NRI: Collaborative Research: Autonomous Quadrotors for 3D Modeling and Inspection of Outdoor Infrastructure

Stergios Roumeliotis (PI, Univ. of Minnesota), Peter Seiler (Univ. of Minnesota) and Philippos Mordohai (Stevens Institute of Technology)

Motivation

- A lack of frequent and thorough inspection of the nation's civil and industrial infrastructure (e.g., bridges, power plants, refineries) increases likelihood and severity of accidents
- Human inspection is limited due to its safety concerns (for tall and narrow structures) and high cost (requires cranes and climbing utilities)
- Autonomous UAV assisted inspections with on-board sensing can provide highly accurate and up-to-date maps of the structure (due to more frequent inspections) while maintaining low cost

Objective

- Develop the sensing, estimation, and control technology necessary for enabling small-size quadrotors to assist humans in visual inspections

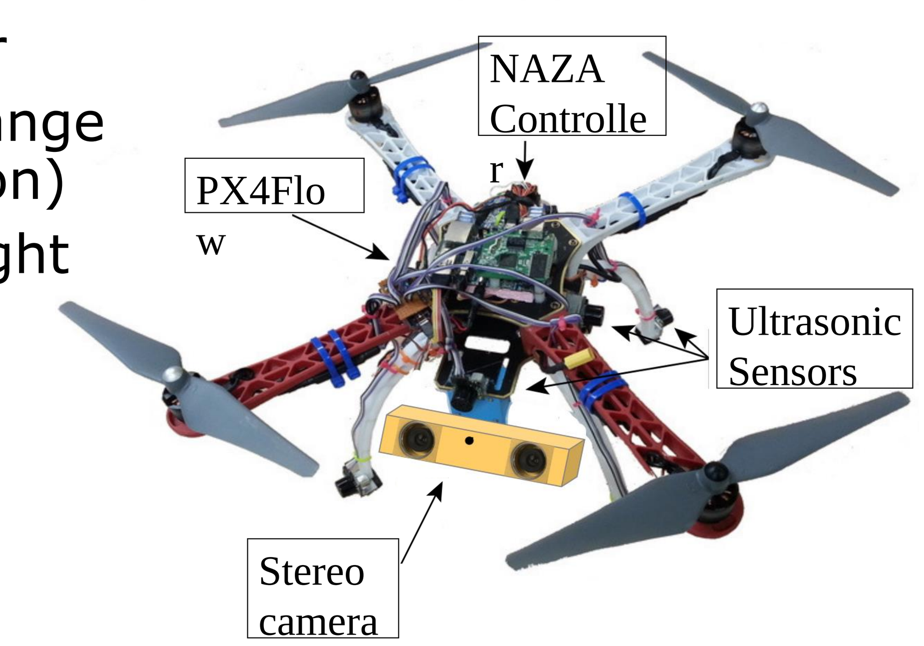
Research Thrusts

1. **Structure mapping:** Combine visual and inertial data to create sparse/dense 3D maps
2. **Representations:** Efficiently represent the map for different purposes (GUI, ODOA)
3. **Active sensing:** Find a minimum deviation path from the predetermined, obstacle-free trajectory which bounds the localization uncertainty and maximizes the information gain for mapping
4. **StereoVINS:** Employ measurement selection in VINS to efficiently perform consistent map-based localization and real-time map expansion
5. **Dense stereo:** Given pose estimates from StereoVINS, develop a dense stereo algorithm for obstacle avoidance and visualization
6. **Control:** Design a robust controller to reject outdoor wind disturbances and reliably avoid un-modeled obstacles

Research Platform

DJI quadrotor equipped with:

- NAZA attitude controller
- 8 MaxBotix ultrasonic range finder (obstacle detection)
- PX4Flow measuring height and velocity
- Stereo cameras & IMU
- NVIDIA TK1 GPU
- ARM processor



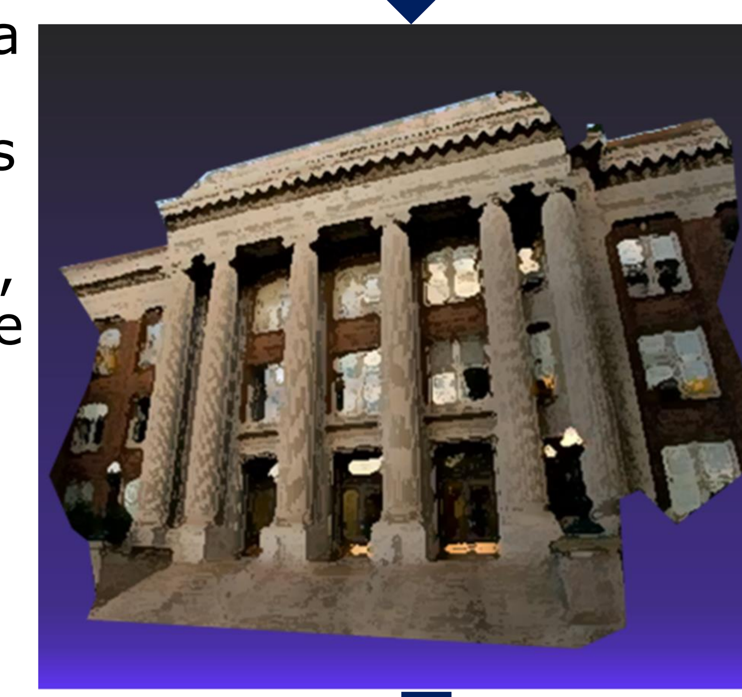
Acknowledgement: This research has been supported by the National Science Foundation awards #1637875 and #1637761.

