  - $\forall i \neq j \in [0,9].\, cellcur[i] \neq cellcur[j] \wedge cellcur[i] \neq cellnext[j]$
- Property 2. Setpoints are 5 times cell values
  - $spcur = 5 \times cellcur$ and $spnxt = 5 \times cellnext$
- 17.5KLOC, 2.9GHz, 16GB RAM, 1900 seconds

Proved that these two properties and the property of movement of a single quadcopter verified earlier using a contract automaton ⇒ distance between centers of distinct quadcopters is always greater that the quadcopter diameter

- Encoded as a SMT formula and proved using Z3
- Implies physical collision avoidance of the distributed system

Conclusion

Presented a compositional approach to verify CPS consisting of an application and a controller

- Combine software model checking with hybrid system reachability and works at the source code level
- Based on a contract automaton to capture application-controller dependencies and a sounds assume-guarantee style proof rule
- Validated on a multi-agent collision avoidance protocol

Future Work

- Manual steps automated and packaged as an end-to-end tool
- Parametric verification can reason about unbounded number of quadcopters and grids