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Final Report: Towards Autonomous Miniature Rotorcrafts in Cluttered Environments for Scene Understanding

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14. ABSTRACT

15. SUBJECT TERMS
Micro-Aerial Vehicle (MAV), Quadrotor, Navigation, 3D SLAM, 3D Map Construction, Computer Vision, Surveillance, Scene Understanding

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Jizhong Xiao
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RPPR Final Report
as of 17-Sep-2018

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Title: Towards Autonomous Miniature Rotorcrafts in Cluttered Environments for Scene Understanding

Begin Performance Period: 01-Oct-2009
End Performance Period: 30-Sep-2014
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STEM Degrees: 5 **STEM Participants:** 6

Major Goals: The objective of this project is to develop control, navigation, computer vision, and 3D mapping algorithms for Micro Aerial Vehicles (MAVs) to autonomously explore obstacle-dense environments by fusing multiple sensors (camera, Omni-stereo vision system, RGB-D sensor, IMU, laser scanner, etc.) for 3D scene understanding. We envision that the autonomous MAVs can be used in various military scenarios, such as surveillance and reconnaissance in urban or wooded environments to enhance tactical situational awareness or in cave search applications to build a 3D map.

During the course of the project, we have made significant accomplishments in tackling the critical challenges of MAV perception, control and 3D SLAM in unknown environments and verify the proposed methods on the experimental test-bed (i.e., quadrotor MAV from AscTec). The achievements include the development of single camera omni-stereo vision system, real-time pose estimation via multimodal sensing (i.e., laser scanner, RGB-D sensor, and Google Tango tablet, etc.), fast visual odometry and 3D mapping algorithms, 3D path planning algorithms, quaternion-based orientation estimation using low-cost Inertia/Magnetic sensors, etc.

The success of this project has taken us a few steps closer to empower the MAVs with the similar exploration capability of flying birds to achieve autonomous navigation in cluttered environments. This final report summarizes the significant technical achievements of the project.

Accomplishments: see PDF file, a summary of most important results.

Training Opportunities: This project provided mentored research experience to many undergraduate and graduate students by involving them in the project.

This project directly supported three Ph.D. students who have successfully conducted dissertation research and received their Ph.D. degrees.

Ivan Dryanovski, Dissertation: "3D Scene Reconstruction with Micro-Aerial Vehicles and Mobile Devices" , Dec. 2015

Roberto G. Valenti, Dissertation: "State Estimation and Multi-Sensor Data Fusion for Micro Aerial Vehicles Navigation", May 2016

Carlos Jaramillo, Dissertation: "Enhancing 3D Visual Odometry with Single-Camera?Stereo Omnidirectional Systems", May 2018,

Results Dissemination: We disseminate the research results through publications in professional conferences and journals.

A partial list of relevant papers:
1. Ivan Dryanovski, Matthew Klingensmith, Siddhartha Srinivasa, Jizhong Xiao, “Large Scale, real-time 3D scene reconstruction on a mobile device”, Autonomous Robots, 41:1423–1445, Springer, Feb. 24, 2017.
2. Anqing Wang, Chi Li, Yan Zhuang, Yisha Liu, Chunguang Bu, Jizhong Xiao, “Laser-Based Online Sliding-Window Approach for UAV Loop-Closure Detection in Urban Environments”, International Journal of Advanced Robotic Systems, Int. J Advanced Robotic Systems, 2016, 13:0 | doi: 10.5772/62755.
3. Fei Yan, Ke Wang, Jizhong Xiao, Ruifeng Li, “A Bio-Inspired Scan Matching Algorithm for Mobile Robots in Outdoor Environments”, Assembly Automation (Emerald Group Publishing Limited), Vol. 36 Issue 2, 2016.
4. Carlos Jaramillo, Roberto G. Valenti, Ling Guo, and Jizhong Xiao, “Design and Analysis of a Single Camera Omnistereo Sensor for Quadrotor Micro Aerial Vehicles (MAVs)”, Sensors 2016, 16(2), 217; Feb 2016, doi:10.3390 /s16020217
5. Roberto G. Valenti, Ivan Dryanovski, and Jizhong Xiao, “A Linear Kalman Filter for MARG Orientation Estimation Using the Algebraic Quaternion Algorithm”, IEEE Transactions on Instrumentation and Measurement, Volume: 65, Issue: 2, Feb., 2016, Pages: 467 – 481.
6. Roberto G. Valenti, Ivan Dryanovski and Jizhong Xiao, “Keeping a Good Attitude: A Quaternion-Based Orientation Filter for IMUs and MARGs”, Sensors 2015, 15 (8), Aug. 2015, pp19302-19330; doi:10.3390 /s150819302,
7. Fei Yan, Yisha Liu, Jizhong Xiao, “Path Planning in Complex 3D Environments Using the Probabilistic Roadmap Method”, Int. J. of Automation and Computing, 10 (6), p525~533, Dec. 2013.
8. Ivan Dryanovski, Roberto Valenti, Jizhong Xiao, “An Open-Source Navigation System for Micro-Air Vehicles”, Autonomous Robots, 34:177~188, March 2013.

9. Fei Yan, Yisha Liu, Jizhong Xiao, “Path Planning in Complex 3D Environments using the Probabilistic Roadmap Method”, Int. J. of Automation and Computing, 10 (6), Dec. 2013, p525`533, DOI: 10.1007/s11633-013-0750-9.
10. Ivan Dryanovski, Roberto Valenti, Jizhong Xiao,“An Open-Source Navigation System for Micro-Air Vehicles”, Autonomous Robots, 34:177~188, 2013.
11. Liang Yang, Juntong Qi, Ziya Jiang, Dalei Song, Jianda Han, and Jizhong Xiao, “Guiding Attraction based Random Tree Path Planning under Uncertainty: Dedicate for UAV”, IEEE Int. Conf. on Mechatronics and Automation (ICMA2014), Tianjin, China, Aug.3~6, 2014, pp1182~1187. (Best Student Paper Award).
12. Liang Yang, Juntong Qi, Jizhong Xiao, Xia Yong, “A literature Review of UAV 3D path Planning”, Proceedings of the 11th World Congress on Intelligent Control and Automation, Shenyang, China, June 29~July 4, 2014, pp2376~2381.
13. Roberto G. Valenti, Ivan Dryanovski, Carlos Jaramillo, Daniel Perea Strom, Jizhong Xiao, “Autonomous Quadrotor Flight Using Onboard RGB-D Visual Odometry”, International Conference on Robotics and Automation (ICRA2014), HongKong, May 31~June 7, pp5233~5238.
14. Carlos Jaramillo, Ivan Dryanovski, Roberto G. Valenti, and Jizhong Xiao*, “6-DoF Pose Localization in 3D Point-Cloud Dense Maps Using a Monocular Camera”, Proceeding of the 2013 IEEE ?International Conference on Robotics and Biomimetics (ROBIO2013) Shenzhen, China, Dec., 2013, pp1747~1752.
15. Roberto G. Valenti, Ivan Dryanovski, Jizhong Xiao, “A Non-inertial Acceleration Suppressor for Low Cost Inertial Measurement Unit Attitude Estimation”, Proceeding of the 2013 IEEE ?International Conference on Robotics and Biomimetics (ROBIO2013) Shenzhen, China, Dec., 2013, pp639~644.
16. Carlos Jaramillo, Ling Guo, Jizhong Xiao, “A Single-Camera Omni-Stereo Vision System for 3D Perception of Micro Aerial Vehicles (MAVs)”, The 8th International Conference on Industrial Electronics and Applications (ICIEA2013), Melbourne, Australia, June 19~21, 2013.
17. Ivan Dryanovski, Roberto Valenti and Jizhong Xiao, “Fast Visual Odometry and Mapping from RGB-D Data”, 2013 International Conference on Robotics and Automation (ICRA2013), p2297~2302, Karlsruhe, Germany, May 6~10, 2013.
18. Fei Yan, Yan Zhuang, Jizhong Xiao, “PRM-based Real-time 3D Path Planning for UAV in Complex Environment”, 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO 2012), Dec. 11-14, 2012, in Guangzhou, China.
19. Ivan Dryanovski, William Morris, Ravi Kaushik, Jizhong Xiao, “Real-Time Pose Estimation with RGB-D Camera”, 2012 IEEE International Conference on Multisensor Fusion and Information Integration, September 13-15, 2012, University of Hamburg, Germany. (Best Paper Award Finalist).
20. Ivan Dryanovski, Carlos Jaramillo, Jizhong Xiao, “Incremental Registration of RGB-D Images”, 2012

