Millimetre-Scale Laser Pointing from Small UAVs:

Feasibility Analysis of Line-of-Sight Stabilization at a 1 m Stand-Off Distance

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Abstract

This work evaluates whether a small multirotor UAV can maintain a laser beam within a 1 mm radius at a 1 m stand-off distance under realistic outdoor conditions. This requirement corresponds to a 1 mrad line-of-sight (LOS) pointing tolerance. We analyse the geometric and mechanical constraints, discuss nested stabilization loops, introduce a tuned rubber isolation mount for high-frequency vibration suppression, incorporate gust-skipping logic, and benchmark performance using the DJI Zenmuse H20 stabilized payload. The H20 specifies an angular vibration range of ±0.01°, which corresponds to only 0.17 mm lateral jitter at 1 m—approximately six times tighter than the requirement—demonstrating that sub-millimetre stabilization is already achieved in commercially available UAV gimbals. Reducing payload mass to 100–300 g increases sensitivity to high-frequency vibration, but this frequency band can be strongly attenuated through a soft isolation interface, while low-frequency disturbances remain manageable through nested gimbal loops. Importantly, the pointing challenge analysed here is mathematically equivalent to the well-studied problem of camera line-of-sight stabilization, and thus can draw extensively on decades of work in UAV imaging, jitter suppression, and LOS control. Short stability windows arise between the 1–3 s gust events typical of mild European summer winds, allowing such transient disturbances to be skipped rather than compensated. Indoor tests consisted of manually positioning a drone-mounted laser over a small tape marker placed on the floor at a stand-off distance of 1 m. Even in the complete absence of gimbal or stabilization hardware, the laser spot could nevertheless be maintained within a sub-centimetre region, illustrating that coarse optical alignment at this range is inherently stable. Although this study focuses solely on pointing mechanics, the findings directly support the feasibility of airborne photonic insecticides, where millimetre-scale optical placement is required to neutralize small insects such as the Colorado potato beetle.

1. Methods

1.1. Analytical Framework for Line-of-Sight (LOS) Precision

The primary requirement examined in this study is maintaining the laser spot within a 1 mm radius at a stand-off distance of 1 m. This geometric constraint was modelled analytically by computing the corresponding angular tolerance of 1 mrad (0.057°). LOS jitter budgets were developed by decomposing platform motion into low-frequency drift, high-frequency vibration, sensor resolution limits, and residual optical steering error. Camera angular resolution was derived from field-of-view and pixel count, showing that sub-millimetre deviations are resolvable at typical UAV imaging geometries. Nested control loops—an inner IMU-based rate loop and an outer image-based LOS loop—were analysed using standard gimbal-stabilization theory to characterize their respective disturbance rejection bandwidths.

1.2. Modelling of Gimbal Stabilization and Isolation Mount Dynamics

To evaluate mechanical disturbance propagation, a simplified mass–spring–damper model was used to represent the payload mounted on soft rubber isolators. The natural frequency of the mount was selected in the 15–30 Hz range, well below typical multirotor propeller excitation bands (≈100–200 Hz), enabling high-frequency attenuation. Lighter payloads in the 100–300 g range were modelled as more susceptible to high-frequency input forces but easier to steer for low-frequency drift, while heavier payloads were treated as having greater passive inertia but requiring higher gimbal torque. These simplified analytical models were used to estimate qualitative trends in transmitted vibration and residual jitter.

1.3. Environmental Disturbance Envelope Analysis

Typical summer wind statistics for central Europe were used as a representative operational envelope. Publicly available hourly wind data for Belgium (June–August) were analysed to identify periods of low wind speed (≈1–4 m/s) and gust–calm cycling behaviour. Prior UAV hover dynamics literature was consulted to contextualize the timescales of gust-driven motion, which generally occur on 1–3 s intervals. For targeting purposes, these intervals were treated as creating “stability windows” during which LOS disturbances decrease sufficiently to enable millimetre-scale alignment. No attempt was made to build a probabilistic model; instead, the environmental analysis served as a feasibility envelope.

