UAV CONTROL FOR SAFE AND LOW-ALTITUDE ECONOMY URBAN DELIVERY SERVICES

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The rapid emergence of the Low-Altitude Economy (LAE) is transforming unmanned aerial vehicles (UAVs) from experimental research platforms into practical carriers of parcels, medical supplies, and sensor data at altitudes below approximately 1000 m. Urban airspace and complex mountain terrain remain among the most demanding operational environments for autonomous UAV control, because flight trajectories must account for dense obstacles, variable meteorological conditions, and strict safety margins during approach and landing. This paper evaluates the readiness of a heuristic UAV control approach, based on an information danger function that relates angle-of-attack and airspeed deviations along the glide path, for delivery-service deployment within the Low-Altitude Economy. The safety model is complemented by an economic model that compares the hourly and life-cycle costs of a UAV complex with those of a medium-class helicopter, based on the amortization of the UAV, the ground control unit, and the retransmission (Scope) network. The results show that the sign of the derivative of the danger function along the landing-time axis can serve as a practical heuristic indicator of approach safety, and that the economic model favours UAV complexes by approximately one order of magnitude in hourly operating cost. Based on both criteria, the paper identifies the advantages and limitations of heuristic UAV control for urban delivery and rescue-oriented logistics within the Low-Altitude Economy framework and defines the conditions under which such control can be regarded as ready for operational deployment.

KEYWORDS

Airport Unmanned Aerial Vehicle (UAV), Low-Altitude Economy, heuristic flight control, flight safety, delivery services, economic efficiency, urban air mobility

1 INTRODUCTION

Autonomous and remotely piloted unmanned aerial vehicles (UAVs) have, over the past decade, moved from isolated flight tests toward operational use in demanding dispersed local environments, particularly in mountain terrain during search-and-rescue (SAR) missions and, increasingly, in urban airspace. In mountain rescue operations, the typical control architecture organizes several mobile UAV units around a stationary remote-control point (Scope) that hosts the ground control workstation, radio retransmission equipment and additional monitoring payload; such a configuration can be deployed within 5 to 30 minutes and can be extended by further retransmission stations to enlarge the effective range of intervention.

Flight control during such missions is largely automatic and relies on an on-board navigation and control complex that combines a satellite navigation receiver (GNSS/GLONASS), an inertial sensor package, an air-data system, and task-specific antennas [Labun 2017, Zajacko 2018]. Typical functions include flight along a predefined route, automatic target tracking, orientation-angle stabilization, altitude and airspeed hold, and continuous telemetry transfer between the UAV and the ground station [Urban 2020]. Depending on mission complexity, one to three operators supervise the vehicle, and their qualifications must cover UAV operating procedures, basic aerodynamics and meteorology, radiocommunication, and safety rules [Clarke 2014].

These solutions indicate that heuristic, threshold-based safety control is already a mature practical approach for UAV operation in dispersed local environments, such as mountain rescue corridors. Although heuristic UAV safety control has been validated in mountain-rescue environments, it is still unclear whether the same approach can be transferred to low-altitude urban delivery corridors, where obstacle density, regulatory constraints, and third-party risk are substantially higher [Burduk 2021, Zidek 2024]. However, its transfer to dense urban airspace, where obstacle density, third-party risk, and traffic intensity are considerably higher, has so far received much less systematic attention [Rao 2016].

A parallel and increasingly important trend is the emergence of the so-called Low-Altitude Economy (LAE), which includes economic activities based on civil manned and unmanned aircraft operating below approximately 1000 m above ground level, and in some cases locally up to 3000 m. These activities include drone delivery, air-taxi and urban-air-mobility (UAM) services, agricultural and inspection UAV operations, and emergency-response applications [Labun 2021].

Global market estimates place the value of the Low-Altitude Economy at approximately USD 4.6 billion in 2024, with projections reaching USD 23.5 billion by 2030 [LAE-Trends 2025]. At the same time, dedicated drone-delivery operators such as Meituan, SF Express, Wing, and Zipline already operate hundreds of routes and have completed from hundreds of thousands to more than one million commercial deliveries [Grepow 2025, LAE-Trends 2025].