International Conference on Robotics and Automation (ICRA2012), May 14~18, St Paul, Minnesota, USA, pp1685-1690.
21. Xuejun Yan, Chunxia Zhao, Jizhong Xiao, “A novel FastSLAM Algorithm based on Iterated Unscented Kalman Filter”, Proceedings of 2011 IEEE International Conference on Robotics and Biomimetics (Robio2011), Phuket, Tailand, Dec. 2011, pp. 1906~1911.
22. Rex Wong, Jizhong Xiao, Samleo Loseph, “An Adaptive Data Association for Robotic SLAM in Search and Rescue Operation”, Proceedings of the 2011 IEEE Int. Conf. on Mechatronics and Automation (ICMA2011), p997~1003.
23. Ivan Dryanovski, William Morris, Jizhong Xiao, “An Open-Source Pose Estimation System for Micro-Air Vehicles”, Proceedings of 2011 International Conference on Robotics and Automation (ICRA2011), pp4449-4454.
24. William Morris, Ivan Dryanovski, Jizhong Xiao, “CityFlyer: Progress Toward Autonomous MAV Navigation and 3D Mapping”, Video, 2011 International Conference on Robotics and Automation (ICRA2011), pp2972-2973.
25. Igor Labutov, Carlos Jaramillo, Jizhong Xiao, “Fusing Optical Flow and Stereo in a Spherical Depth Panorama Using a Single-Camera Folded Catadioptric Rig”, Proceedings of 2011 International Conference on Robotics and Automation (ICRA2011), pp3092-3097. (ICRA2011 Best Vision Paper Award Finalist)
26. Ravi Kaushik, Jizhong Xiao, Samleo L. Joseph, William Morris, “Polygon-based Laser Scan Registration by Heterogeneous Robots”, Proceedings of 2010 IEEE International Conference on Robotics and Biomimetics (Robio2010), pp1618~1623, Tianjin, Dec. 2010.
27. Rex Wong, Jizhong Xiao, Samleo L. Joseph, and Zeyong Shan, “Data Association for Simultaneous Localization and Mapping in Robotic Wireless Sensor Networks”, Proceedings of 2010 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp459~464, Montréal, Canada, July 6-9, 2010
28. Ling Guo, Igor Labutov, Jizhong Xiao, “Design and calibration of single-camera catadioptric omnistereo system for Miniature Aerial Vehicles (MAVs)”, Proceedings of 2010 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2010), pp622~627, Taipei, Oct. 18~22, 2010.
29. Ivan Dryanovski, William Morris?Jizhong Xiao, “Multi-Volume Occupancy Grids: an Efficient Probabilistic 3D Mapping Model for Micro Aerial Vehicles”, Proceedings of 2010 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2010), pp1553~1559, Taipei, Oct. 18~22, 2010.
30. Rex Wong, Jizhong Xiao, Samleo L. Joseph, “Clutter-sensitive Data Association for Simultaneous Localization and Mapping in Robotic Wireless Sensor Networks”, Proceedings of 2010 IEEE International Conference on Mechatronics and Automation (ICMA 2010), p1976~1981, August 4-7, 2010, in Xi'an, China.
31. Ravi Kaushik, Jizhong Xiao, Samleo L. Joseph, William Morris, “Fast Planar Clustering and Polygon Extraction from Noisy Range Images Acquired in Indoor Environments”, Proceedings of 2010 IEEE International Conference on Mechatronics and Automation (ICMA 2010), pp483~488, August 4-7, 2010, in Xi'an, China.
32. William Morris, Ivan Dryanovski and Jizhong Xiao, “3D Indoor Mapping for Micro-UAVs Using Hybrid Range Finders and Multi-Volume Occupancy Grids”, the workshop on RGB-D: Advanced Reasoning with Depth Cameras, o

Honors and Awards: •Yingli Tian, elected to be IEEE fellow, 2018
• Jizhong Xiao, Recipient of Humboldt Fellowship for Experienced Researchers, Alexander von Humboldt Foundation, Germany, 2013~2015
• Jizhong Xiao, Recipient of CCNY Outstanding Mentoring Award, 2010~2011.

• RSS2015 Best System Paper Award: The paper “Chisel: Real-time Dense Reconstruction on a Mobile Device using Spatially Hashed Truncated Signed Distance Fields”, (authors: Matthew Klingensmith, Ivan Dryanovski, Sidd Srinivasa, and Jizhong Xiao) was selected as the BEST System Paper Award Finalist at 2015 Robotics: Science and Systems Conference, (RSS2015), July 13~15, Sapienza University of Rome.
• ICMA2014 Best Student Paper Award: The paper “Guiding Attraction Based Random Tree Path Planning Under Uncertainty: Dedicate for UAV”, (authors: “Liang Yang, Juntong Qi, Ziya Jiang, Dalei Song, Jianda Han, and Jizhong Xiao) won the Best Student Paper Award at 2014 IEEE Int. Conf. on Mechatronics and Automation (ICMA2014), Tianjin, China, Aug. 3 ~ 6, 2014.
• MFI2012 Best Paper Finalist: The paper “Real-time Pose Estimation with RGB-D Camera” (authors: Ivan Dryanovski, William Morris, Ravi Kaushik and Dr. Jizhong Xiao) was selected as the Best Paper Award Finalist at 2012 IEEE Int. Conf. on Multisensor Fusion and Information Integration (MFI 2012), Sept. 13~15, Hamburg, Germany.
• ICRA2011 Best Vision Paper Award finalist: "Fusing Optical Flow and Stereo in a Spherical Depth Panorama Using a Single-Camera Folded Catadioptric Rig” (Igor Labutov, Carlos Jaramillo, Jizhong Xiao), was selected as the Best Vision Paper Award finalist, 2011 Int. Conf. on Robotics and Automation (ICRA2011), May 9~13, 2011.

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PARTICIPANTS:

Participant Type: PD/PI
Participant: Jizhong Xiao
Person Months Worked: 2.00 **Funding Support:**
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International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Yingli Tian
Person Months Worked: 1.00 **Funding Support:**
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National Academy Member: N
Other Collaborators:

