# The Use of Multi-Scale Fiducial Markers To Aid Takeoff and Landing Navigation by Rotorcraft

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We collect datasets of rotorcraft TOLD scenarios in diverse visibility conditions

**Introduction** | **Experiments** | **Results and Discussion** | **Conclusion**

We investigate the use of multi-scale fiducial markers in visual SLAM for rotorcraft TOLD scenarios under diverse visibility conditions

We present the SLAM performance across diverse visibility conditions

**TOLD**: takeoff and landing

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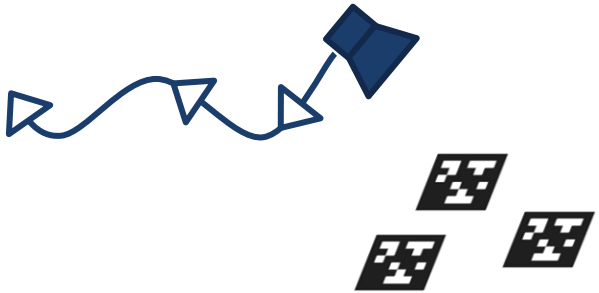
# What is visual SLAM with fiducial markers (marker SLAM)?

- Simultaneous localization and mapping (SLAM) is a process through which a mobile robot constructs a map of its environment while simultaneously determining its own location
- Visual SLAM with fiducial markers (marker SLAM) uses easily detectable artificial visual patterns, called fiducial markers, to aid in tracking and mapping

The examples of various fiducial markers:
AprilTag. ARTag,. ARToolKit, and ArUco, from left to right



# Why is marker SLAM useful during TOLD scenarios of rotorcraft under VFR?

- In TOLD navigation scenarios for rotorcraft following VFR, accurate and reliable positioning is crucial
- Marker SLAM outperforms generic visual SLAM in various aspects, including both accuracy and reliability
- Therefore, choosing marker SLAM over generic visual SLAM is advantageous for TOLD navigation scenarios of rotorcraft adhering to VFR

**TOLD**: takeoff and landing; **VFR**: visual flight rule

# Existing works on marker SLAM

- Some works (e.g., TagSLAM) entirely rely on marker detection results
- UcoSLAM introduces a hybrid approach using both marker and feature detection results, showing improved performance compared to relying solely on markers or features
- WOLF, an open-source modular SLAM framework, provides SLAM implementation using either marker and/or feature detections

[1] Pfrommer, B., and Daniilidis, K., "Tagslam: Robust slam with fiducial markers," arXiv preprint arXiv:1910.00679, 2019.
[2] Munoz-Salinas, R., and Medina-Carnicer, R., "UcoSLAM: Simultaneous localization and mapping by fusion of keypoints and squared planar markers," Pattern Recognition, Vol. 101, 2020, p. 107193.
[3] Sola, J., Vallvé, J., Casals, J., Deray, J., Fourmy, M., Atchuthan, D., Corominas-Murtra, A., and Andrade-Cetto, J., "WOLF: A modular estimation framework for robotics based on factor graphs," IEEE Robotics and Automation Letters, Vol. 7, No. 2, 2022, pp. 4710–4717.

# Ambiguities in existing literature regarding the evaluation of marker SLAM for application in rotorcraft TOLD scenarios

- Existing marker SLAM assessments use fiducial markers of uniform size, limiting their detectable distance range

  → The use of single-scale markers may constrain SLAM performance in TOLD scenarios, where the distance between ground markers and the rotorcraft's camera varies significantly

- Existing marker SLAM assessments are conducted in controlled indoor environments with constant visibility conditions

  → It is crucial to investigate how marker SLAM performs under various weather conditions, which are likely to be encountered during actual TOLD scenarios of rotorcraft

# Contributions of our work

- We employ multi-scale fiducial markers to expand the detectable range during TOLD scenario of rotorcraft
- We evaluate marker SLAM using a dataset collected outdoors during actual TOLD scenario of rotorcraft in various weather conditions

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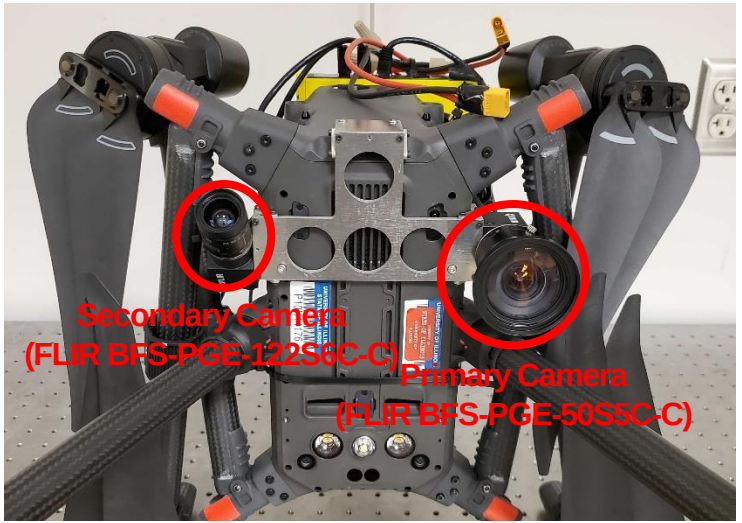
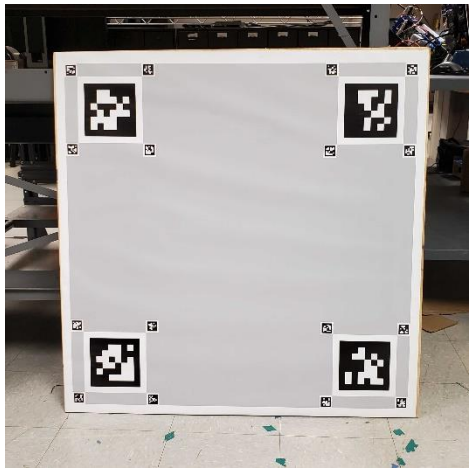
# System for data collection

