Methodologies for Engineering with Plug-and-Learn Components: Synthesis and Analysis Across Abstraction Layers

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1 Introduction

Cyber-Physical Systems (CPS) that modify themselves to improve performance or repair damage often recast the modular relationships among system components that enable Verification and Validation (V&V).

We focus on in-flight control adaptation of damaged Flapping-Wing Micro Air Vehicles (FW-MAV). Each of our three partner institutions is making a related, but distinct, attack on the problem of encapsulating adaptation into "plug-and-learn" modules and using them to *adapt flight control in a way that enables, rather than destroys, V&V capability.* Each project partner institution is, additionally, focusing on a different level of abstraction in the system's control abstraction hierarchy.

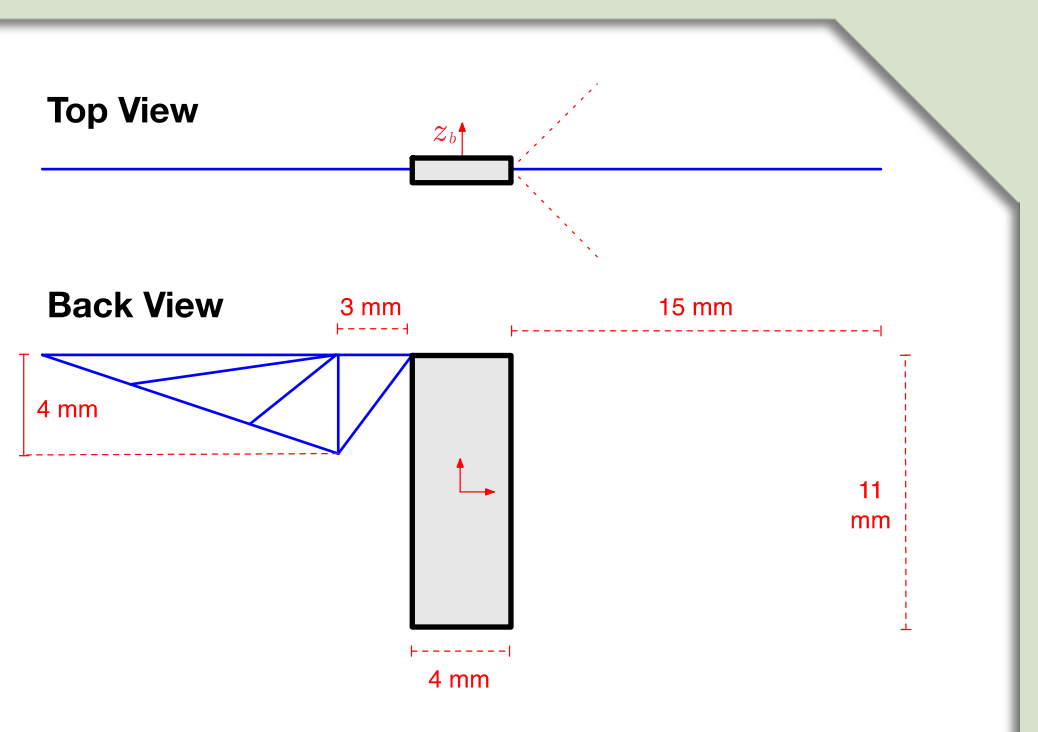

Figure One: A schematic FW-MAV based on the Harvard RoboFly. Our simulation work is based on a full 3D pendulum stable model of this vehicle. In the model, it is presumed that wing gaits and wing flapping frequencies are independently controllable.

2 Layers of Flight Control Adaptation and V&V

All partner sites use either or both of an aero-static, pendulum-stable, FW-MAV model based on the Harvard RoboFly (Figure One) or a physical flapping-wing device that is floated on water or an air cushion to emulate fine maneuvering at a set hover altitude (Figure Two).

A conceptual control model, based on work originated at the US Air Force Research Laboratory, is given in Figure Three. In this model, a high-level path planner (dark orange element in Figure 3) decides *where* the vehicle should be *relative to its current position* and produces desired altitude (body x axis, see Figure 1), forward (body z axis, see Figure 1) and roll angle (angle around body x axis, see Figure 1).