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Volume: 0 Issue: 0 First Page #: 0
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Article Title: Generating Near-Spherical Range Panoramas by Fusing Optical Flow and Stereo from a Single-Camera Folded Catadioptric Rig
Authors:
Keywords: catadioptrics, sensor fusion, omnidirectional vision, stereoscopy, optical flow
Abstract: We design a novel "folded" spherical catadioptric rig (formed by two coaxially-aligned spherical mirrors of distinct radii and a single perspective camera) to recover near-spherical range panoramas (about 360♬x153♬) from the fusion of depth given by optical flow and stereoscopy. We observe that for rigid motion that is parallel to a plane, optical flow and stereo generate nearly complementary distributions of depth resolution. While optical flow provides strong depth cues in the periphery and near the poles of the view-sphere, stereo generates reliable depth in a narrow band about the equator instead.We exploit this dual-modality principle by modeling (separately) the depth resolution of optical flow and stereo in order to fuse them later on a probabilistic spherical panorama. We achieve a desired vertical field-of-view and optical resolution by deriving a linearized model of the rig in terms of three parameters (radii of the two mirrors plus axial distance between the mirrors' centers
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Article Title: An Open-Source State Estimation System for Micro-Air Vehicles
Authors:
Keywords: micro-air vehicle; quadrotor; pose estimation; state estimation; open-source; mapping;SLAM
Abstract: This paper presents a state estimation system for micro-air vehicles and considers the benefits of its free, open-source implementation. The system is designed to provide high frequency 9-state (6 degree-of-freedom pose and linear velocity) estimates in unknown, GPS-denied indoor environments. It requires a minimal set of sensors including a planar laser range-finder and an inertial measurement unit. The algorithms are designed to run entirely onboard, so no wireless link and ground station are explicitly needed. A major focus in our work is modularity, allowing each component to be benchmarked individually, or swapped out for a different implementation, without change to the rest of the system. We demonstrate how the state estimation can be used for 2D SLAM or 3D mapping experiments. All the software and hardware which we have developed, as well as extensive documentation and test data, is available online.
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Article Title: Text String Detection from Natural Scenes byStructure-based Partition and Grouping
Authors:
Keywords: Adjacent character grouping, Characterproperty, Image partition, Text line grouping, Text stringdetection, Text string structure.
Abstract: Text information in natural scene images serves as important clues for many image-based applications such as scene understanding, content-based image retrieval, assistive navigation, and automatic geocoding. However, locating text from complex background with multiple colors is a challenging task. In this paper, we explore a new framework to detect text strings with arbitrary orientations in complex natural scene images. Our proposed framework of text string detection consists of two steps: 1) Image partition to find text character candidates based on local gradient features and color uniformity of character components. 2) Character candidate grouping to detect text strings based on joint structural features of text characters in each text string such as character size differences, distances between neighboring characters, and character alignment. By assuming that a text string has at least three characters, we propose two algorithms of text string detection: 1) adjacent character grou
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Article Title: An Open-Source Navigation System for Micro-Air Vehicles
Authors:
Keywords: Micro-air vehicle ┌ Open-source ┌ Navigation ┌ Quadrotor ┌ State estimation ┌ Control ┌Mapping ┌ SLAM
Abstract: This paper presents an open-source navigation system for quadrotor micro-air vehicles, implemented in the ROS framework. The system requires a minimal set of sensors including a planar laser range-finder and an inertial measurement unit. We address the issues of autonomous control, state estimation, pathplanning, and teleoperation, and provide interfaces that allow the system to seamlessly integrate with existing ROS navigation tools for 2D SLAM and 3D mapping. All components run in real time onboard the MAV, with state estimation and control operating at 1Khz. A major focus in our work is modularity and abstraction, allowing the system to be both exible and hardwareindependent. All the software and hardware components which we have developed, as well as documentation and test data, are available online.
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Article Title: A Scan Matching Algorithm Based on Layered Model Graph for Mobile Robots in Outdoor Environments
Authors: Fei Yan, Yi-Sha Liu, Jizhong Xiao
Keywords: topological graph, layered model, object recognition, scan matching, iterative closest points algorithm
Abstract: This paper proposes a scan matching algorithm for mobile robots based on layered model graph in an outdoor environment. The environments are represented by elevation maps, in which each cell is divided into two categories: flat units and upright units. The upright units are clustered to represent objects which the robot cannot cross over. The object cluster is further discretized to generate layered model consisting of cross-section ellipses of the object. The layered model provides simplified features which facilitate an object recognition algorithm to discriminate among common objects in outdoor environments. A layered model graph is constructed with the recognized objects as nodes. In order to match different local maps, the similarities of sub-graphs are computed as the decisive factor for choosing matching pairs. Then we propose a modified Iterative Closest Points (ICP) algorithm to increase matching accuracy which uses the result of layered model graph-based matching as initial p
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Article Title: An Open-Source Navigation System for Micro-Air Vehicles
Authors: Ivan Dryanovski, Roberto Valenti, Jizhong Xiao
Keywords: Micro aerial vehicle · Open-source · Naviga- tion · Quadrotor · State estimation · Control · Mapping · SLAM · Path-planning
Abstract: This paper presents an open-source indoor navigation system for quadrotor micro aerial vehicles (MAVs), implemented in the ROS framework. The system requires a minimal set of sensors including a planar laser range-finder and an inertial measurement unit. We address the issues of autonomous control, state estimation, path-planning, and teleoperation, and provide interfaces that allow the system to seamlessly integrate with existing ROS navigation tools for 2D SLAM and 3D mapping. All components run in real time onboard the MAV, with state estimation and control operating at 1 kHz. A major focus in our work is modularity and abstraction, allowing the system to be both flexible and hardware-independent. All the software and hardware components which we have developed, as well as documentation and test data, are available online.
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Article Title: A Linear Kalman Filter for MARG Orientation Estimation Using the Algebraic Quaternion Algorithm
Authors: Roberto G. Valenti, Ivan Dryanovski, Jizhong Xiao
Keywords: Inertial sensors, Kalman sensors, orientation estimation, quaternions.
Abstract: Real-time orientation estimation using low-cost inertial sensors is essential for all the applications where size and power consumption are critical constraints. Such applications include robotics, human motion analysis, and mobile devices. This paper presents a linear Kalman filter for magnetic angular rate and gravity sensors that process angular rate, acceleration, and magnetic field data to obtain an estimation of the orien- tation in quaternion representation. Acceleration and magnetic field observations are preprocessed through a novel external algorithm, which computes the quaternion orientation as the composition of two algebraic quaternions. The decoupled nature of the two quaternions makes the roll and pitch components of the orientation immune to magnetic disturbances. The external algorithm reduces the complexity of the filter, making the measurement equations linear. Real-time implementation and the test results of the Kalman filter are presented.
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Article Title: Path Planning in Complex 3D Environments Using a Probabilistic Roadmap Method
Authors: Fei Yan, Yi-Sha Liu, Ji-Zhong Xiao
Keywords: 3D path planning, complex environment, unmanned aerial vehicle (UAV), probabilistic roadmap methed (PRM), octree
Abstract: This paper presents a 3D path planning algorithm for an unmanned aerial vehicle (UAV) in complex environments. In this algorithm, the environments are divided into voxels by octree algorithm. In order to satisfy the safety requirement of the UAV, free space is represented by free voxels, which have enough space margin for the UAV to pass through. A bounding box array is created in the whole 3D space to evaluate the free voxel connectivity. The probabilistic roadmap method (PRM) is improved by random sampling in the bounding box array to ensure a more efficient distribution of roadmap nodes in 3D space. According to the connectivity evaluation, the roadmap is used to plan a feasible path by using A* algorithm. Experimental results indicate that the proposed algorithm is valid in complex 3D environments.
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Article Title: Large-scale, real-time 3D scene reconstruction on a mobile device
Authors: Ivan Dryanovski, Matthew Klingensmith, Siddhartha S. Srinivasa, Jizhong Xiao
Keywords: 3D reconstruction, Mobile technology, SLAM, Computer vision, Mapping, Pose estimation
Abstract: State of the art approaches in large-scale dense reconstruction require large amounts of memory and high-performance GPU computing. Other exist- ing 3D reconstruction approaches on mobile devices either only build a sparse reconstruction, offload their computation to other devices, or require long post-processing to extract the geometric mesh. In contrast, we can reconstruct and render a global mesh on the fly, using only the mobile device's CPU, in very large (300m2) scenes, at a resolution of 2–3cm. To achieve this, we divide the scene into spatial volumes indexed by a hash map. Each volume contains the truncated signed distance function for that area of space, as well as the mesh segment derived from the distance function. This approach allows us to focus computational and memory resources only in areas of the scene which are currently observed, as well as leverage parallelization techniques for multi-core processing. Furthermore, we describe an on-device post-processing method f
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Article Title: Design and Analysis of a Single—Camera Omnistereo Sensor for Quadrotor Micro Aerial Vehicles (MAVs)
Authors: Carlos Jaramillo, Roberto Valenti, Ling Guo, Jizhong Xiao
Keywords: catadioptrics; omnistereo; 3D perception; Micro Aerial Vehicles (MAVs)
Abstract: We describe the design and 3D sensing performance of an omnidirectional stereo (omnistereo) vision system applied to Micro Aerial Vehicles (MAVs). The proposed omnistereo sensor employs a monocular camera that is co-axially aligned with a pair of hyperboloidal mirrors (a vertically-folded catadioptric configuration). We show that this arrangement provides a compact solution for omnidirectional 3D perception while mounted on top of propeller-based MAVs (not capable of large payloads). The theoretical single viewpoint (SVP) constraint helps us derive analytical solutions for the sensor's projective geometry and generate SVP-compliant panoramic images to compute 3D information from stereo correspondences (in a truly synchronous fashion). We perform extensive analysis on various system characteristics such as its size, catadioptric spatial resolution, field-of-view. We pose a probabilistic model for the uncertainty estimation of 3D information from triangulation of back-projected rays.
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Abstract: Orientation estimation using low-cost sensors is an important task for Micro Aerial Vehicles (MAVs) in order to obtain a good feedback for the attitude controller. The challenges come from the low accuracy and noisy data of the MicroElectroMechanical System (MEMS) technology, which is the basis of modern, miniaturized inertial sensors. In this article, we describe a novel approach to obtain an estimation of the orientation in quaternion form from the observations of gravity and magnetic field. Our approach provides a quaternion estimation as the algebraic solution of a system from inertial/magnetic observations. We separate the problems of finding the "tilt" quaternion and the heading quaternion in two sub-parts of our system. This procedure is the key to avoiding the impact of the magnetic disturbances on the roll and pitch components of the orientation when the sensor is surrounded by unwanted magnetic flux. We validate our method first analytically and then empirically.
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Authors: Carlos Jaramillo
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Summary of the Most Important Results

This project has made significant achievement in terms of developing a single-camera omni-stereo vision system for MAV navigation, real-time pose/trajectory estimation via multimodal sensing (i.e., laser scanner, RGB-D sensor, and Google Tango tablet, etc.), fast visual odometry and 3D mapping algorithms, 3D path planning algorithms, quaternion-based orientation estimation using low-cost Inertia/Magnetic sensors, computer vision research for scene understanding. We summarize the most important results in the following sections.

A. Design and Analysis of a Single Camera Omnistereo Vision Sensor for MAVs to Enhance Visual Odometry and 3D Mapping

We have prototyped a single-camera catadioptric omni-stereo vision system and developed algorithms to retrieve depth information for fast 3D reconstruction and MAV navigation. The omni-stereo vision system consists of a pair of custom-designed hyperboloidal mirrors in a coaxial-folded configuration (i.e., one hyperboloidal mirror on the bottom, one hyperbloidal-planar mirror on the top, and one conventional camera on the bottom, all installed inside a transparent cylinder transparent tube as shown in Figure 1 and Figure 2. This arrangement satisfies the theoretical single viewpoint (SVP) constraint that facilitates the study of its projective geometry. Our system is compact, lightweight, and provides an optimal baseline length, which allows for real-life 3D depth perception using stereo vision from truly synchronous images (omni-stereo).

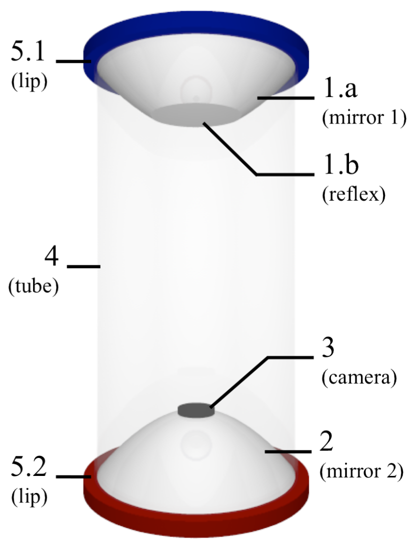


Fig1


Fig2

Fig. 1 Synthetic catadioptric single-camera omnistereo system, whose main tangible are components: 1.a-b) hyperboloid- planar combined mirror at top, 2) hyperboloidal mirror at bottom, 3) camera, 4) transparent cylindrical support, and 5.1-2) blue-red lips acting as circular markers during image processing. Fig. 2 The omnistereo vision prototype installed on the AscTec quadrotor MAV

The initial contribution mainly focused on the optimization of design geometry such as the mirror profile, rig size, system height (h_{sys}) and weight (m_{sys}), and its field-of- view capability. The camera's nominal field of view α_{cam} and its opening radius r_{cam} also determine the physical areas of the mirrors that can be fully imaged. Since a hyperboloidal mirror has two foci, the effective viewpoint is the primary focus F inside the physical mirror and the secondary (outer) focus F' is where the center (pinhole) of the perspective camera should be placed. The projective geometry is illustrated in Fig. 3. Theoretically, the mirrors' vertical axis of symmetry (coaxial configuration) produces two image points that are radially collinear. This property is advantageous for the correspondence search during stereo sensing with a baseline measured as $b = |c_1 + c_2 - d|$. We derive the projective model which has 6 primary design parameters given as a vector $[c1, c2, k1, k2, d, rsys]$, and perform a numerical optimization of the parameters with the goal to maximize the baseline while satisfying the physical constraints (i.e., mirrors radii, system height h_{sys} and mass m_{sys}), geometric constraints (i.e., SVP and reflex constraint) and performance constraints (i.e. spatial resolution, desired view angle) as detailed in our publication.