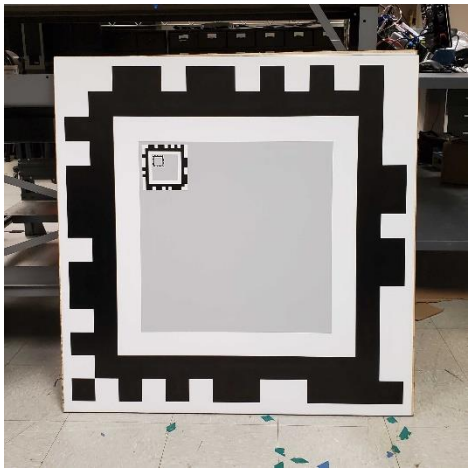
- We used a DJI Matrice 300 RTK rotorcraft equipped with two color cameras mounted at the bottom — one facing downward and the other oriented 45° forward



# Multi-scale fiducial markers for data collection

- We proposed the use of two types of multi-scale fiducial markers integrated into the $1\mathrm{m}^2$ TLOF area aligning with the CD of the rotorcraft, namely non-nested and nested layouts





**TLOF**: touchdown and liftoff; **CD**: control dimension

# Data collection

- We implemented a trajectory covering the TOLD phases of the rotorcraft, adhering to VFR approach/departure path requirements set by the FAA, maintaining an 8:1 ratio
  - Step 1: Ascend vertically to 5m altitude
  - Step 2: Move horizontally for 40m distance at 1m/s speed
  - Step 3: Return above the TLOF area at 1m/s speed
  - Step 4: Descend and land
- We collected data on two distinct dates (Nov. 30$^{th}$ and Dec. 2$^{nd}$, 2023) at various times and weathers to encompass various visibility scenarios

# Data collection (continued)

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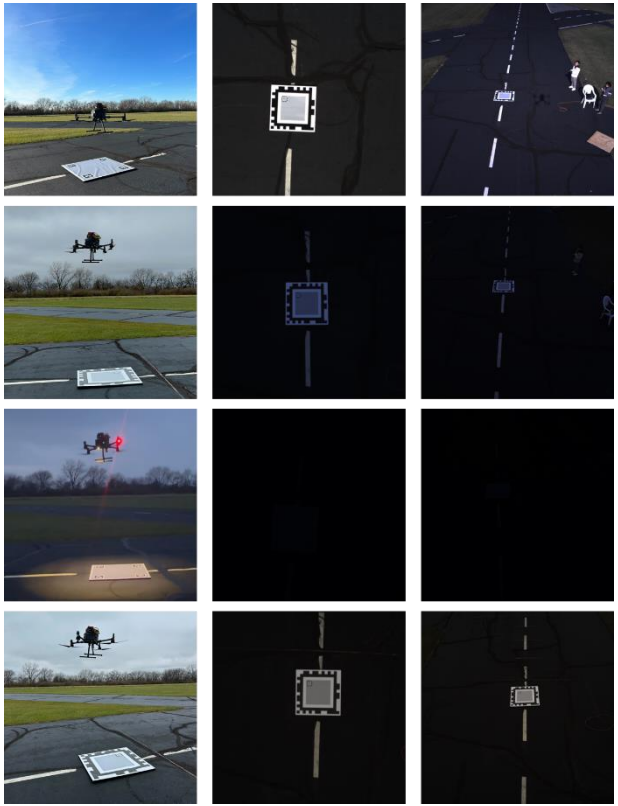

| Date | Weather | | | |
|---|---|---|---|---|
| | state | temp. | wind | illumination |
| Nov. 30, 2023 | sunny | 10 °C | 5.3 m/s NE | 6000 Lux (day) |
| | drizzle | 10 °C | 6.5 m/s NE | 1200 Lux (day) |
| | drizzle | 9 °C | 7.3 m/s N | 10-50 Lux (dusk) |
| Dec. 2, 2023 | cloudy | 6 °C | 1.3 m/s S | 4000 Lux (day) |

← Rotorcraft flights under diverse weathers (left column), with examples of images captured from the primary camera (mid column) and the secondary camera (right column) during each flight mission