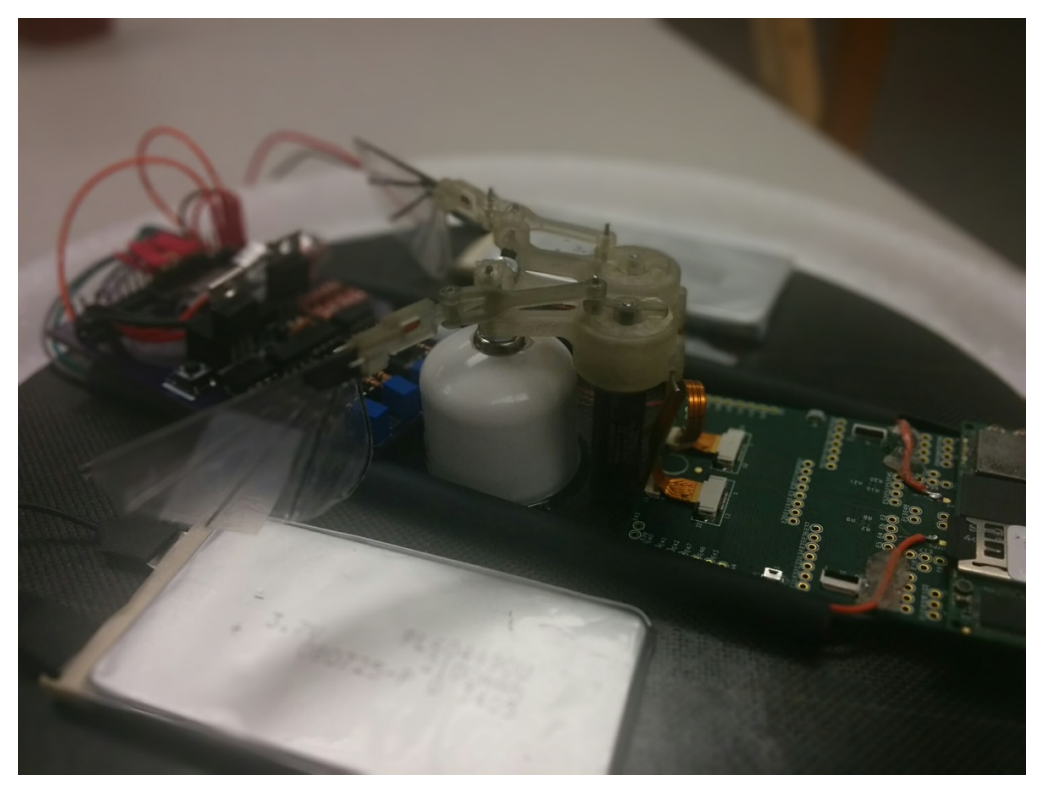

Figure Two: A FW-MAV test vehicle. This vehicle is attached to a puck that is floated on a cushion of air or in a tank of water. It propels itself using wing generated aero forces along the surface of the table. The wing gaits (wingtip trajectory shapes) and flapping frequencies are independently controllable via onboard commutation electronics. The vehicle can receive higher-level control actions via a built-in WIFI interface.

Each of these values is communicated to one of three independent proportional differential "axis controllers" that compute desired body x and body z translational forces and a desired body x roll torque. Those desired forces and torque are ran through an inverted model of the vehicle to compute wingbeat "shape parameters" that modify the presumed cosine wingbeat shape (wing gait). Those wingbeat shape parameters are ran through an allocator to combine what may be contradictory commands, and the final shape parameters are communicated to hardware wingbeat oscillators (light orange component of Figure 3) to actuate the wings in the desired manner.

Naturally, however, there are many loci of failure in such a system. Even minor damage to wings and/or other components can render the inversion models insufficient. Full system identification of the "new" broken vehicle could restore correct flight, but is not likely practical.

3 Cross-Layer Adaptation

The coupled controller, wing motion oscillators, and linkage actuated winged airframe *is a self-contained cyberphysical system.* Our work explores multiple means of exploiting *in system* interactions to restore correct control behavior after damage and to diagnose the faults that necessitated any corrections applied.