1.4. Indoor Laser-Pointing Experiment

A qualitative indoor experiment was conducted using a DJI Mini 3 drone equipped with a low-power laser diode rigidly mounted and oriented downward. The UAV was placed at approximately 1 m stand-off from a small tape marker on the floor. No gimbal, isolation mount, or stabilization hardware was used. The operator manually adjusted the drone position until the laser aligned with the target. In addition to a recording, stability was evaluated visually by observing whether the spot could be held within a sub-centimetre region. This experiment was intended to assess inherent coarse stability of short-range laser alignment under minimal supporting hardware.

1.5. Outdoor Mechanical Contact Experiment

A second qualitative experiment was carried out outdoors in a garden setting using the same DJI Mini 3 platform. A lightweight multi-link remote-controlled servo arm, constructed from simple materials such as drinking straws, was mounted laterally on the drone. One person was controlling the drone and another was controlling the robotic arm. The person controlling the robotic arm had no prior training in this. A Colorado potato beetle was affixed to a leaf at a convenient height, and the drone–arm system was manually piloted to attempt repeated contact with the insect. The drone was flown away from the target multiple times, after which the contract with the target was again attempted, this was done 3 times, and 3 times contact was established. Contact repeatability was measured by visual inspection and determined to be on the order of 5 mm. The goal of this experiment was not mechanical precision per se but rather demonstrating that millimetre-to-centimetre insect-scale interaction is physically achievable on lightweight hardware with minimal stabilization and inexpensive hardware, be it excluding sensor and processing hardware.

1.6. Field Observation of UAV Downwash Interaction

Additional field observations were conducted in a potato field using a DJI Mini 3 drone flown at approximately 0.5 m above the canopy. The UAV was positioned directly above a Colorado potato beetle resting on a plant. Video recordings (Reyntjens, 2025c) were used to assess:

1. **Insect behavioural response** to rotor noise and airflow, and
2. **Vegetation motion** at lateral and vertical positions beneath the UAV.

Plants laterally offset by 0.5 m exhibited no measurable movement, while the plant directly below the UAV experienced a small-amplitude, low-frequency oscillation. These qualitative observations were compared with known aerodynamic models of multirotor downwash to assess whether lateral wake influence is negligible at operationally relevant stand-off distances.

1.7. Data Recording and Interpretation

All observations were recorded using the DJI Mini 3's onboard 4K camera. No external motion capture, accelerometers, or high-speed imaging were used; instead, the experiments were intended as practical feasibility demonstrations. Video data were manually reviewed frame-by-frame to assess vegetation movement, insect behaviour, and coarse alignment stability. Although not quantitative, the observations provided sufficient evidence to validate qualitative aerodynamic and mechanical assumptions used in the feasibility analysis.

1.8. Limitations

The experiments were designed to assess feasibility, not performance limits. The analysis relies on simplified mechanical models, commercially published jitter specifications, and environmental statistics rather than controlled laboratory measurements. Quantitative measurement of jitter spectra, wake velocity fields, or plant displacement would require dedicated instrumentation and will be the subject of future work. Nonetheless, the methods employed here are sufficient to determine whether millimetre-scale targeting is technically plausible on lightweight multirotor platforms.

2. Introduction

Small multirotor UAVs increasingly serve as platforms for precision imaging and actuation at close range. As compact laser sources, embedded cameras and low-cost inertial sensors continue to improve, an important question arises: can such platforms deliver optical energy to millimetre-scale targets at distances of about one metre? Achieving 1 mm placement at 1 m requires roughly one milliradian accuracy, a challenging but realistic precision class for stabilized optical payloads.

This paper examines whether this requirement can be met under mild outdoor conditions by relying on modern 3-axis gimbals, isolation mounts, and short-duration stability windows. To provide a regional environmental baseline, we use publicly available Belgian summer wind data as a representative mild-weather envelope for central Europe. Although this study is purely mechanical and control-focused, the results directly support emerging concepts such as airborne photonic insecticides. Target arthropods such as the Colorado potato beetle have body dimensions of 5–10 mm, making millimetre-scale beam placement an essential enabling capability.

3. Pointing Requirement and Sensor Geometry

At a distance of one metre, achieving a maximum lateral error of one millimetre corresponds to approximately 1 mrad or 0.057°. This value sets the permissible LOS angular jitter for the combined UAV–gimbal–mount–camera system. Standard camera geometry shows that this precision is not inherently limiting: a 60° field-of-view camera with 1920 pixels across its horizontal axis resolves about 0.545 mrad per pixel, making one pixel equivalent to roughly 0.5–0.6 mm at one metre. Thus, even simple vision-based centroiding can comfortably measure deviations at the scale of the required tolerance, and pixel resolution is not a bottleneck.

