

Multi-Fidelity Predictive Control as an Enabler for Unconventional Aerial Robot Design

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Abstract—Unconventional robots challenge the standard separation between morphology, modeling, and control. This is especially evident in aerial systems with compliant or morphologically adaptive structures: their added degrees of freedom can improve resilience, impact tolerance, and safety, but they also make real-time planning and control substantially harder. Building on two recent multi-phase predictive-control studies for quadrotors, this extended abstract argues that *multi-fidelity model predictive control* is a practical systems methodology for unconventional robot design. The key idea is to allocate model fidelity where it matters most: use a high-fidelity model near the current state for fast dynamic stabilization and constraint satisfaction, and use lower-fidelity surrogates deeper in the horizon for long-range reasoning. For quadrotors, this yields a unified planner-controller that couples a short-horizon high-fidelity model to a long-horizon point-mass model within one optimization, together with feasibility-preserving transition constraints and progressive obstacle smoothing. For compliant aerial robots, the same principle extends to multi-phase model predictive contouring control, where a flexible-joint model in differential-algebraic form is followed by rigid-body and point-mass surrogates. Across simulation and real flights reported in the source manuscripts, these formulations reduce computational burden while improving closed-loop performance, including up to 75% lower closed-loop cost in obstacle-rich tracking and enabling real-time MPC via a reduction in step time from 120 ± 60 ms to 17.0 ± 0.2 ms in racing simulations for a morphing drone. We argue that such results support a broader thesis for unconventional robotics: morphology becomes significantly more usable when paired with control architectures that explicitly manage fidelity, feasibility, and horizon length together.

I. INTRODUCTION

Conventional robots can be controlled well when structure, modeling assumptions, and control pipelines are tightly standardized. Unconventional robots, by contrast, gain value from violating these assumptions. In aerial robotics, compliant joints, adaptive arms, and other non-rigid structures promise impact resilience, safer interaction, and improved operation in cluttered environments, but they also introduce extra states and complicated system models [1], [2]. This results in the challenge that accurate but computationally highly expensive models are needed to stabilize the true robot.

For quadrotors, classical hierarchical pipelines address this tension by separating planning and control. A low-fidelity planner provides a feasible reference, and a tracking controller follows it. Our recent results show that planning and control can be *unified* inside a single nonlinear MPC by cascading models along the prediction horizon: a high-fidelity rigid-body model for the short horizon and a third-order point-mass model for the long horizon. Our further research applied the same systems principle to a more unconventional setting: agile flight of a flexible-joint quadrotor, where a high-fidelity



Fig. 1. Flexible “morphy” drone [1], which was infeasible to stabilize with conventional MPC methods. The proposed multi-fidelity controller achieved real-time agile racing performance.

flexible model is used only where its accuracy is indispensable, and lower-fidelity surrogates carry long-horizon reasoning.

This abstract synthesizes these studies around a the question: *what kind of control architecture makes unconventional robot morphologies deployable?* We argue that multi-fidelity predictive control [3] is a viable design framework, because it allows challenging models and optimization under real-time constraints.

II. TECHNICAL PERSPECTIVE

A. Unified planning and control for high-speed flight

The multiphase quadrotor framework proposed in [4], formulates one optimal control problem with two consecutive phases. The first phase uses a 17-state high-fidelity quadrotor model including quaternion attitude, body rates, and rotor-thrust states; the second phase uses a point-mass model with position, velocity, and acceleration states and jerk inputs. The two phases are coupled via nonlinear constraints matching position, velocity, and thrust-induced acceleration, together with a jerk/body-rate consistency relation. To keep the long-horizon phase compatible with the true vehicle, the source manuscript derives feasibility-preserving low-fidelity constraints for thrust and body rates, including conservative inner approximations suitable for real-time optimization.

A central numerical issue in long-horizon nonlinear MPC is the abundance of local minima in cluttered environments. The source manuscript addresses this with two mechanisms. First, it adapts *progressive smoothing* of norm-based obstacle constraints to 3D, morphing cube-like obstacles to smoother ellipsoidal surrogates along the horizon while preserving safety. Second, it runs parallel low-fidelity MPC instances from randomized initial guesses and reinitializes the second

horizon of the main multi-phase problem whenever a lower-cost feasible solution is found. This retains a single on-line planner-controller while injecting global-search behavior where the cheap model makes it computationally affordable.