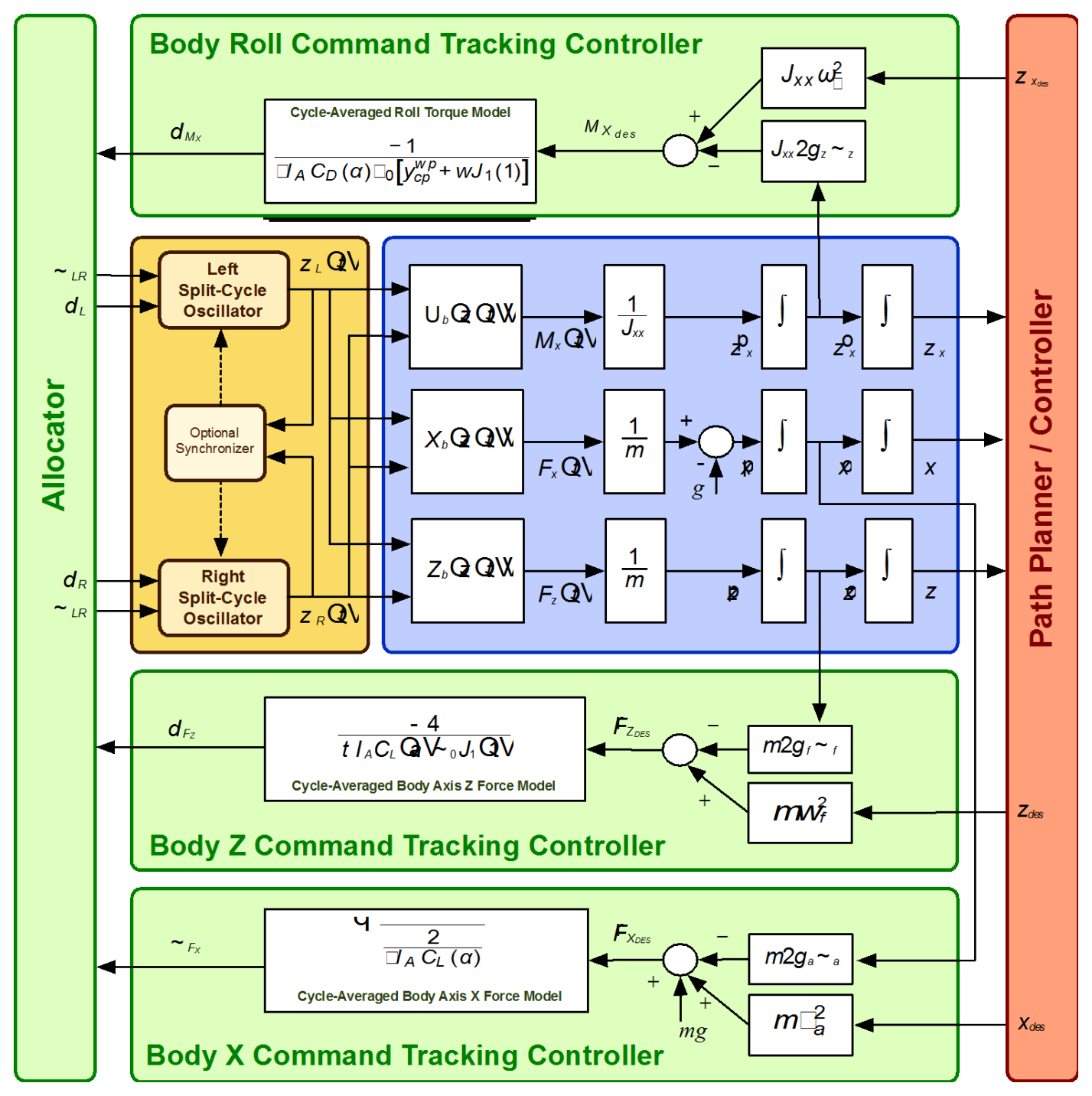

Figure Three: A conceptual control scheme for a pendulum-stable FW-MAV. Force and torque models inside each tracking controller would have their physical parameters tuned to the requirements of the specific vehicle being controlled.