# Marker SLAM implementation

- We used WOLF, which offers SLAM using either marker and/or feature detections
- We evaluated two modes of marker SLAM provided by WOLF:
  - The mode relying solely on marker detection results (marker SLAM)
  - The mode using both marker and feature detection results (marker + feature SLAM)

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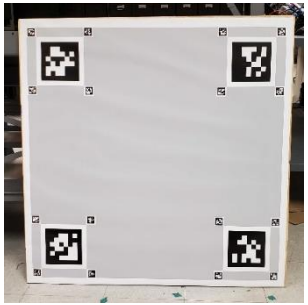
# Results for non-nested multi-scale fiducial marker

| Date | Weather | | | | Trial | Marker SLAM | | Marker + Feature SLAM | |
|---|---|---|---|---|---|---|---|---|---|
| | state | temp. | wind | illumination | | ATE (m) | Availability | ATE (m) | Availability |
| Nov. 30, 2023 | sunny | 10 °C | 5.3 m/s NE | 6000 Lux (day) | 1 | 0.47 | 0.84 | 0.39 | 0.84 |
| | | | | | 2 | 2.04 | 0.84 | 2.56 | 0.83 |
| | | | | | 3 | 1.46 | 0.84 | 1.70 | 0.84 |
| | drizzle | 10 °C | 6.5 m/s NE | 1200 Lux (day) | 1 | 2.19 | 0.84 | 2.58 | 0.84 |
| | | | | | 2 | 3.56 | 0.84 | 4.92 | 0.84 |
| | | | | | 3 | 1.86 | 0.85 | 1.59 | 0.84 |
| | drizzle | 9 °C | 7.3 m/s N | 10-50 Lux (dusk) | 1 | - | - | - | - |
| | | | | | 2 | - | - | - | - |
| Dec. 2, 2023 | cloudy | 6 °C | 1.3 m/s S | 4000 Lux (day) | 1 | 2.00 | 0.84 | 1.82 | 0.84 |
| | | | | | 2 | - | - | 4.95 | 0.84 |
| | | | | | 3 | 0.33 | 0.84 | 0.54 | 0.84 |
| | | | | | 4 | 0.49 | 0.89 | 1.61 | 0.83 |



non-nested multi-scale fiducial marker

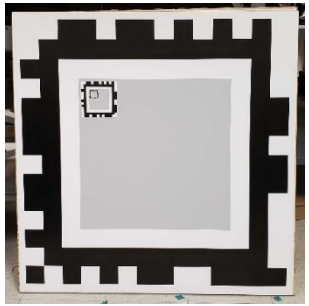
The evaluation metrics include:
- absolute trajectory error (**ATE**; lower is better)
- the fraction of the number of estimated poses to the total frame (**availability**; higher is better)

- SLAM fails under the lowest illumination condition (10-50 Lux)
- In comparing marker SLAM and marker + feature SLAM, no significant differences are evident in terms of both ATE and availability

→ This may be due to the rotorcraft flying over a runway with limited texture, impacting feature point detection

# Results for nested multi-scale fiducial marker

| Date | Weather | | | | Trial | Marker SLAM | | Marker + Feature SLAM | |
|---|---|---|---|---|---|---|---|---|---|
| | state | temp. | wind | illumination | | ATE (m) | Availability | ATE (m) | Availability |
| Nov. 30, 2023 | sunny | 10 °C | 5.3 m/s NE | 6000 Lux (day) | 1 | 1.00 | 0.80 | 0.77 | 0.82 |
| | | | | | 2 | 0.92 | 0.80 | 1.11 | 0.81 |
| | | | | | 3 | 0.69 | 0.80 | 0.78 | 0.81 |
| | drizzle | 10 °C | 6.5 m/s NE | 1200 Lux (day) | 1 | - | - | - | - |
| | | | | | 2 | 0.90 | 0.81 | 0.96 | 0.83 |
| | drizzle | 9 °C | 7.3 m/s N | 10-50 Lux (dusk) | 1 | - | - | - | - |
| | | | | | 2 | - | - | - | - |
| | | | | | 3 | - | - | - | - |
| Dec. 2, 2023 | cloudy | 6 °C | 1.3 m/s S | 4000 Lux (day) | 1 | 0.69 | 0.84 | 0.83 | 0.84 |
| | | | | | 2 | 1.46 | 0.80 | 0.98 | 0.82 |
| | | | | | 3 | 0.99 | 0.80 | 1.05 | 0.82 |
| | | | | | 4 | 0.77 | 0.80 | 0.90 | 0.81 |
| | | | | | 5 | 1.31 | 0.80 | 1.39 | 0.82 |
| | | | | | 6 | 0.79 | 0.78 | 0.88 | 0.97 |



nested multi-scale fiducial marker

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# Conclusion

- This work studies the application of visual SLAM with multi-scale fiducial markers in rotorcraft's TOLD scenario across diverse visibility conditions
- Future work particularly involves incorporating inertial measurement data to enhance SLAM accuracy and efficiency

# Q&As


- This work is supported by Supernal, LLC.

- Both the code and dataset used in this paper are available online: https://github.com/tag-nav/wolf_ros

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