Regulatory frameworks such as the U.S. FAA BEYOND/BVLOS programme and the EU U-space concept are also being adapted to support routine, performance-based UAV logistics in shared low-altitude airspace [LAE-Trends 2025].

The aim of this paper is to assess whether the heuristic safety approach previously validated for UAV-supported mountain rescue [Kurdel 2018, Lazar 2018] can be considered ready for delivery-service deployment within the Low-Altitude Economy, from both flight-safety and economic perspectives.

In this paper, readiness is understood as the ability of the heuristic control approach to provide a computationally simple safety indicator, while also supporting economically viable deployment under realistic low-altitude delivery conditions. Section 2 formulates the heuristic information danger function of the glide path and the accompanying economic model of UAV-complex operation [Draganova 2024]. Section 3 discusses the resulting safety and cost indicators and identifies the advantages and limitations of heuristic UAV control for urban and complex-terrain delivery logistics. Section 4 summarizes the readiness assessment [Dorling 2017].

2 SAFETY FUNCTION AND ECONOMIC MODEL OF UAV OPERATION

2.1 Heuristic safety function of the glide path

Landing along the glide path is the flight phase most sensitive to control errors [Stolaroff 2018]. Its safety can be expressed heuristically by an information danger function that combines the deviation of the angle of attack α from its permissible and critical limits with the deviation of vertical or airspeed from its corresponding permissible and critical limits.

$$F_{nb} = 1 - \left(1 - \sqrt{\frac{\alpha - \alpha_{perm}}{\alpha_{crit} - \alpha_{perm}}}\right)\left(1 - \left(\frac{v_{a,crit.} - V_a}{v_{a,perm,} - v_{a,crit.}}\right)^{\frac{\alpha_{crit} - \alpha}{\alpha_{crit} - \alpha_{perm}}}\right) \quad (1)$$

The function saturates at its limits: if the angle of attack reaches its critical value, then the danger indicator equals 1 for every airspeed value; similarly, if the airspeed reaches its critical value, then the danger indicator equals 1 for every angle of attack. This saturation property is useful for envelope protection because it indicates maximum danger whenever either variable reaches its critical limit, independently of the other variable. For a representative glide-path descent with α ≈ 1.25 and measured pairs of α and Va, the normalized danger function abs was evaluated over the landing-time interval t = {0,2.7,5.4,8.1,10.8,13.5,16.2,18.9,21.6,24.3,27.0,29.7,32.4} s and approximated by a second-order polynomial obtained from the flight-test data:

$$\left|F_{nb,N}(t_{\,lg})\right| = 1.5 \times 10^{-5} t_{lg}^2 - 8.1 \times 10^{-4} t_{lg} + 0.98 \quad (2)$$

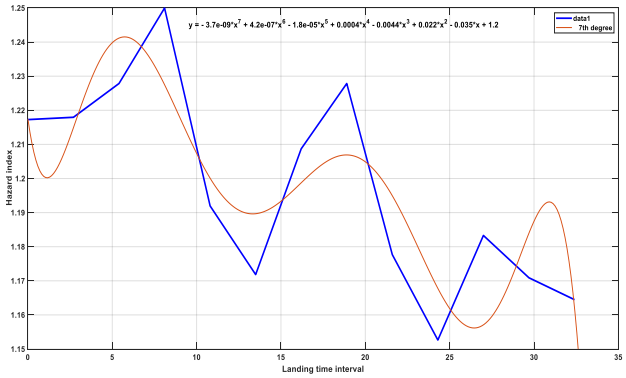


Figure 1. Time course of the normalized danger function abs during the landing phase

Its derivative, obtained analytically from (2), indicates the direction of the danger trend and can serve as an on-board heuristic control signal (e.g., to trigger a go-around):

$$\frac{d\left|F_{nb,N}\right|}{dt_{\,lg}} = 3.0 \times 10^{-5} t_{\,lg} - 8.1 \times 10^{-4} \quad (3)$$