The Wright State partner site is primarily responsible for exploiting adaptations occurring inside the oscillator components (light orange section of Figure 3). The Portland State partner site is primarily responsible for exploiting adaptations in the path planner and allocator components (labeled as such in Figure 3).

The Purdue site is primarily responsible for extracting whole-vehicle health information in a manner that can drive adaptation in either the oscillator or the planner/allocator.

4 Oscillator Adaptation (WSU)

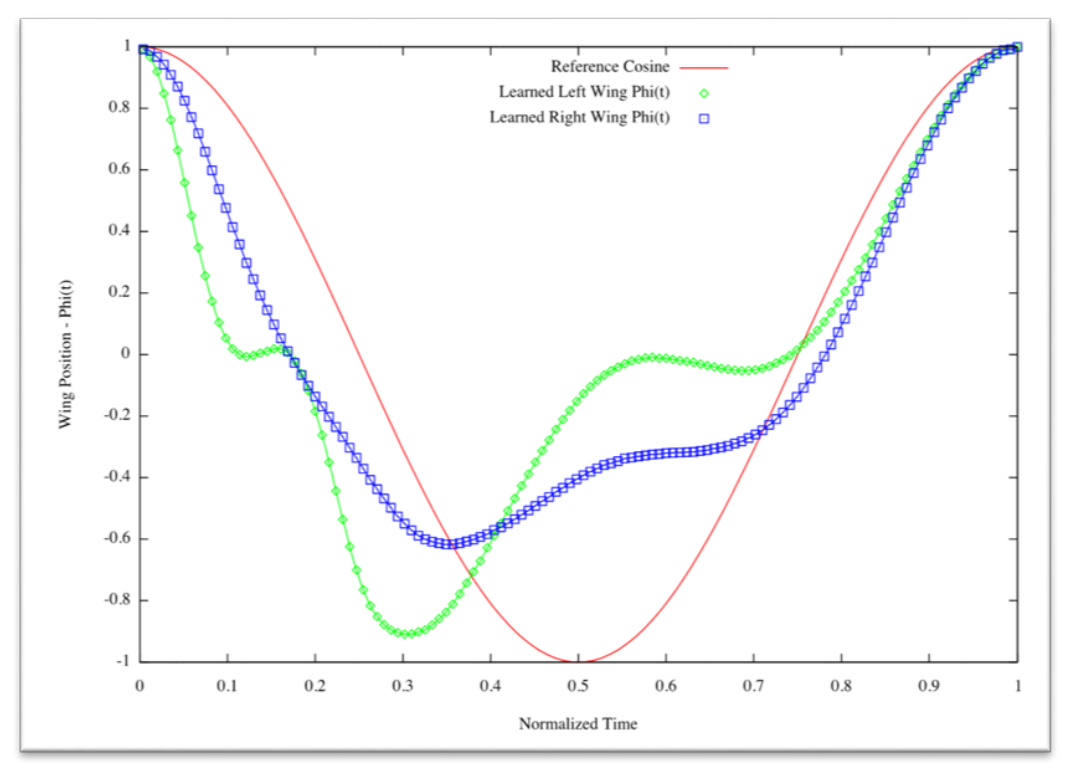

Figure Four: EMCC learned wing beat gaits that correct for damaged wings and, when run on the vehicle, provide diagnoses of the nature of the faults.

The WSU site has developed a technique now termed *Evolutionary Model Consistency Checking* that modifies adaptation rules in isolated components (in this case, the wing gait functions in the wing motion oscillators) to, as a side effect of "fixing" inconsistencies between component action and external models (in this case, the models implicit in the axis controllers) actually diagnoses the wing faults that necessitated the repair to begin with. (Figure 4) This is accomplished by modifying the objective functions of the oscillator component adaptation to also solve a system of equations that nails down force and torque faults. This technique has been tested and verified in our simulation models and is in the process of being verified in our physical model system.

5 Allocator/Planner Adaptation (PSU)

The PSU site has described the design of a multi-agent adaptive controller for the target FW-MAV (Figure 5). This controller is responsible for estimating the vehicle pose (position and orientation) and then generating four parameters needed for split-cycle control of wing movements to correct pose and position errors. These parameters are produced via a subsumption architecture rule base. Using an online learning process an agent continuously monitors the vehicle's behavior and initiates diagnostics if the behavior has degraded. This agent can then autonomously adapt the rule base if necessary. Each rule base is constructed using a combination of extrinsic and intrinsic evolution.