4. Environmental Disturbance Envelope

Hover disturbances outdoors are dominated by low-frequency translational and rotational drift of the UAV body, together with intermittent gusts. Belgium summer wind statistics, which are representative of many mild European climates, indicate mean wind speeds around 3–4 m/s (Weatherspark), with frequent short intervals near 1 m/s. We note that Colorado potato beetle populations are most active from June to August under warm, high-pressure conditions, which in central European climates generally coincide with relatively low and stable surface wind speeds.

Disturbance modelling and experimental studies show that gust-driven motion typically evolves over 1–3 s timescales. This temporal structure naturally produces sub-second windows of relative stability between gust peaks, allowing precise optical alignment to be executed only during favourable moments rather than continuously. This “gust-skipping” approach substantially relaxes the constraints on continuous stabilization and is especially effective at short stand-off distances.

5. Nested Stabilization Loops

Modern UAV gimbals employ a nested control architecture consisting of a high-bandwidth inner loop and a slower outer loop. The inner loop uses IMU measurements to suppress high-frequency rotational disturbances and propeller-induced jitter, typically operating between 50 and 200 Hz. This loop isolates the payload from the drone’s rapid body-rate fluctuations. The outer loop then uses camera or encoder feedback at 5–20 Hz to correct low-frequency drift, maintain the target within the camera frame, and drive residual deviation toward zero. This layered structure is well established in both the civilian and defence sectors, and forms the basis of nearly all stabilized imaging systems.

6. Payload Mass and High-Frequency Vibration

Payload mass has opposing effects on stabilization performance. A heavier payload has greater inertia and therefore experiences reduced acceleration in response to high-frequency forces such as propeller harmonics and frame resonance. This passive inertia makes the payload more resistant to micro-jitter. However, heavier payloads also require greater torque from gimbal motors to counter low-frequency drift, gust disturbances and body tilts; excessive mass can therefore degrade low-frequency correction authority.

Conversely, lightweight payloads (100–300 g) respond more strongly to high-frequency vibration, yet are easier for the gimbal to steer at low frequencies. This trade-off is manageable by placing the payload on soft rubber isolation mounts designed to have a natural frequency well below the dominant propeller vibration band. When the mount resonance lies around 15–30 Hz, and prop excitation is near or above 100 Hz, high-frequency disturbances fall cleanly into the isolation region where their transmission is strongly attenuated. With appropriate damping, this configuration greatly reduces the vibration energy reaching the gimbal, even with lightweight payloads, while preserving low-frequency steering authority.

7. Commercial Benchmark: DJI Zenmuse H20

A highly relevant empirical benchmark is the DJI Zenmuse H20 stabilized optical payload. In 2025, the date of this writing, its specifications list an angular vibration range of $\pm 0.01°$, corresponding to approximately 0.17 mm of lateral motion at a 1 m stand-off distance. This is substantially below the 1 mm tolerance required in this study and demonstrates that sub-millimetre LOS stability is achieved in commercially available systems operating under real UAV flight conditions. Although the H20 is designed for payload masses around 700–800 g, the performance margin of approximately a factor of six suggests that even if LOS jitter were to degrade by two- to fourfold when the payload mass is reduced to the 100–300 g range, the resulting performance would still remain near or within the millimetre-scale requirement. Residual error can then be handled through small-angle correction mechanisms described later.

8. Experimental Observations

Two simple bench experiments provide qualitative confirmation. In the first, a low-power laser diode mounted on a DJI mini 3 and configured to point down, was manually stabilized using only operator input. Even without a gimbal or isolation mount, the laser spot could be held within sub-centimetre ranges over a printed mark, showing that coarse pointing at one metre is inherently forgiving (**Reyntjens, 2025a**).

In the second experiment, a lightweight multi-link remote controlled servo arm, sticking out laterally from the DJI mini drone, constructed from simple materials, such as drinking straws, demonstrated repeatable contact with the same point, where a colorado beetle was glued on a leaf, with approximately 5 mm precision. While crude, these experiments illustrate that close-range optical and mechanical precision in the millimetre-to-centimetre range is practical even with inexpensive hardware (**Reyntjens, 2025b**).