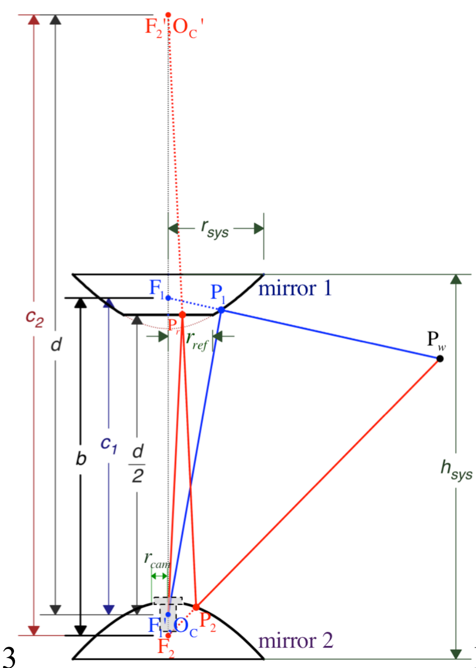


Fig. 3

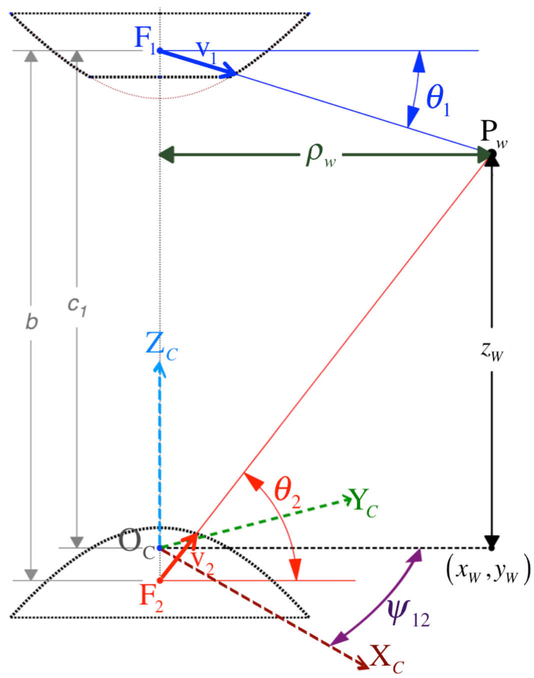


Fig. 4

Fig. 3. 2D cross-section of the geometric model and dimensions for observable constraint parameters: $c_1, c_2, d, r_{sys}, r_{ref}, r_{cam}$; and relevant by-product parameters: baseline b and system height h_{sys}. The projection paths corresponding to a world point P_W are also traced in route to the mirrors real foci, F_1 and F_2, and their respective reflection points, P_1 and P_2 , to the real camera O_C . The equivalent projection of P_2 via the virtual camera O_C' achieved by a reflex

mirror located at $d/2$ from O_C.

The theoretical single viewpoint (SVP) constraint helps us derive analytical solutions for the sensor's projective geometry and generate SVP-compliant panoramic images to compute 3D information from stereo correspondences (in a truly synchronous fashion). We perform an extensive analysis on various system characteristics such as its size, catadioptric spatial resolution, field-of-view. In addition, we pose a probabilistic model for the uncertainty estimation of 3D information from triangulation of back-projected rays. We validate the projection error of the design using both synthetic and real-life images against ground-truth data. Qualitatively, we show 3D point clouds (dense and sparse) resulting out of a single image captured from a real-life experiment. We expect the reproducibility of our sensor as its model parameters can be optimized to satisfy other catadioptric-based omnistereo vision under different circumstances.

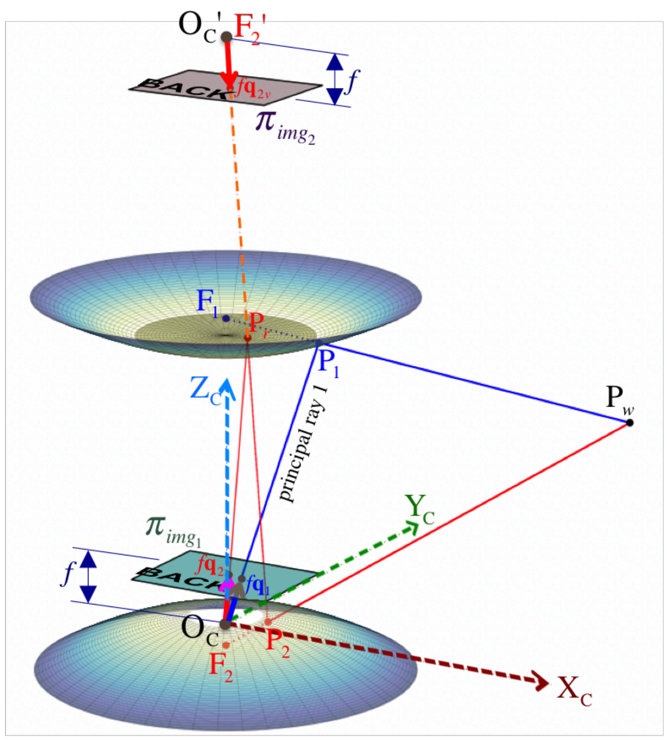


Fig. 4. Omnistereo projection of a 3D point P_w to obtain image points ${}^{[I]}\boldsymbol{m}_1$ and ${}^{[I]}\boldsymbol{m}_2$.

We derived and analyzed the expressions for the various system parameters, forward and back projective geometry, as well as a probabilistic error-tolerance model for depth sensing obtained via triangulation. After obtaining the respective pair of back-projected rays ${}^{[F1]}\mathrm{v}, {}^{[F2]}\mathrm{v}$, emanating from their respective physical viewpoints, F_1 and F_2, which are separated by baseline *b,* we compute elevation angles θ_1 and θ_2 in order to triangulate the back-projected rays and calculate the horizontal range ρ_W as

$$\rho_w = \left| \frac{b \cos(\theta_1)\cos(\theta_2)}{\sin(\theta_1 - \theta_2)} \right|$$

As shown in Fig. 4, we obtain the 3D position of P_W:

$$^{[C]}\mathbf{p}_w = \begin{bmatrix} -\rho_w \cos(\psi_{12}) \\ -\rho_w \sin(\psi_{12}) \\ c_1 - \rho_w \tan(\theta_1) \end{bmatrix}$$

In order to find point correspondences we employ algorithms, such as semi-global block matching (SGBM), among the pair of panoramic images ($[\Xi_1]$,$[\Xi_2]$) constructed from the omnidirectional image as shown in Fig 5.

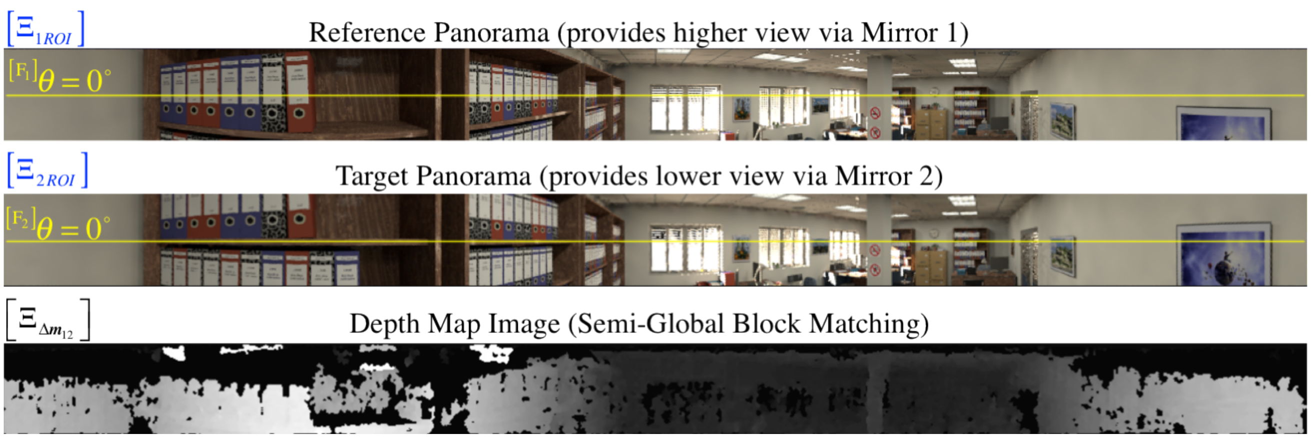
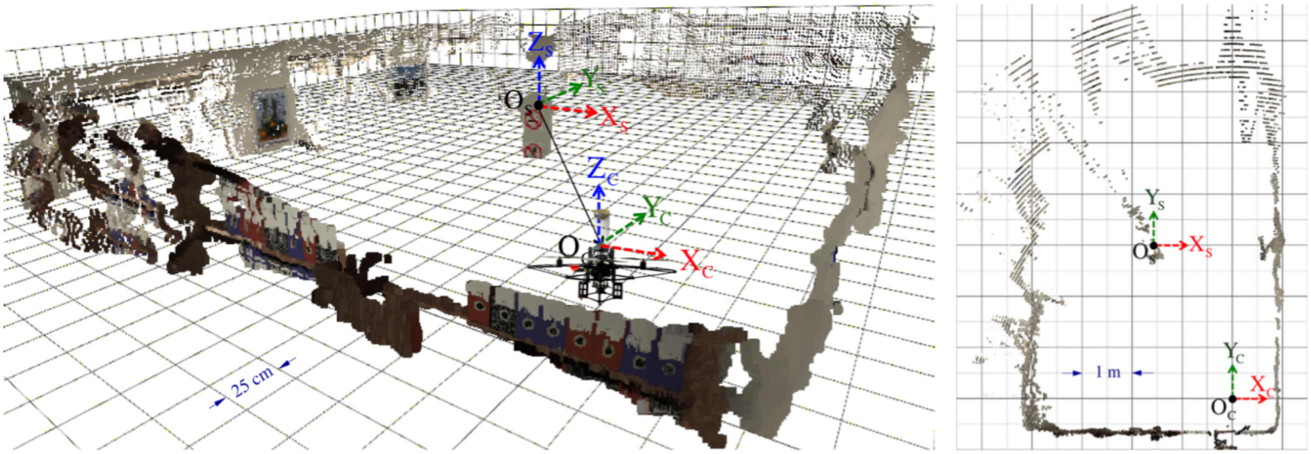


Fig. 5. The resulting disparity map, □ΞΔm bottom as a gray-scale panoramic image normalized about its 256 intensity levels, where brighter colors imply larger disparity values. To aid the relative vertical view of both panoramas, we have annotated the row position of the zero-elevation.