Proposed Approach

1. **Data collection:** A pilot tele-operates the quadrotor near the structure of interest to collect visual (stereoscopic) and inertial data along its path

   Note: This step, which requires a pilot, is only executed once

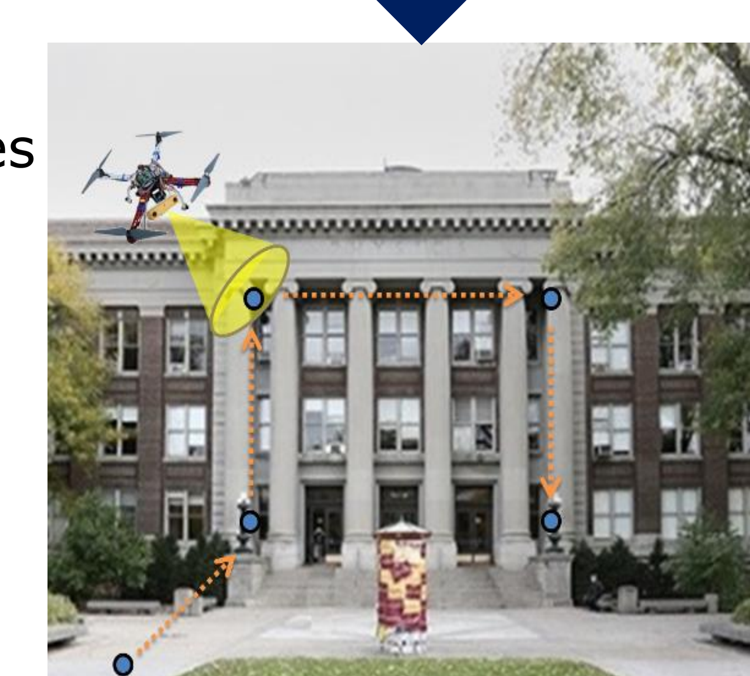
2. **Offline mapping:** Data collected offline in Step 1 (or online in Step 4) is processed to create (or update) a photorealistic, multi-purpose, 3D dense map of the structure of interest



3. **Path specification:** The inspection engineer uses a GUI to inspect the 3D map of the structure (Step 2), then selects the waypoints that the quadrotor must visit during the subsequent autonomous inspection

4. **Online inspection:** The quadrotor navigates autonomously through the waypoints (Step 3) to collect additional data, while avoiding obstacles

   Note: After Step 4, the collected data is used to update the multi-purpose map in Step 2



Research highlights and directions

1. **Optimal feature selection**: Reduce processing cost of online 3D pose determination by selecting and processing the most informative subset of visual features
   - *Key results*
     - Proof that the convex relaxation of [1] yields a sparse solution with almost certainty
     - An O(n) approximate algorithm based on primal-dual algorithm to solve the convex problem defined in [1]
   - *Ongoing Research*
     - Keyframe selection for mapping based on the criteria of [2] for creating a sparse visual graph
2. **Real-time Stereo Matching**: Accelerate binocular stereo matching to support obstacle avoidance on board
   - *Key results*
     - Novel stereo matching approach that does not require exhaustive photoconsistency computation [3]
     - Released multi-threaded software for stereo matching on CPU and GPU achieving up to 30 fps, including SGM optimization
   - *Ongoing Research*
     - Coarse 3D map generation via depth map integration
3. **Dense 3D Mapping**: Generate accurate 3D models offline
   - *Key result*
     - Published and released software for novel learning-based stereo matching that generalizes to novel datasets [4]
   - *Ongoing Research*
     - Multi-view, learning-based 3D occupancy grid estimation
4. **Quadrotor motion planning:** Combine motion primitives for performing online motion planning (reach destination while avoiding obstacles)
   - *Key result*
     - Proof of closed-form solution for simple motion primitives (straight line, uniform tilted circular, helix, etc.) based on the differential flatness principle [5]
   - *Ongoing Research*
     - Design and test trajectory follower [5], [6]

References

[1] S. Joshi and S. Boyd, "Sensor selection via convex optimization", IEEE Trans. Signal Process., 57(2), 451-462, 2009
[2] T. Do, L. C. Carrillo-Arce, and S. I. Roumeliotis, "High-speed autonomous quadrotor navigation through visual and inertial paths." *The International Journal of Robotics Research* (2018): 0278364918786575.
[3] C. LeGendre, K. Batsos and P. Mordohai, "High-Resolution Stereo Matching based on Sampled Photoconsistency Computation." British Machine Vision Conference, 2017
[4] K. Batsos, C. Cai and P. Mordohai, "CBMV: A Coalesced Bidirectional Matching Volume for Disparity Estimation." IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2018
[5] D. Mellinger, N. Michael, and V. Kumar, "Trajectory generation and control for precise aggressive maneuvers with quadrotors", Int. J. Robot. Res., 31(5), 664-674, 2012
[6] T. Lee, M. Leoky, and NH. McClamroch, "Geometric tracking control of a quadrotor UAV on SE (3)." In *IEEE Conf. on Decision and Control (CDC),* pp. 5420-5425. 2010.