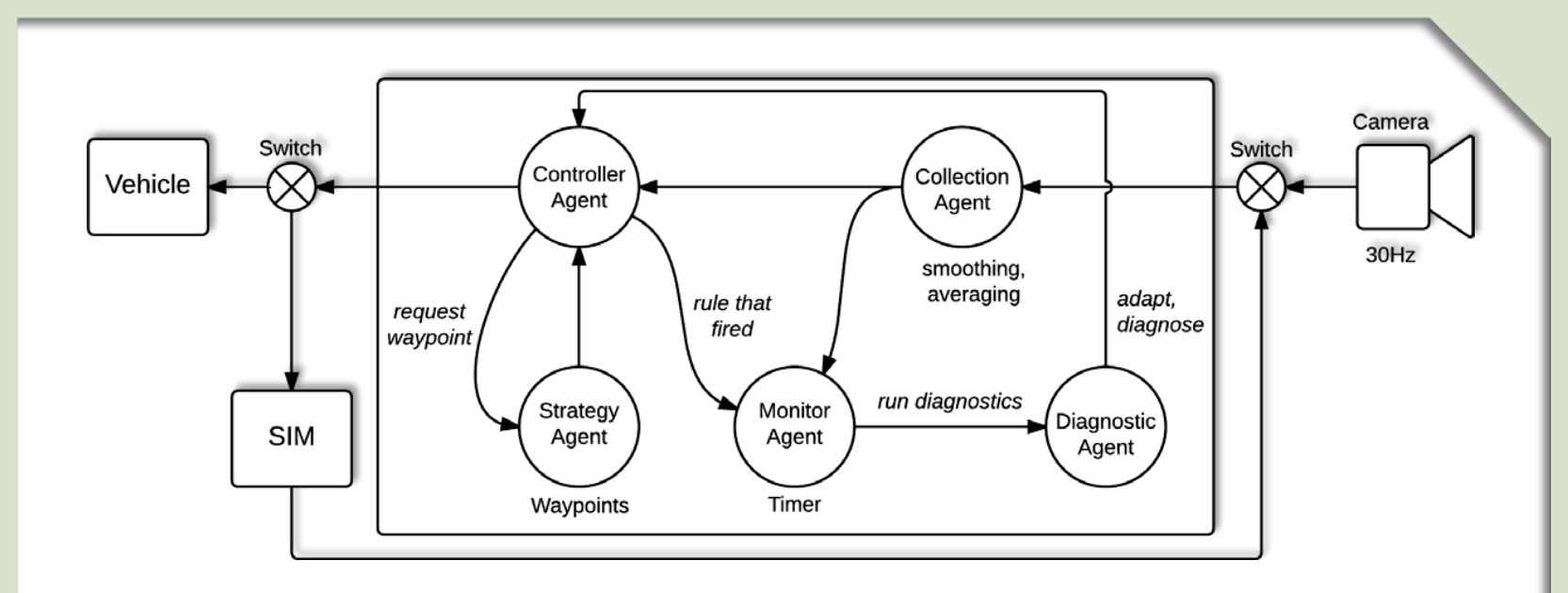

Figure Five: An Agent-Based Position and Pose Control Architecture

6 Whole-Vehicle Model Checking (Purdue)

The Purdue site has extended existing algorithms for V&V of Polyhedral Invariant Hybrid Automatons (PIHAs) to account for bounded disturbances in linear hybrid systems using the H-infinity norm. In addition, they have shown that the method can be coupled with dynamic inversion based controllers to extend it to nonlinear hybrid systems. The H-infinity norm of the system can be computed efficiently and only requires updating when the linear system model changes. Coupled with the efficient reachable set computations for linear systems, this makes our approach attractive for runtime-assurance of adaptive systems. The Purdue site has done this with our FW-MAV model and has provided a pathway to applying model-checking to verify whole-vehicle health. When folded back into the adaptations being done at the wing gait and/or allocator planner levels, this represents a very direct way of assessing future faults in post-adapted systems.