A 3-D dense point cloud computed out of a synthetic model rendered via POV-Ray simulating the rig's camera. Pixel correspondences are established via the panoramic depth map visualized in Fig. 6. The 3D point triangulation implements the aforementioned triangulation method. The position of the omnistereo sensor mounted on the quadrotor is annotated as frame [C] with respect to the scene's coordinates frame [S]. Fig. 6 shows the visualization of the point cloud generated from our sensor.

We believe this is the first thorough walkthrough on the design of a catadioptric omnistereo model aimed at MAVs autonomous navigation in 3D environments. The prototype and the 3D sensing algorithms are integrated with our current autonomous navigation framework.



(a) 3D Perspective View **(b)** Orthographic View

Fig. 6. (a) 3D visualization of the point cloud (the quadrotor with the omnistereo rig has been added for visualization only). (b) Orthographic projection of the point cloud to the XY-plane of the visualization grid

Since our omnidirectional stereo (omnistereo) views are captured by a single camera, a truly instantaneous pair of panoramic images is possible for 3D perception tasks. Finally, we address the VO problem as a direct multichannel tracking approach, which increases the pose estimation accuracy of the baseline method (i.e., using only grayscale or color information) under the photometric error minimization as the heart of the "direct" tracking algorithm.

B. State Estimation and Open Source Navigation System

One of the major difficulties with the development of an autonomous MAV is how to determine its pose/trajectory in GPS-denied environments. To tackle this problem, we have designed a state estimation and open source navigation system for MAVs that provides high frequency 9-state (6 degree-of-freedom pose and linear velocity) readings in unknown GPS-denied indoor environments. The system requires a minimal set of sensors including a planar laser range-finder (as shown in Fig. 7) and an inertial measurement unit (IMU) and uses scan matching to estimate the pose. We address the issues of autonomous control, state estimation, path-planning, teleoperation, and provide interfaces that allow the system to seamlessly integrate with existing ROS navigation tools for 2D SLAM and 3D mapping. All components run in real time onboard the MAV, with state estimation and control operating at 1 kHz. A major focus in our work is modularity and abstraction, allowing the system to be both flexible and hardware-independent. All the software and hardware components which we have developed, as well as documentation and test data, are available online [J paper].

Fig. 7 The City-Flyer quadrotor MAV equipped with a Hokuyo laser scanner

The complete system architecture is shown in Fig. 8, which is distributed between a ground station, onboard CPU, and onboard microcontrollers. The state estimation system reads the roll, pitch, and yaw angles of the MAV in the inertial frame, as well as the linear accelerations (a_x, a_y, a_z) in the body frame from the IMU sensor. During the scan projection step, laser data is orthogonally projected onto the horizontal x-y plane by using the roll and pitch angles of the last state. The projected data is then passed to a scan matcher, where the PL-ICP algorithm is employed which uses a point-to-line metric to solve the iterated corresponding point (ICP) problem to get a desired solution for the rigid transformation between two consecutive scans. The scan matcher employs a predictive scan matching method which uses the yaw angle reading from the IMU as an initial guess for the orientation of the MAV and achieves an update speed of 40 Hz onboard the MAV. The output of the scan matcher includes x, y, and yaw angle pose

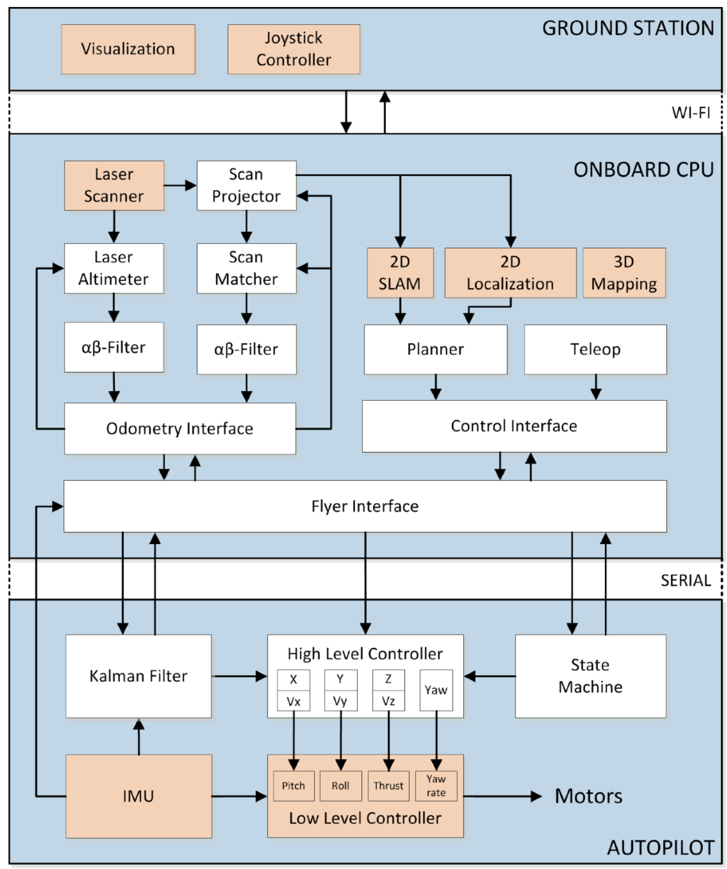


Fig. 8: Complete system block diagram. The system is distributed between an optional ground station, an onboard CPU, and Autopilot mictrocontroller. The onboard CPU calculates odometry, path planning, and SLAM. The autopilot micro-controller performs the 1KHz sensor fusion and control.

components. A laser altimeter uses a mirror to direct a portion of the horizontal laser scanner's beams downwards and uses the roll and pitch orientation of the MAV to estimate the altitude (z) of the vehicle. A histogram and threshold filters are applied to detect discontinuities on the floor. A rough estimate of the linear velocities is computed from the derivative of the position readings, and passed though an alpha-beta filter. The 9-dimention states (position, angles, and linear velocities) of the MAV are estimated at a rate of 40Hz, and fused together with IMU readings at a rate of 1Khz using a Kalman Filter. The Kalman Filter algorithm allows for external sensor updates to be provided, so the system can be extended beyond the laser sensor.

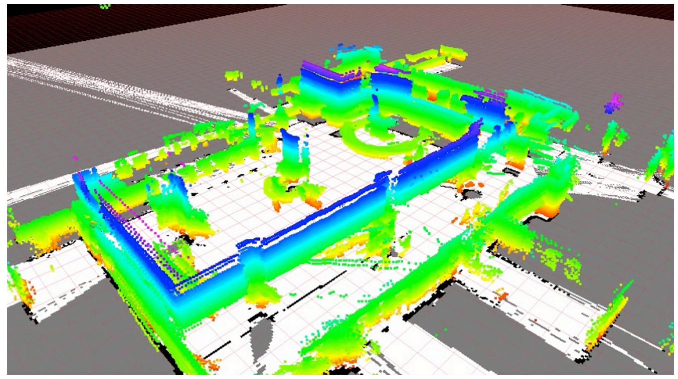


Fig. 9: 3D map of the Steinman Hall lobby at CCNY, generated by the quadrotor robot in the form of a height-colored point cloud.

We demonstrate that the navigation estimation system can be used to build 2D and 3D maps, comparable in accuracy to maps built using ground vehicles with odometric sensors (Fig. 9). We further demonstrate that we can provide easy and intuitive interactions between the MAV and the human operator for teleoperation and waypoint control. We have developed several open source software packages and published on ROS.org website (http://www.ros.org/wiki/ccny-ros-pkg), which include the flight control drivers, computer vision stacks for tracking markers, scanner tools, and ground station interface.

C. Fast Visual Odometry and 3D Mapping from RGB-D Data

The MAV is required to fly up and down to scan the environment using the planar laser range finder in order to construct 3D map. To overcome this limitation, we equipped the MAV with the RGB-D sensor for 3D mapping in indoor environments as shown in Fig. 10. An RGB-D sensor has wide field of view (FOV) and outputs the distances to objects in a scene in addition to their RGB color images. An RGB-D scan can be treated in two different ways: as a 3D point cloud, where each point has additional color information, or as 2D images. We can go back and forth between the two representations at any time. This redundancy is useful because we can exploit the structure of the data based on our needs.