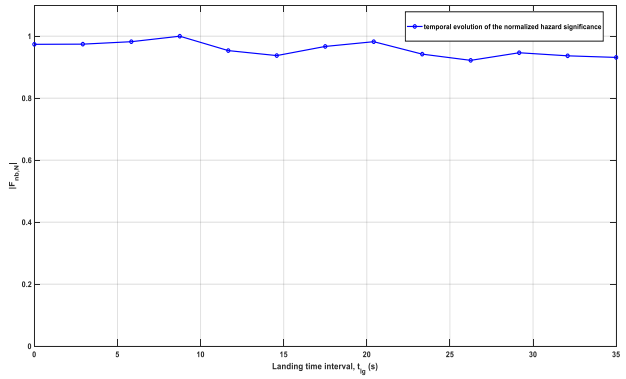


Figure 2. Trend of the normalized hazard indicator during landing

Because the slope in (3) is negative over the entire evaluated interval, the danger level decreases monotonically as the UAV progresses along the glide path. According to the model, the landing is therefore heuristically classified as safe. If constant-coefficient fitting of new flight-test data produces a positive slope, the model would instead classify the approach as unsafe. This is the heuristic decision rule proposed for automatic monitoring of the landing phase.

2.2 Economic model of UAV-complex operation

The hourly operating cost C of a UAV complex is modelled as the sum of UAV airframe amortization (), amortization of the ground control or remote-control TPU unit (), the UAV energy or fuel cost (), the operating cost of the retransmission Scope point (C_scope), and the crew or operator cost ():

$$C = C_{UAV} + C_{GCS} + C_{AF} + C_{SCOPE} + C_{OP} \quad (4)$$

Where:
C_{UAV} – acquisition cost of the UAV,
C_{GCS} – ground control station cost,
C_{AF} – airframe cost,
C_{scope} – mission scope (or payload) cost,
C_{op} – operational cost.
Amortization terms are obtained from acquisition price N and service life R (in operating hours):

$$A_{UAV} = \frac{N_{UAV}}{R_{UAV}} \quad (5)$$

$$A_{TPU} = \frac{C_{TPU}}{R_{TPU}} \quad (6)$$

Where:
A_{TPU} – depreciation (amortization) cost of the TPU per operating period,
C_{TPU} – acquisition cost of the TPU (Ground Control/Remote-Control TPU unit),
R_{TPU} – service life of the TPU (years, operating hours, or missions).
For the reference UAV complex used in mountain-rescue deployment, the acquisition price ranges from €6,000 to €12,000, the service life of the UAV airframe is approximately 300 flight hours at a unit price of €1,500, and the TPU/remote-control equipment has a service life of at least 10 years. With an annual utilization fund of 1,080 hours, the TPU service life expressed in operating hours is 1,080 · 10 = 10,800 h.

3 RESULTS

Based on the proposed safety model and the accompanying economic framework, the readiness of the heuristic UAV control approach for real-world deployment within the Low-Altitude Economy can be assessed. The following section first interprets the results from a flight-safety perspective and then from an economic perspective. This structure clarifies how the technical and financial parameters complement each other when evaluating the practical usability of the system. The two-level assessment also makes it possible to identify not only the direct benefits of the proposed solution, but also the limitations that must be considered when implementing it in urban and mountain environments.

3.1 Safety readiness for low-altitude economy delivery

The monotonically decreasing danger function obtained in Section 2.1 confirms that the heuristic model is a practical, computationally efficient indicator of glide-path safety that is suitable for real-time execution on a small on-board autopilot. Its direct reuse in urban delivery corridors is, however, conditional. The boundary values , , V were identified for a specific airframe

and a mountain glide profile. Urban approach segments are typically shorter, more turbulent because of building wake effects, and subject to mandatory geofencing. Therefore, the boundary values must be re-identified for each UAV type and delivery corridor before the model can be used operationally [Ceskovic 2022].

3.2 Economic readiness

Applying (4)–(6) to the reference UAV complex and comparing the result with a medium-class helicopter operated at approximately €2,000/h gives the illustrative hourly cost comparison shown in Table 1. Energy, Scope-station, and crew costs are presented as order-of-magnitude assumptions because the source data did not specify them numerically. These values should therefore be replaced with operator-specific figures before the estimate is used for investment decisions [Kurdel 2022].

