Design of a Predictive Guidance System for Damaged Aircraft via Long-Horizon Path Planning and Short-Horizon MPC[1]

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Abstract — This paper presents the design of a model predictive guidance framework for the safe landing of a damaged aircraft using a three-dimensional kinematic model. We use a two-layer guidance stack in which a long-horizon geometric planner generates a 3D waypoint reference to the runway threshold and a short-horizon guidance MPC tracks a local segment under degraded control authority. The MPC outputs guidance commands assumed trackable by a lower-level autopilot. Simulation results demonstrate successful runway-aligned landing trajectories with smooth control inputs and constraint satisfaction throughout the approach. An overview on this report can be found here: https://youtu.be/2CVDGiku7zo

I. INTRODUCTION

Safe landing of a damaged aircraft is a challenging guidance problem due to degraded control authority and the need for real-time decision making. In such scenarios, guidance laws must anticipate future feasibility under strict operational limits. Model Predictive Control (MPC) is attractive here because it provides a systematic way to generate feasible guidance commands under explicit limits.

Prior work has explored both predictive control and structured trajectory planning as means of addressing constrained aircraft guidance problems. *Reinhardt et al.* [1] formulate a nonlinear MPC framework for fixed-wing UAV path-following in which the controller operates directly at the actuator level while tracking a pre-defined geometric path. Their approach highlights the effectiveness of MPC for enforcing constraints and anticipating future motion, but assumes the availability of a feasible reference trajectory. Atkins *et al.* [2] proposed a segmented trajectory planning framework for total loss-of-thrust scenarios, in which altitude is treated explicitly as a finite energy resource and waypoint-based glide segments are synthesized to reach a feasible runway.

Motivated by these works, we propose a predictive guidance framework for damaged-aircraft landing that combines fast geometric path shaping with constraint-aware optimization to maintain feasibility under reduced control authority.

The remainder of this paper is organized as follows. Section II presents the problem formulation and overall guidance architecture. Section III describes the geometric path planner. Section IV presents the short-horizon MPC guidance framework, including the aircraft model and modeling of degraded control authority. Section V presents simulation results. Section VI concludes the paper.

II. CONTROLLER ARCHITECTURE

The guidance stack shown in Figure 1 comprises two modules. First, a long-horizon geometric planner generates a 3D waypoint reference from the current aircraft position to the runway threshold. Second, a short-horizon MPC follows a local segment of this reference to produce feasible guidance commands under degraded control authority.

We assume the presence of a lower-level autopilot that can track the guidance commands produced by the MPC (thrust, heading-rate, and climb-rate). This assumption decouples guidance from attitude dynamics and allows us to focus on path planning and constraint-aware command generation.

III. GEOMETRIC PATH PLANNER

This section presents the long-horizon geometric path planner, formulated as a convex quadratic program (QP) that connects the current aircraft position to the runway threshold while enforcing runway alignment and glide-slope shaping objectives. The planner outputs a sequence of three-dimensional waypoints (x_i, y_i, h_i) for $i = 0, \dots, N$ where N is the number of segments. These waypoints define the desired spatial structure of the approach from current position to runway threshold.

Unlike conventional architectures that replan the geometric path at every guidance update, the planner regenerates the path only when the guidance MPC determines that the current path has become infeasible to track. The specific criteria used to declare path infeasibility will be discussed in section IV.

A. Optimization Formulation

The optimization solved for the stacked waypoint vector

$$z = [x_0, y_0, h_0, \dots, x_N, y_N, h_N].$$

Hard equality constraints fix the first waypoint to the current aircraft position (x_0, y_0, h_0) and fix the final waypoint to the runway threshold $(0, 0, 0)$. The remaining waypoints are chosen to minimize a weighted combination of smoothness, length, glide-slope tracking, cross-track tracking, and heading-alignment penalties, described next.

[1] Code and simulation results are available at: https://github.com/elijah-waichong-chan/damaged-aircraft-mpc

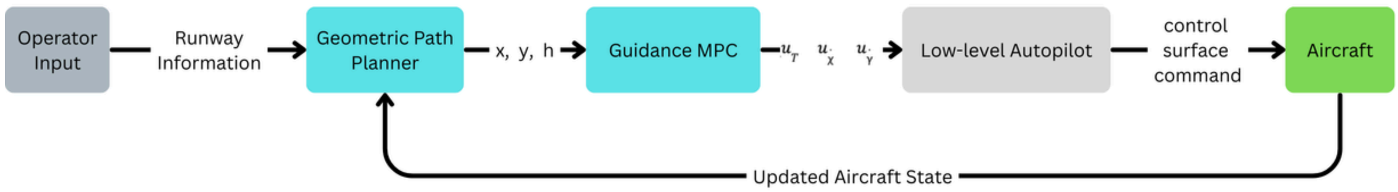

Fig. 1. Hierarchical guidance architecture combining fast geometric path planning with constraint-aware model predictive guidance. Blocks shaded in blue indicate components designed and studied in this work, while blocks shaded in light gray represent existing system components not addressed in this paper.