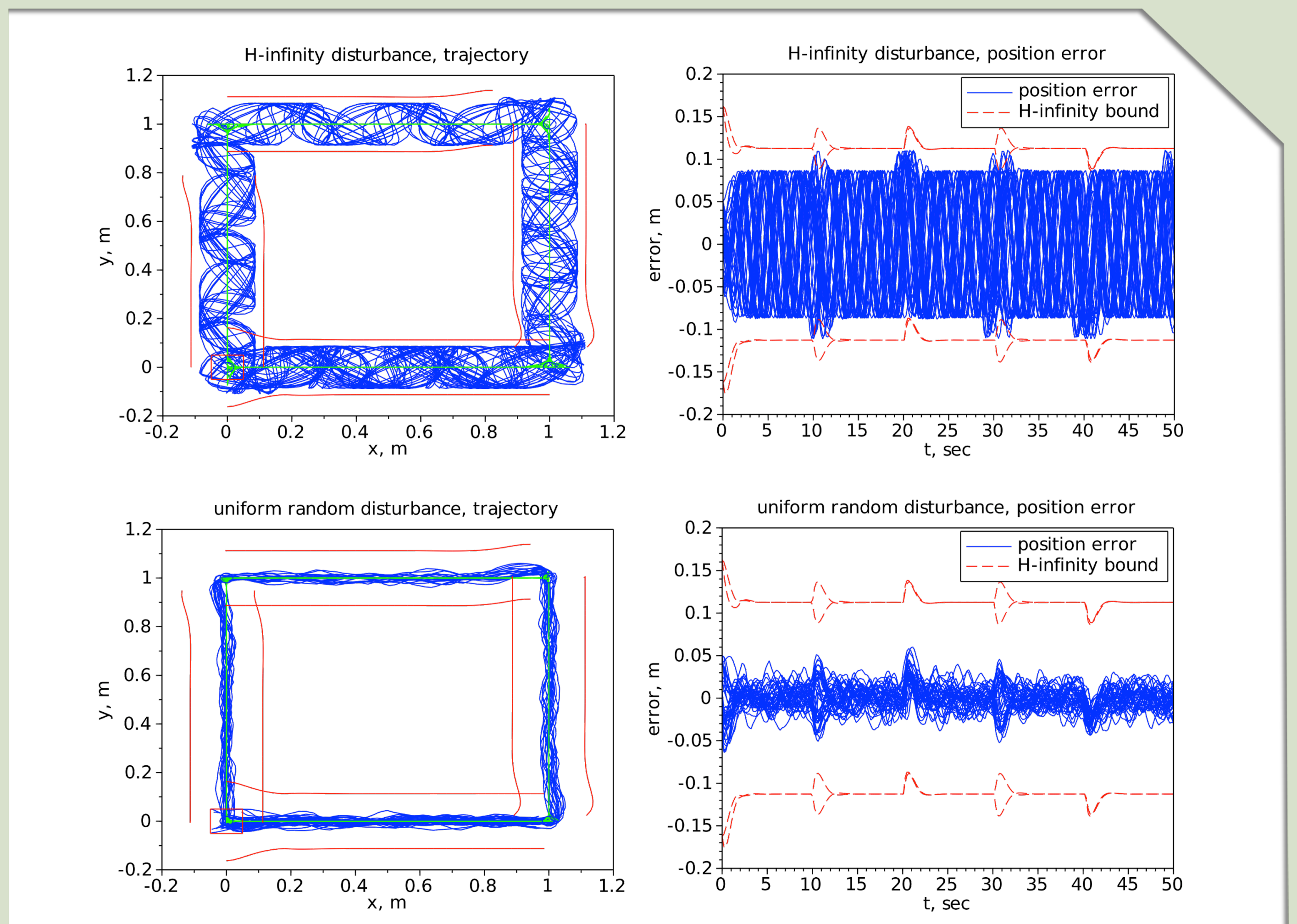

Figure Six: Monte-Carlo simulation results demonstrating that track-based waypoint transition guards are resilient in the presence of disturbances.

7 References

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