B. Extending the idea to compliant and unconventional morphologies

New results on, *Multi-Phase Model Predictive Quadrotor Contouring Control*, considers a flexible-joint aerial robot and makes the same argument from a viewpoint where the model fidelity is the limiting factor. Here the near-horizon model is substantially more complex: the drone is modeled as a central body plus four propeller modules connected by passive rotational spring-damper joints. The dynamics are formulated in differential-algebraic form so that implicit integration can be embedded inside the MPC. This high-fidelity phase is followed by a rigid-body quadrotor surrogate and then by a point-mass surrogate, all sharing a common progress variable for contouring control.

The crucial insight is that the additional mechanical expressivity of the robot does not require the full model to be propagated across the entire prediction horizon. Instead, fidelity is scheduled according to control relevance. Near the current state, the controller must capture compliance-induced fast dynamics and internal couplings. Farther ahead, the optimization primarily needs a model rich enough to preserve progress reasoning and tunnel safety on the track. This is precisely the regime in which surrogate models become valuable. This compelling example of hardware and control co-design shows that the more unconventional the morphology, the more important it becomes to distribute model complexity strategically rather than uniformly.

III. RESULTS AND THEIR DESIGN IMPLICATIONS

Our results show that, under equal computational budgets, the multi-phase MPC [4] improves closed-loop position or velocity tracking by up to 75% relative to standard MPC and hierarchical baselines. In real-world tracking experiments, mean position error for the proposed method ranged from 0.32 m on a sinusoidal track with seven obstacles to 0.83 m on a highly cluttered figure-eight track with 34 obstacles. In the most difficult figure-eight setting, the reported mean error increased to 3.33 m for standard MPC and 1.83 m for the hierarchical baseline, highlighting both the value of long-horizon reasoning and the cost of keeping planning and tracking separate.

The flexible-drone multi-phase implementation shows complementary evidence for aggressive contouring control. In simulation on the Figure-8 mini track, the three-phase controller reduced average MPC step time from 120 ± 60 ms for the single-phase high-fidelity baseline to 17.0 ± 0.2 ms, while improving lap time from 3.8 ± 0.1 s to 3.4 ± 0.2 s. In real-world experiments on a rigid quadrotor using a two-phase variant, the reported average step time was 3.0 ± 0.2 ms, compared with 5.1 ± 0.3 ms for a single-phase low-fidelity MPCC baseline [5], with similar lap times. Remarkably, the multi

phase formulation was the only MPC version that enabled stable control, all other variants lacked model fidelity or exceeded real-time computation budgets.

When evaluating the closed-loop cost we achieve up to 75% lower closed-loop cost for obstacle-rich tracking in the rigid setting, a mean error of 0.83 m versus 3.33 m for standard MPC on the most cluttered real-world figure-eight track, and, for flexible-drone racing simulation outperforming an reinforcement learning agent. In real-world rigid-quadrotor racing, the two-phase MPCC variant reported 3.0 ± 0.2 ms average step time versus 5.1 ± 0.3 ms for a single-phase low-fidelity MPCC baseline, with a faster lap time.

The recent results show a viable control strategy for unconventional robotics: the key challenge is allocating computational effort across time and model structure. Multi-fidelity predictive control provides one principled answer by reserving high-fidelity physics for local stability and feasibility, while pushing long-horizon foresight to cheaper models that preserve the essential task geometry.

IV. CONCLUSION

Unconventional robots often fail to transition from compelling prototypes to robust systems because their complicated morphology leads to complicated system models that are hard to control. Our recent results point toward a practical solution for aerial robots: unify planning and control across a hierarchy of models, and let model fidelity vary with prediction time. This approach preserves the advantages of unconventional morphology without sacrifices on the model while managing the computational cost of the controller. Similar works extend this principle extends beyond quadrotors to a wider class of soft, underactuated, and hybrid robotic systems [6], [7], where the path from novelty to deployment depends on treating morphology and control as a coupled design problem rather than as separate stages.

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