B. Cost Structure

The path planner objective is composed of four geometric terms:

$$J = J_{smooth} + J_{GS} + J_{lat} + J_{align}$$

Spatial smoothness is encouraged through

$$J_{\text{smooth}} = w_{\text{smooth}} \sum_{i=1}^{N-1} \|\mathbf{p}_{i+1} - 2\mathbf{p}_i + \mathbf{p}_{i-1}\|_2^2$$

which penalizes second finite differences of the waypoint positions.

The planner also penalizes deviation from the glide-slope altitude reference and the runway centerline. These terms are applied at every waypoint and are scaled to increase in importance as the trajectory approaches the runway:

$$J_{\text{gs}} = W_{\text{GS}} \sum_{i=0}^{N} w_i \left(h_i - h_{\text{ref},i}\right)^2 \qquad J_{\text{lat}} = W_{\text{LAT}} \sum_{i=0}^{N} w_i \, c_i^2$$

In addition, a shaping term biases the final portion of the path to align with the runway heading. This is imposed by penalizing deviation from the runway direction and is applied over the terminal segment of the trajectory.:

$$J_{\text{align}} = W_{\text{align}} \sum_{i=i_{\text{align}}}^{N-1} w_i \left((x_{i+1} - x_i)d_y - (y_{i+1} - y_i)d_x\right)^2$$

IV. PREDICTIVE GUIDANCE CONTROLLER

This section presents the short-horizon MPC formulation used to track the geometric reference while enforcing model and operational constraints. At each guidance update, the MPC solves a convex quadratic program (QP) based on a locally linearized and discretized prediction model.

A. Aircraft Model

The aircraft is modeled as a three-dimensional point-mass kinematic system in which it's suitable for guidance-level trajectory generation. The state vector is defined as

$$x = [x \quad y \quad h \quad V \quad \chi \quad \gamma]^T$$

where x and y denote the horizontal position in the world frame (m), h is the altitude (m), V is the airspeed (m/s), χ is the heading angle (rad), and γ is the flight-path angle (rad). The control input vector is given by

$$u = [u_{accel} \quad u_{\dot\chi} \quad u_{\dot\gamma}]^T$$

where u_{accel} represents the longitudinal acceleration command (m/s^2), $u_{\dot\chi}$ and $u_{\dot\gamma}$ are the commanded heading-rate (rad/s^2) and climb-rate (rad/s^2), respectively.

B. Modeling of Degraded Control Authority

Aircraft damage is modeled through degradation of available control authority. Specifically, reduced state bounds are imposed on the model to represent restricted motion while preserving the underlying kinematic structure. This approach handles damage effects directly through tightened MPC constraint bounds while preserving the same kinematic prediction model. Modification of the aircraft's allowable angle range, particularly placing negative bounds on γ_{max} mid flight, was done to simulate sudden limitations on sustained flight. This damage mode has the capacity to render the original flight plan infeasible, for which, alternative methods of control discussed in later in the section are employed.

C. Objective Function Design

The MPC objective is designed to track the path planner's geometric reference while producing smooth commands. At each time step, the controller minimizes a quadratic cost over a finite horizon that penalizes deviation from the reference trajectory as well as control effort.

The objective function is given by

$$J = \sum_{k=0}^{N} [(x_k - x_k^{ref})^{\mathsf{T}} Q (x_k - x_k^{ref}) + u_k^{\mathsf{T}} R u_k]$$

where x_k and u_k denote the state and input at prediction step k, and x_k^{ref} is the state reference provided by the path planner.

The planner directly specifies reference quantities for position and altitude, and in the implement ed stack a tracking penalty is applied primarily to the subset (x, y, h, V). Since the geometric planner does not explicitly provide reference profiles for the angular states (χ, γ), a gradient based reference angle is calculated from the geometric path as reference values. Terminal cost is chosen to be identical to the stage cost.