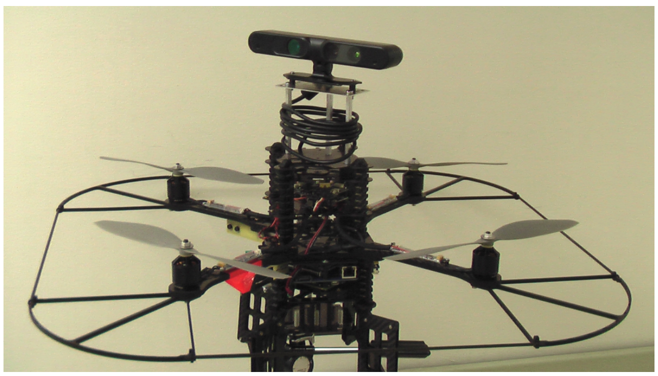
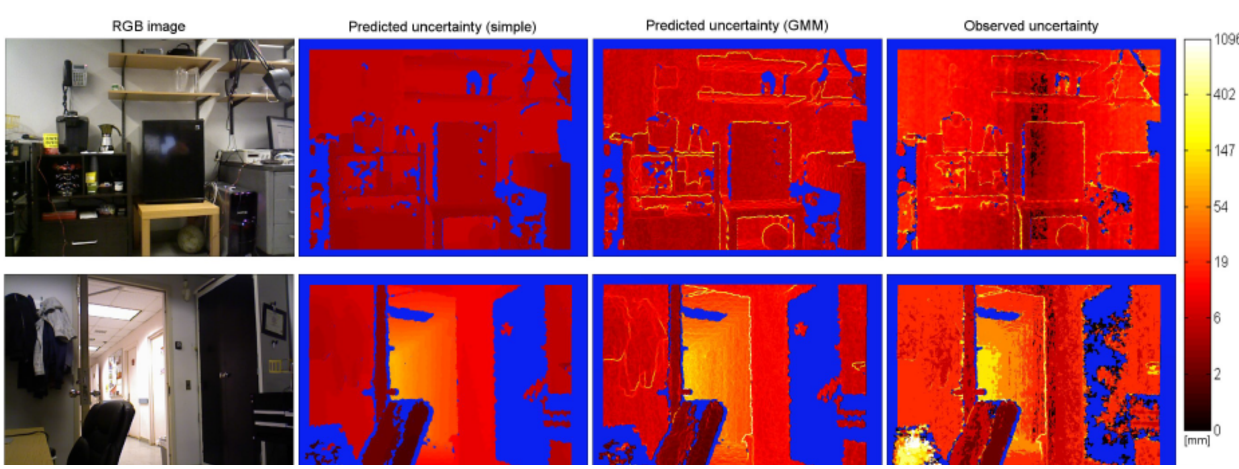


Fig. 10. The CityFlyer MAV equipped with an Asus Xtion Pro Live RGB-D

We have developed a visual odometry algorithm for estimating the trajectory of a moving RGB-D camera with applications to building maps of large indoor environments. The first problem we address is the measurement model of the RGB-D sensor. We present a calibration procedure capable of removing systematic errors in the depth readings of the camera, as well as a model for the random noise based on a mixture of Gaussians. The Gaussian mixture model is able to accurately capture the high uncertainty of the depth in problematic areas such as object edges. This Gaussian mixed distribution is modeled as following; first, we assume the locations of features detected by a sparse feature detector are subject to error, therefore, we allow for uncertainty in the *u* and *v* dimensions. Second, we assume that the depth uncertainty is dependent not only on the depth readings of a given pixel, but also on its neighbors in a local window. We show that using these assumptions, we can predict the magnitude of the depth uncertainty better



than the previously published model. The comparison is shown in Fig. 11.

Fig11. Uncertainty analysis for the depth readings of an RGB-D camera. Left: RGB image, shown for visualization only. Right: observed (ground truth) uncertainty, obtained by taking 200 depth images of a static scene and calculating the mean and standard deviation on a per-pixel basis. Color is scaled as the log of the uncertainty. Center-left: uncertainty predicted from a single depth image, according to the simple model. Center-right: uncertainty predicted from the same depth image, according to the Gaussian mixture model. We demonstrate the Gaussian model uncertainty predicts the true uncertainty more accurately, especially around object edges.

Next, we develop a visual odometry pipeline as shown in Fig. 12, which recovers the unconstrained 6-DoF trajectory of the moving camera by aligning sparse features observed in the current RGB-D image against a model of previously seen features.

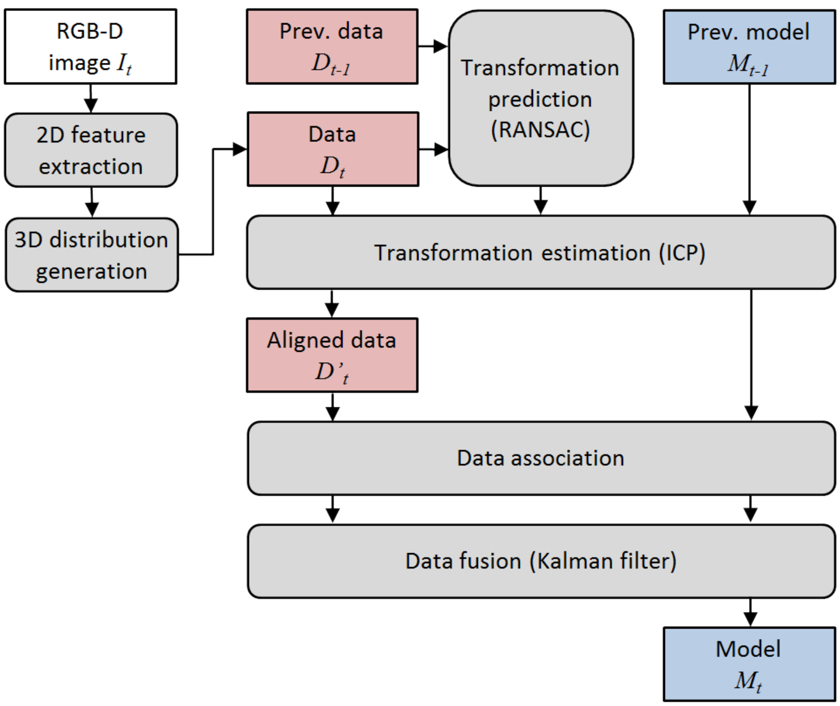


Fig. 12. Pipeline for the trajectory estimation. We align sparse feature data from the current RGB-D frame to a persistent model. The data is represented by 3D points with covariance matrices.

The trajectory estimation begins with extracting sparse features in each incoming RGB-D image I_t. The features are detected on the intensity channel of the RGB image. We have experimented with several choices of feature detectors, including SURF, ORB, and Shi-Tomasi keypoints, and found that the Shi-Tomasi features offer the best trade-off between robustness and computational speed.

According to the Gaussian uncertainty equations, we generate a set of the 3D features as Gaussian normal distribution, with each feature $d = \{\mu^{[D]}, \Sigma^{[D]}\}$ has a mean and covariance matrix. The D set is expressed in the camera reference frame. We have a similar model set of 3D features, $M_t = \{m_j\}$ with $m = \{\mu^{[M]}, \Sigma^{[M]}\}$ expressed in the fixed frame of reference. The D set needs to be aligned to the M set. This happens in 2 steps. First, we align D_t to D_{t-1} using a 3-point RANSAC transformation estimation. The feature correspondences between the two frames are established using feature matching with ORB descriptors, computed on the Shi-Tomasi corners. This step eliminates any outlier features. Next, we align D_t to the previous model M_{t-1}, using the transformation estimated by RANSAC as a prediction to do Iterative Closest Points (ICP)

Next, we align these features against a global model dataset of 3D features, expressed in the fixed coordinate frame. Aligning is performed with the ICP algorithm. After calculating the transformation, the model is augmented with the new data. We associate features from the RGB-D image with features in the model, and update them using a Kalman Filter framework. Any features from the image which cannot be associated are inserted as new landmarks in the model set. The model (which starts out empty) gradually grows in size as new data is accumulated.

The model is persistent and dynamically updated from new observations using a Kalman filter. The visual odometry runs at frequencies of 30Hz and higher, on VGA images, in a single thread on a desktop CPU with no GPU acceleration required. Compared to state-of-the-art methods, this achieves a significant increase in performance, for a small trade-off in accuracy.

Finally, we examine the problem of place recognition from RGB-D images, in order to form a pose-graph SLAM approach to refining the trajectory and closing loops. We evaluate the effectiveness of the system on multiple datasets, including publicly available trajectories with ground-truth data. The entire system is available for free and open-source online.

By performing alignment against a persistent model instead of only the last frame, we are able to achieve significant decrease in the drift of the pose estimation. We show that even with a small model size, we can accurately map out an environment the size of a room or office, and accurately close the loop without the need of any additional backend processing techniques typically associated with V-SLAM algorithms. as shown in Figure 13.

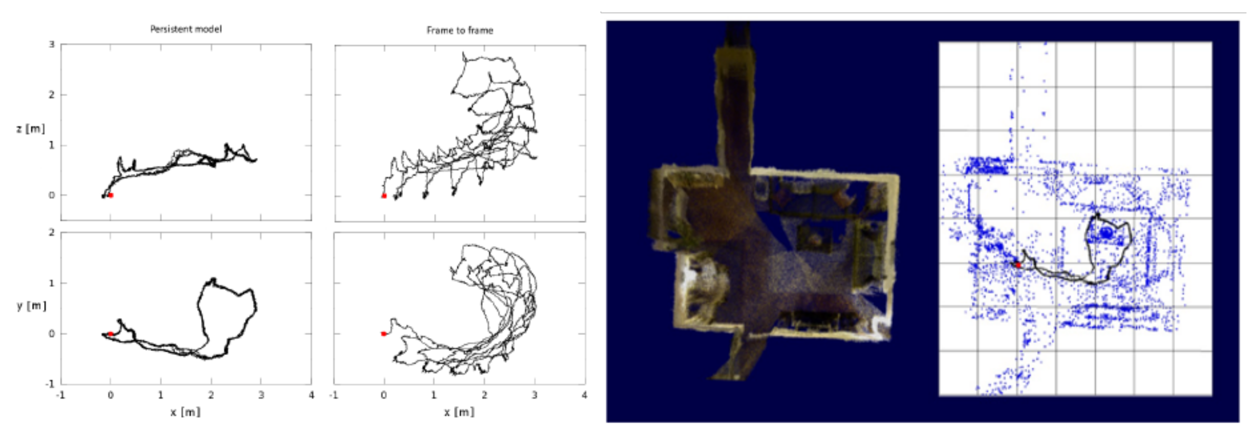


Figure 13. Left: Comparison of trajectory estimation with persistent model (left) vs frame-to-frame ICP (right). The trajectory shown consists of 5 repeated loops, with approximately 2000 images processed in each loop.
Right: orthographic view of the dense 3D map (left), as well as the final Model set (right).