Cost item	Helicopter (medium class)	Heuristic UAV complex
Direct operating cost	2 000 €/h	≈ 52 €/h (illustrative)
Amortization of the aircraft/UAV	included above	≈ 5.00 €/h (N_UAV/R_UAV)
Amortization of ground/TPU unit	included above	≈ 0.42 €/h (C_TPU/R_TPU)
Energy / fuel cost	included above	≈ 2 €/h (assumption)
Retransmission (Scope) point	n/a	≈ 5 €/h (assumption)
Crew / operator cost	crew of ~10 persons	≈ 40 €/h (1-3 operators)

Table 1. Illustrative hourly cost comparison of a medium-class helicopter and a heuristic UAV complex

Even with a wide margin of uncertainty in the assumed cost items, the UAV complex remains approximately one order of magnitude cheaper per flight hour than the helicopter. This advantage is mainly due to the much smaller crew requirement, with one to three UAV operators compared with approximately ten helicopter crew and support staff, and to the low airframe acquisition cost relative to its service life.

3.3 Advantages and disadvantages of Low-Altitude Economy delivery services

Advantages of heuristic UAV control identified for delivery services under the LAE trend:

- substantially lower hourly operating cost than helicopter operations, by roughly an order of magnitude in the illustrative estimate;
- rapid deployment (5-30 minutes) and scalability of coverage through additional retransmission (Scope) points;
- low crew requirement (one to three operators) compared with a multi-person helicopter crew;
- low computational load of the F_{nb}-type heuristic indicator, suitable for real-time execution on small on-board autopilots;
- compatibility with the existing GNSS/inertial on-board architecture already validated in SAR operations, which can shorten certification of delivery variants.

Disadvantages and open issues:

- boundary values α_{perm}, α_{crit},, V$v_{a,perm,}$ $v_{a,crit.}$ are empirically calibrated for a specific airframe and glide profile and must be re-identified for each UAV type and urban corridor, which limits direct generalization;
- the model saturates danger at the boundary ($F_{nb} \rightarrow 1$) but does not explicitly quantify third-party ground risk, which is the dominant safety concern in dense urban delivery corridors;
- as already noted for the rescue-operation case, the method is not yet supported by dedicated legislation or normative documents, so that safety remains, for now, the sole practical acceptance criterion;
- integration with Scope-type retransmission infrastructure and with Unmanned Traffic Management / U-space systems introduces coordination overhead that the simple cost model in Section 2.2 does not capture;
- the energy and payload limits of small electric UAV restrict range and cargo mass relative to helicopters, confining heuristic UAV control mainly to last-mile and light-cargo segments of the Low-Altitude Economy.

Overall, the heuristic UAV control approach can be regarded as conditionally ready for Low-Altitude Economy delivery services. The safety heuristic is sufficiently mature for controlled glide-path phases, and the economic case is strongly favourable. However, urban-specific recalibration of the danger-function boundaries, explicit treatment of third-party risk, and appropriate regulatory coverage remain necessary before large-scale operational deployment can be achieved.

4 CONCLUSIONS

This paper combined a heuristic flight-safety model, based on the information danger function of the glide path, with an economic amortization model of UAV-complex operation to assess the readiness of heuristic UAV control for delivery services within the emerging Low-Altitude Economy. The safety analysis showed that the sign of the derivative of the danger function along the landing-time axis is a practical, low-cost heuristic criterion for distinguishing a safe approach from an unsafe one. The economic analysis showed a clear cost advantage of UAV complexes over medium-class helicopters, amounting to approximately one order of magnitude per flight hour.

At the same time, both the safety and economic models rely on parameters, including danger-function boundaries and energy, Scope-station, and crew costs, that were identified for mountain rescue operations. These parameters must be recalibrated for dense urban delivery corridors before the approach can be considered fully operational within the Low-Altitude Economy. The method presented in this paper does not yet have a basis in aviation legislation and is not covered by a dedicated normative document. For this reason, flight safety remains, for the time being, the primary practical criterion governing its application.

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