D. Model Constraints

The model constraints in the MPC enforce a locally linear approximation of the aircraft's nonlinear guidance–level motion model over the prediction horizon. The continuous-time aircraft dynamics are given by

$$\dot{x} = V\cos\gamma\cos\chi,\ \ \dot{y} = V\cos\gamma\sin\chi,\ \dot{h} = V\sin\gamma$$

$$\dot{V} = u_T,\ \ \dot{\chi} = u_{\dot{\chi}},\ \ \dot{\gamma} = u_{\dot{\gamma}}$$

At each control update, the nonlinear aircraft dynamics are linearised about the current operating point. The model is then discretised using the forward Euler method. These constraints are enforced for all prediction steps with the initial state fixed to the current measured aircraft state.

E. State and Input Constraints

The airspeed is constrained to remain within the aircraft's operational envelope and the flight-path angle γ is constrained to lie within a symmetric envelope about level flight:

$$V_{min} \le V_k \le V_{max}$$

$$\gamma_{min} \le \gamma_k \le \gamma_{max}$$

In addition, each input is subject to hard bounds reflecting achievable guidance authority with separate bounds specified for acceleration, heading-rate, and flight-path-angle-rate commands.:

$$u_{min} \le u_k \le u_{max}$$

Lastly, to prevent aggressive or oscillatory control behavior, additional constraints are imposed on the rate of change of the guidance inputs:

$$\left|u_k - u_{k-1}\right| \le \Delta u_{max}$$

E. Alternate Control for Unreachable Endpoint

Severe degradation of control authority can render the runway threshold unreachable, particularly when limits on the flight-path angle γ restrict the aircraft's achievable horizontal range. To detect this condition, the guidance system compares the remaining horizontal distance along the current geometric reference to the maximum achievable glide range,

$$R_{max} \approx h / \tan(\gamma_{max})$$

where h is the current altitude and $\gamma_{max} < 0$ is the largest allowable descent angle under damage. If the remaining path length exceeds R_{max}, the runway is declared infeasible and the governing control shifts, opting to minimize damage in a crash scenario.

When preparing for unconventional landing, the control must specify zones where landing must be avoided. Therefore, the nominal long-horizon path planner is bypassed, as incorporating the avoidance constraints directly into the planner's convex QP would introduce nonconvexity and compromise performance. Instead, touchdown selection is performed using geometric sampling and scoring. The avoided landing regions are modeled as elliptical exclusion sets, and candidate touchdown points are generated by sampling directions within the remaining glide range and rejecting any candidate whose path intersects an excluded region. Among feasible candidates, a normalized clearance score:

$$v(x, y) = \min_j \left(\frac{(x - c_{x,j})^2}{a_j^2} + \frac{(y - c_{y,j})^2}{b_j^2} \right)$$

, where $(c_{x,j}, c_{y,j})$ denote the ellipse center and a_j, b_j its semi-axes, is maximized, favoring touchdown locations that remain far from restricted areas. If the aircraft initially lies within a specified no landing region, an intermediate escape point is first generated just outside the ellipse boundary before selecting a touchdown direction.

The resulting crash-mode reference trajectory consists of a straight segment toward the selected touchdown point followed by a monotonic descent to ground. This reference is tracked by a modified guidance MPC that retains the same kinematic model and constraints but augments the objective to penalize vertical kinetic energy by,

$$J_{impact} = \sum_{k=0}^{N} w_h (V_k \sin\gamma_k)^2$$

where V_k is airspeed, γ_k is flight-path angle, and w_h is a function of altitude that increases as altitude decreases, weighting the additional cost more at lower altitudes.

V. SIMULATION RESULTS

The proposed guidance framework is evaluated in simulation using a closed-loop setup that integrates the geometric path planner, the guidance-level MPC, and the aircraft kinematic model. At each time step, the path planner generates a long-horizon geometric reference consisting of $N_p = 100$ spatial waypoints, while the MPC solves a receding-horizon optimal control problem with a prediction horizon of $N = 10$ steps where each time step is $\Delta t = 1$.

The environment contains a single runway with threshold at the origin and fixed heading in the world frame. Initial conditions are chosen to represent displaced, elevated, and misaligned approaches.

Both modules run online using the current aircraft state. Cost weights shown in Table I are held constant across all trials.