D. Quaternion-based orientation estimation of low-cost IMU with application to MAV Control

In the field of orientation estimation using low-cost Inertial/Magnetic sensors we developed an estimation of the orientation in quaternion form from the observations of gravity and magnetic field. At the best of our knowledge, our approach is the first to provide quaternion estimation as the closed form solution of a system from inertial/magnetic observations. We separate the problems of finding the tilt quaternion and the heading quaternion in two sub-parts of our system. This procedure is the key for avoiding the impact of the magnetic disturbances on the roll and pitch components of the orientation when the sensor is surrounded by unwanted magnetic flux. Given the representation of the acceleration vector in the body-frame (measured by the accelerometer) and in the global frame (known as gravity vector) we can mathematically found a solution of a system that satisfies the transformation between the two frames.
This solution is the quaternion (q_{acc}) which holds useful information about the roll and pitch with unknown yaw. Then we use q_{acc} to rotate the body-frame magnetic field vector (measured by the magnetometer) into an intermediate frame whose z-axis is the same as the global coordinate frame with orthogonal x-, y- axis pointing in unknown directions due to the unknown yaw of q_{acc}. Next, we find the quaternion (q_{mag}) which rotates the "intermediate" vector into a vector which x-component is aligned with the earth north pole. Note that the latter rotation occurs only around the global z-axis. Finally, the quaternion multiplication between q_{acc} and q_{mag} will result in a quaternion representing the total orientation of the global-frame with respect to the body frame.
Furthermore, we use the above method to fuse together gyroscope data with accelerometer and magnetic field readings in a novel complementary filter. The correction part of the filter is based on the method described above and works for both IMU (Inertial Measurement Unit) and MARG (Magnetic, Angular Rate and Gravity) sensors. We evaluate the effectiveness of the filter and show that it significantly outperforms other common methods, using publicly available datasets with ground-truth data, recorded during real flight experiment of a micro quadrotor helicopter. Table I, II and III compare the RMS error of the output of our complementary filter, in Euler representation, with the output of other common techniques using the datasets mentioned above.

TABLE I: RMS roll angle error [radians]

Dataset	Proposed	Madgwick	AscTec
1LoopDown	0.0233	0.0370	0.0464
2LoopsDown	0.0292	0.0470	0.0338
3LoopsDown	0.0277	0.0405	0.0315

TABLE II: RMS pitch angle error [radians]

Dataset	Proposed	Madgwick	AscTec
1LoopDown	0.0209	0.0336	0.0369
2LoopsDown	0.0223	0.0369	0.0313
3LoopsDown	0.0202	0.0360	0.0329

TABLE III: RMS yaw angle error [radians]

Dataset	Proposed	Madgwick	AscTec
1LoopDown	0.1429	0.2543	0.3388
2LoopsDown	0.1309	0.9229	0.3182
3LoopsDown	0.2890	1.3327	0.3255

The presented algorithm offers several advantages over other implementations:

- Fast initialization in quaternion form allowing any starting configuration.
- Fast convergence of the orientation quaternion due to the analytical formulation of the correction quaternions.
- Two different gains to separately filter acceleration and magnetic field noises.

- Magnetic distortion compensation which involves a two-fold advantage: avoids the impact of the magnetic disturbances on the roll and pitch components of the orientation when the sensor is
- surrounded by unwanted magnetic flux and eliminates the need of a predefined magnetic field direction.

Moreover, our algorithm does not compute any matrix inversion or matrix multiplication, maintaining a low computational cost making it suitable for on-board implementation.

E. 3D Scene Reconstruction with Micro-Aerial Vehicles and Mobile Devices

Scene reconstruction is the process of building an accurate geometric model of one's environment from sensor data. We explore the problem of real-time, large-scale 3D scene reconstruction in indoor environments using small laser range-finders and low-cost RGB-D (color plus depth) cameras. We focus on computationally-constrained platforms such as micro-aerial vehicles (MAVs) and mobile devices. These platforms present a set of fundamental challenges - estimating the state and trajectory of the device as it moves within its environment and utilizing lightweight, dynamic data structures to hold the representation of the reconstructed scene. The system needs to be computationally and memory-efficient, so that it can run in real time, onboard the platform.

We present three scene reconstruction systems. The first system uses a laser range-finder and operates onboard a quadrotor MAV. We address the issues of autonomous control, state estimation, path planning, and teleoperation. We propose the multi-volume occupancy grid (MVOG) - a novel data structure for building 3D maps from laser data, which provides a compact, probabilistic scene representation.

The second system uses an RGB-D camera to recover the 6-DoF trajectory of the platform by aligning sparse features observed in the current RGB-D image against a model of previously seen features. We discuss our work on camera calibration and the depth measurement model. We apply the system onboard an MAV to produce occupancy-based 3D maps, which we utilize for path planning.

Finally, we present our contributions to a scene reconstruction system for mobile devices with built-in depth sensing and motion-tracking capabilities. We demonstrate reconstructing and rendering a global mesh on the fly, using only the mobile device's CPU, in very large (300 square meter) scenes, at a resolutions of 2-3cm. To achieve this, we divide the scene into spatial volumes indexed by a hash map. Each volume contains the truncated signed distance function for that area of space, as well as the mesh segment derived from the distance function. This approach allows us to focus computational and memory resources only in areas of the scene which are currently observed, as well as leverage parallelization techniques for multi-core processing. Our experiments demonstrated that UAV equipped with the mobile device can perform the 3D scene re-construction in real-time.

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F. Computer Vision Research for Scene Understanding:

1. Text Extraction for Scene Understanding

We continue focus on developing new algorithms to detect text information from natural scene images. Our method combines scene text detection and scene text recognition algorithms. Fig. 1 presents a flowchart of scene text extraction method. By the character recognizer, text understanding is able to provide surrounding text information, and by the character classifier of each character category, text retrieval is able to help search for expect objects from environment. Similar to other methods, our proposed feature representation is based on the state-of-the-art low-level feature descriptors and coding/pooling schemes. Different from other methods, our method combines the low-level feature descriptors with stroke configuration to model text character structure. Also, we present the respective concepts of text understanding and text retrieval and evaluate our proposed character feature representation based on the two schemes in our experiments.

We propose a novel character descriptor to model character structure for effective character recognition. Fig. 2 depicts the flowchart of our proposed character descriptor. We design two character recognition schemes. In text understanding, character recognition is a multi-class classification problem. We train a character recognizer to classify the 62 classes of characters. In text retrieval, character recognition is a binary classification problem. For each of the 62 character classes, we train a binary classifier to distinguish a character class from the other classes or non-text outliers. For example, we train a binary classifier for character class ‘A’, then this classifier will predict a patch containing ‘A’ as positive, and predict a patch containing other character classes or non-text outliers as negative. The specified character classes are defined as queried characters. In both schemes, a robust character descriptor is required to extract structure features from character patches. In text retrieval, to better model character structure, we define stroke configuration for each character class based on specific partitions of character boundary and skeleton. We employ four types of keypoint detectors, Harris detector (HD) to extract keypoints from corners and junctions, MSER detector (MD) to extract keypoints from stroke components, Dense detector (DD) to uniformly extract keypoints, and Random detector (RD) to extract the preset number of keypoints in a random pattern.

We use accuracy rate (AR) as evaluation measure, which is defined as the ratio between the number of correctly recognized text characters and the total number of text characters. Table I presents the AR of our proposed character descriptor in Chars74K dataset by integrating BOW-based and GMM-based feature representations. Table II presents the AR of our proposed character descriptor in ICDAR-2003 dataset. The experimental results in Tables I & II demonstrate that our proposed descriptor outperforms the existing methods.