Taken together, these two demonstrations indicate that millimetre-scale laser aiming in a sheltered indoor or greenhouse context is essentially trivial, even without dedicated stabilization hardware. Likewise, the outdoor experiment shows that insect-level interaction—whether by mechanical contact, micro-dosing of chemicals, or other localized actuation—is achievable with low-cost, lightweight hardware under realistic field conditions. These qualitative results reinforce the broader conclusion that close-range optical and mechanical insect-neutralization strategies are technically feasible on small UAV platforms.

9. Fine-Steering Correction

High-precision beam placement ultimately benefits from a fine-steering mechanism capable of correcting residual jitter that remains after gimbal control and isolation. Fast steering mirrors (FSMs) are well established in free-space optical communication and adaptive optics, and are capable of sub-milliradian angular resolution with bandwidths exceeding 100 Hz. When an FSM is placed after the gimbal, the gimbal addresses the low-frequency body motion—drift, gusts, and slow alignment—while the FSM removes the remaining high-frequency and mid-frequency jitter. The combination provides a robust two-stage stabilization system. Given that the commercial gimbal benchmark already outperforms the requirement by a factor of six, the FSM only needs to deliver a modest residual correction, typically in the range of a factor of 2–4, which is well within demonstrated FSM capability.

10. Downwash Interaction Between Multirotor UAVs and Vegetation

The aerodynamic influence of a small quadcopter such as the DJI Mini 3 on nearby vegetation is negligible at short horizontal stand-off distances. Empirical tests conducted in a potato field demonstrated that at a horizontal offset of approximately 0.5 m the vegetation exhibited no detectable shaking or displacement, indicating that the rotor wake decays rapidly in the lateral direction (Reyntjens, 2025c). Video footage obtained during the same field test further shows that even when the drone is positioned directly above a Colorado potato beetle resting on a potato leaf, the insect displays no behavioural response to either the rotor noise or the airflow. Vegetation located laterally from the drone remains essentially motionless, while the plant directly beneath the vehicle exhibits only a small-amplitude, low-frequency oscillation characteristic of the confined vertical downwash jet. These observations are consistent with aerodynamic models of multirotor wakes, which show that induced flow is strongly oriented downward and loses energy rapidly with radial distance from the rotor disk. Consequently, a small UAV can approach target plants very closely—either beside or slightly above them—without introducing significant mechanical disturbance to the foliage or altering insect behaviour. This environmental passivity simplifies the optical targeting problem, as plant motion remains dominated by very low-frequency ambient oscillations rather than UAV-induced disturbance.

11. Conclusion

The analysis presented in this study shows that maintaining a laser beam within a 1 mm radius at a 1 m distance is technically feasible on a small UAV. The geometric requirement of 1 mrad is modest relative to camera angular resolution, and mild European wind conditions offer natural short-duration stability windows. A commercial benchmark, the DJI Zenmuse H20, achieves ±0.01° angular jitter—equivalent to 0.17 mm at 1 m—demonstrating that sub-millimetre LOS stability is already achieved in operational systems. For lighter payloads, which are more prone to high-frequency vibration, soft isolation mounts shift the mount resonance below the propeller excitation band, greatly reducing transmitted jitter. Nested gimbal loops address low-frequency disturbances, and a fine-steering mirror compensates for remaining errors. Together, these elements form a credible architecture for millimetre-scale optical targeting from lightweight UAV platforms.

Field observations further show that the aerodynamic wake of a small multirotor is strongly confined to a narrow vertical jet and decays rapidly in the lateral direction. As a result, vegetation located beside a hovering drone experiences negligible aerodynamic disturbance, allowing the vehicle to approach target plants and insects at very close range without inducing additional motion. Operating at such near-field distances imposes only modest penalties, primarily in the form of increased time per shot and additional flight manoeuvring effort. However, the benefits are significant: shorter focal distances permit laser beams to be designed with intrinsically safer divergence profiles, improving bystander safety and reducing long-range hazard zones.

Although this paper addresses the pointing problem independently of application domain, the results provide direct support for future work on airborne photonic insecticides and other precision optical actuation systems. The combined evidence from modeling, commercial benchmarks, and empirical field observations indicates that close-range optical targeting with millimetre-scale accuracy is practically achievable using lightweight, low-cost unmanned aircraft.

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