Table I: Optimization Cost Weight

PATH PLANNER	Value	GUIDANCE MPC	Value
Path Smoothness	500.0	Position	10.0
Glide Slope Tracking	10.0	Altitude	50.0
CenterlineTracking	1.0	Airspeed	10.0
Final Runway Alignment	1.0	Heading	1.0
		Climb-angle	1.0
		Acceleration effort	0.1
		Heading-rate effort	0.1
		Climb-angle-rate rate effort	0.1

A. Nominal Landing Scenario

Table II: Nominal Guidance MPC Constraints.

Constraints	Value
Maximum heading-rate command	5.0 deg/s
Maximum climb-angle-rate command	3.0 deg/s
Maximum heading-rate change	2.0 deg/s/step
Maximum climb-angle-rate change	1.0 deg/s/step
Maximum/minimum climb-angle	30 deg

The nominal landing scenario is used to validate the baseline performance of the proposed two-layer guidance architecture under favorable and no degraded control conditions. In this case, the aircraft is initialized with moderate lateral displacement and altitude while remaining reasonably aligned with the runway heading. This scenario is designed to evaluate the controller's ability to track a feasible long-horizon path without requiring replanning.

Figure 2 and 3 illustrate the closed-loop guidance behavior for the nominal case. The long-horizon planner generates a smooth reference trajectory consistent with the geometric approach objectives defined in Section III. The MPC follows a local segment of this path with constraints defined in Table II. The resulting aircraft ground track closely follows the planned trajectory. Figure 4 shows the MPC generated control input.

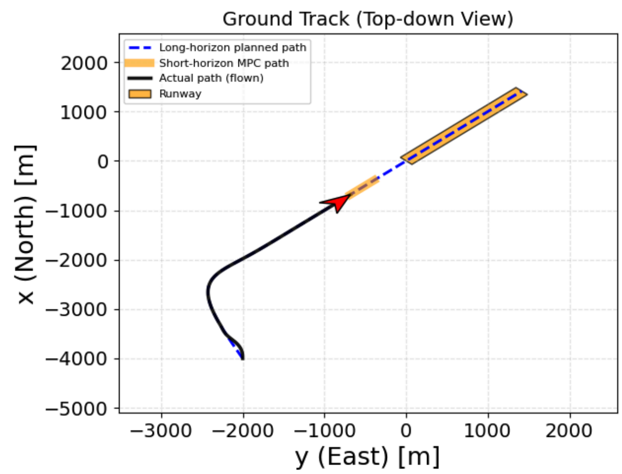

Fig. 2. Closed-loop behavior of the two-layer controller stack.

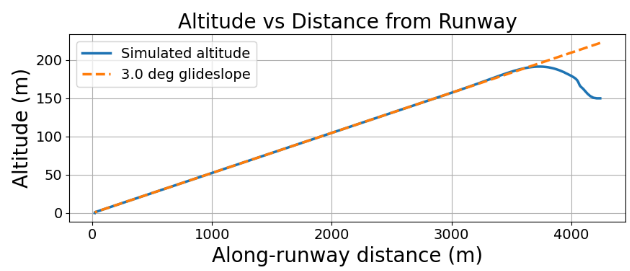

Fig. 3. Altitude tracking shows it closely follows the glideslope.

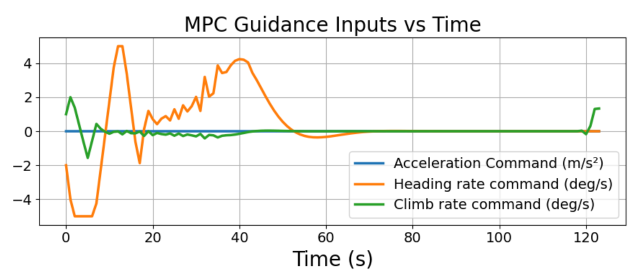

Fig. 4. MPC generated control Input.

B. Misaligned Scenario

To evaluate the interaction between the long-horizon planner and the guidance MPC under poor initial alignment, the runway heading is set to 90°. The aircraft starts at $(x, y, h) = (-2000\,m, -4000\,m, 500\,m)$ with heading 170°, resulting in a large initial heading error and a substantial lateral offset from the runway centerline.

During flight, the MPC monitors tracking feasibility using (i) a cross-track error accumulation counter and (ii) a progress-stall detector based on insufficient along-path progress. If either trigger persists for several consecutive steps, the current plan is declared infeasible and the planner is called to replan.

Six replans occur in this case; all candidate plans are shown as gray dashed lines in Figure 5, and the cross-track error with replan markers is shown in Figure 6.

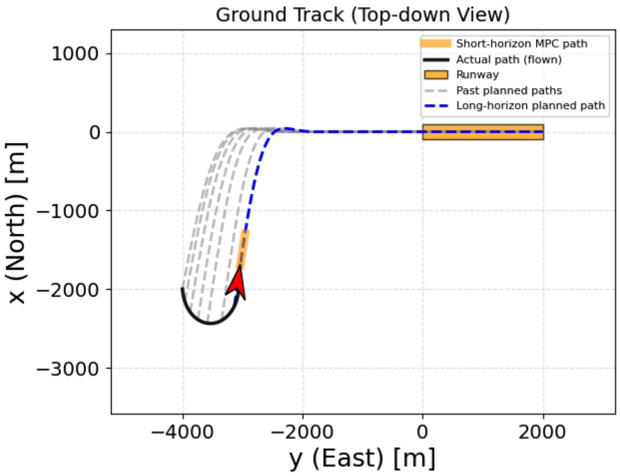

Fig. 5. Closed-loop guidance and replanning behavior of the misaligned scenario. Repeatedly generated plans are shown as gray dashed lines. After six replanning events, the aircraft is observed to regain tracking feasibility and successfully follow the planned path.

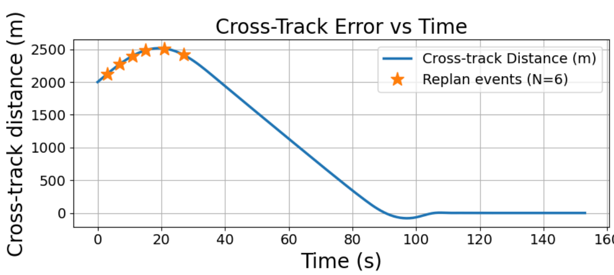

Fig. 6. The figure shows that the cross-track error increases at the beginning, triggering replanning events. Once the cross-track error starts to decrease, the controller deems the path feasible to track.

C. Degraded Control Authority Scenario

Table III: Degraded Guidance MPC Constraints.

Constraints	Value
Maximum climb-angle	-10.0 deg
Minimum climb-angle	-30.0 deg

The degraded control authority scenario is used to validate function of the damaged range estimator, in conjunction with the alternate reference trajectory generator and MPC designed for crash mitigation. In this case, damage is applied to the system 60 seconds into flight, restricting the maximum climb angle to -10 degrees as shown in Table III. Range estimation finds that this pitch limit rendered landing at the runway infeasible, prompting alternate control activation. As the plane starts in a defined no-landing zone, an intermediate waypoint is generated outside of the ellipse, before generating the true planned path. Once near landing, the MPC keeps flight angle near its maximum of -10 degrees, so that impact energy is minimized. This whole process is visualized in Figure 7.

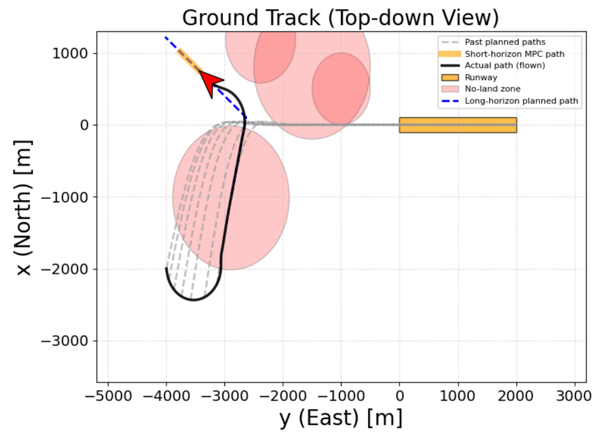

Fig. 7. Closed-loop guidance under crash landing MPC and trajectory planner. The restricted landing zones are represented by red ellipses.

VI. CONCLUSION

We demonstrated a two-layer predictive guidance framework in which geometric planning provides approach path shaping and short-horizon MPC provides constraint-aware tracking and feasibility recovery. By decoupling global path shaping from local feasibility enforcement, the proposed architecture reduces computational complexity. Simulation results show that the guidance MPC successfully tracks planned approach trajectories and robustly recovers feasibility through online replanning in both nominal and misaligned scenarios. In addition, the damage demonstration validates the framework's ability to handle authority loss: when a damage event imposes a tighter climb-angle envelope, it triggers a crash-landing replanning with no-land-zone constraints. Overall, these results suggest the approach is a solid starting point for real-time emergency guidance.

REFERENCES

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