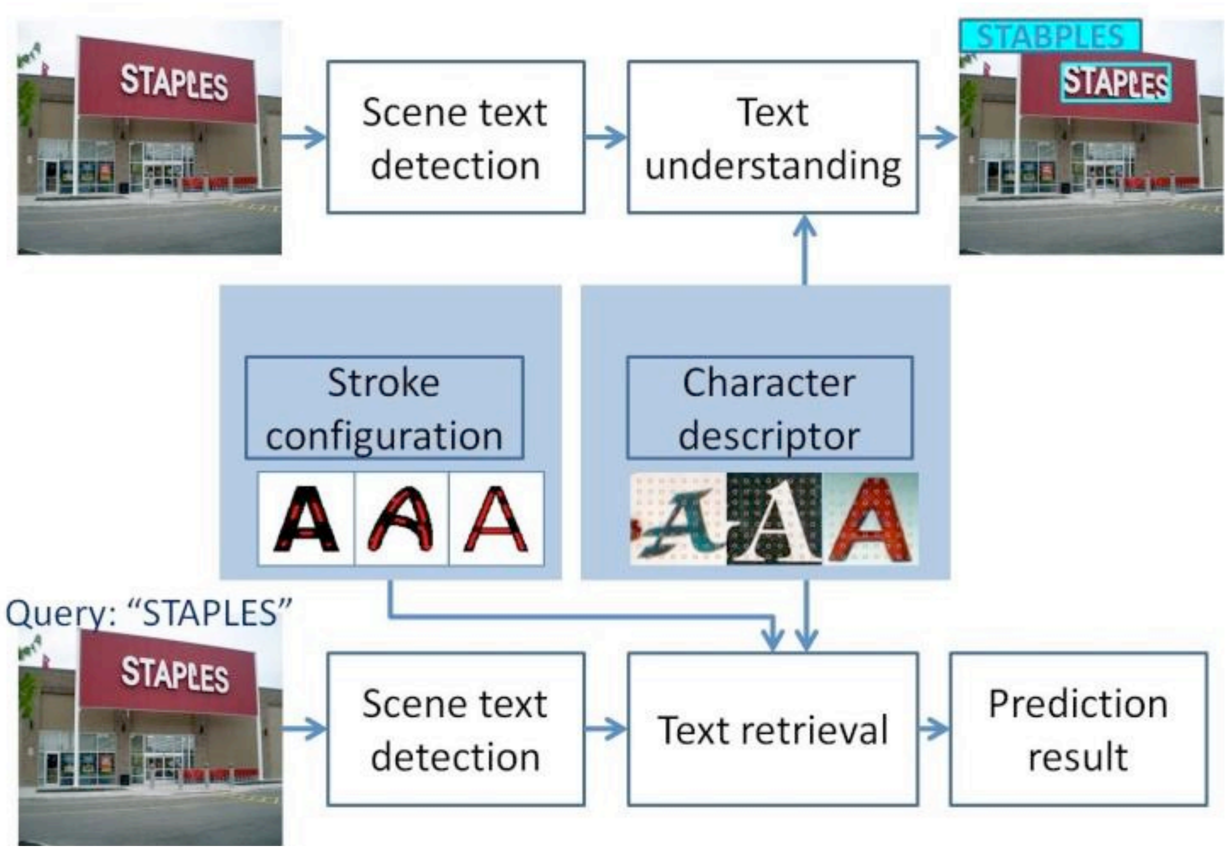

Figure 1. The flowchart of our designed scene text extraction method: text understanding and text retrieval. It includes scene text detection and two scene text recognition schemes. In recognition, character descriptor and stroke configuration are designed to model character structure and compute discriminative character features.

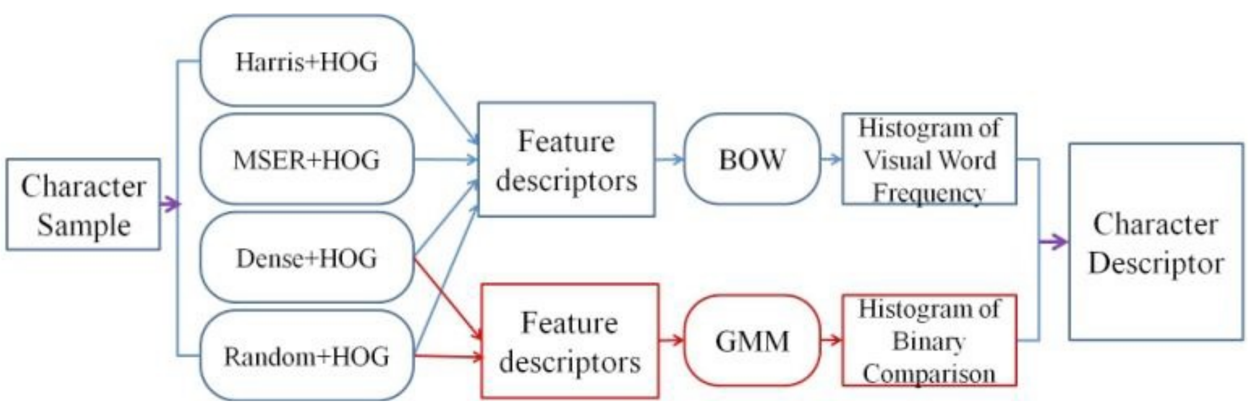

Figure 2. Flowchart of our proposed character descriptor, which combines four keypoint detectors, and HOG features are extracted at keypoints. Then BOW and GMM are employed to respectively obtain visual word histogram and binary comparison histogram.

TABLE I: ACCURACY RATES OF SCENE CHARACTER RECOGNITION IN CHARS74K DATASET, COMPARED WITH THE STATE OF THE ART RESULTS

Chars74K Dataset	AR
Ours	0.60
Ours (BOW-based representation only)	0.53
Ours (GMM-based representation only)	0.47
ABBYY	0.31
HOG+NN	0.58
SYNTH+FERNS	0.47
NATIVE+FERNS	0.54
MKL	0.55

TABLE II: ACCURACY RATES OF SCENE CHARACTER RECOGNITION IN ICDAR-2003 DATASET, COMPARED WITH PREVIOUSLY PUBLISHED RESULTS.

ICDAR-2003 Dataset	AR
Ours	0.628
HOG+NN	0.515
SYNTH+FERNS	0.520
NATIVE+FERNS	0.640

NN: Nearest neighbor; SYNTH: synchronic character patch for training for training; NATIVE: Nature scene characters for training; FERNS: Random ferns algorithm; MKL: Multiple-kernel learning

2. Scene Recognition

As shown in Figure 3, we propose a Pyramid of Spatial Relatons (PSR) model to capture both absolute and relative spatial relationship of local features to effectively incorporate spatial information into the BOW model for the scene classification,. Unlike the conventional co-occurrence approach to describe pairwise spatial relationships between local features, the PSR model employs a novel concept of spatial relaton to describe relative spatial relationship of a group of local features. As the result, the storage cost of the PSR model only linearly increases with the visual word codebook size instead of the quadratic relationship as in the co-occurrence approach. The PSR model is robust to translation and rotation variations, and demonstrates excellent performance for the application of remotely sensed land use classification.

The proposed method is evaluated on the Land Use and Land Cover image database. The Land Use or Land Cover (LULC) dataset [42] is one of the largest geographical image databases with ground truth, which are publically available. The images are downloaded from the United States Geographical Survey (USGS) national map. There are total of 21 categories, including agricultural, beach, buildings, chaparral, dense residential, and forest etc. Sample geographical images of each land use category are shown in the Figure 4. Each class has 100 images with same size, i.e., 256 by 256 pixels. The pixel resolutions of all images are 30cm per pixel. As shown in Figure 5, our method achieves 8% higher in the classification accuracy than the state of the art. If using only gray images, it outperforms the state of the art by more than 11%.

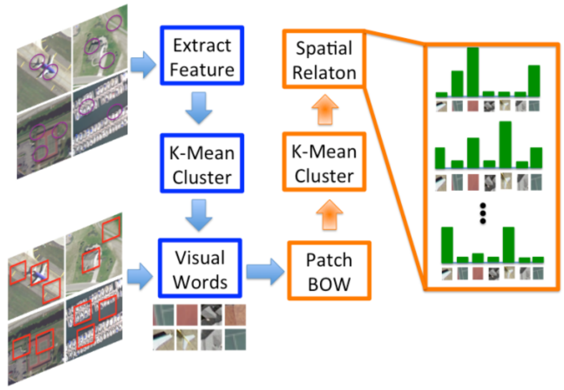

Figure 3: Illustrate the flowchart to generate a dictionary of spatial relatons.

Figure 4: Sample geographical images from each of 21 categories in the Land Use or Land Cover (LULC) database.

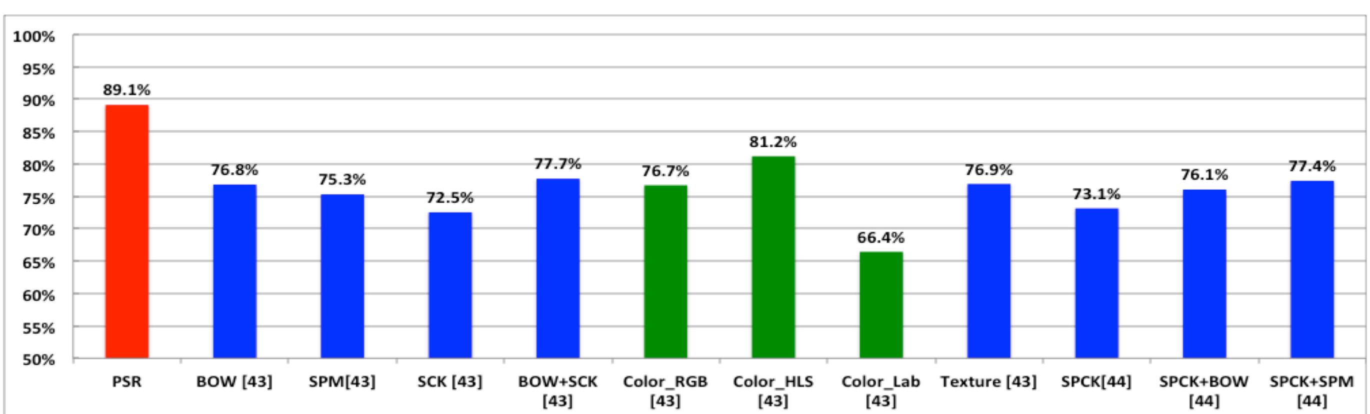

Figure 5: Compare the Pyramid of Spatial Relatons (PSR) with the state of the art performance reported in the literature on the LULC database. The blue bars are the performance based on gray images. The green bars are based on color images. The performance reported in the PSR is only based on gray images.

3. Recognition of Stairs, Pedestrian Crosswalks, and Traffic Signs

As shown in Figure 6, we develop a new framework to detect and recognize stairs, pedestrian crosswalks, and traffic signals based on RGB-D (Red, Green, Blue, and Depth) images. Since both stairs and pedestrian crosswalks are featured by a group of parallel lines, we first apply Hough transform to extract the concurrent parallel lines based on the RGB (Red, Green, and Blue) channels. Then, the Depth channel is employed to recognize pedestrian crosswalks and stairs. The detected stairs are further identified as stairs going up (upstairs) and stairs going down (downstairs). The distance between the camera and stairs is also estimated for blind users. Furthermore, the traffic signs of pedestrian crosswalks are recognized. The detection and recognition results on our collected datasets demonstrate the effectiveness and efficiency of our proposed framework. Some results are displayed in Tables 3, 4 and Figure 7.

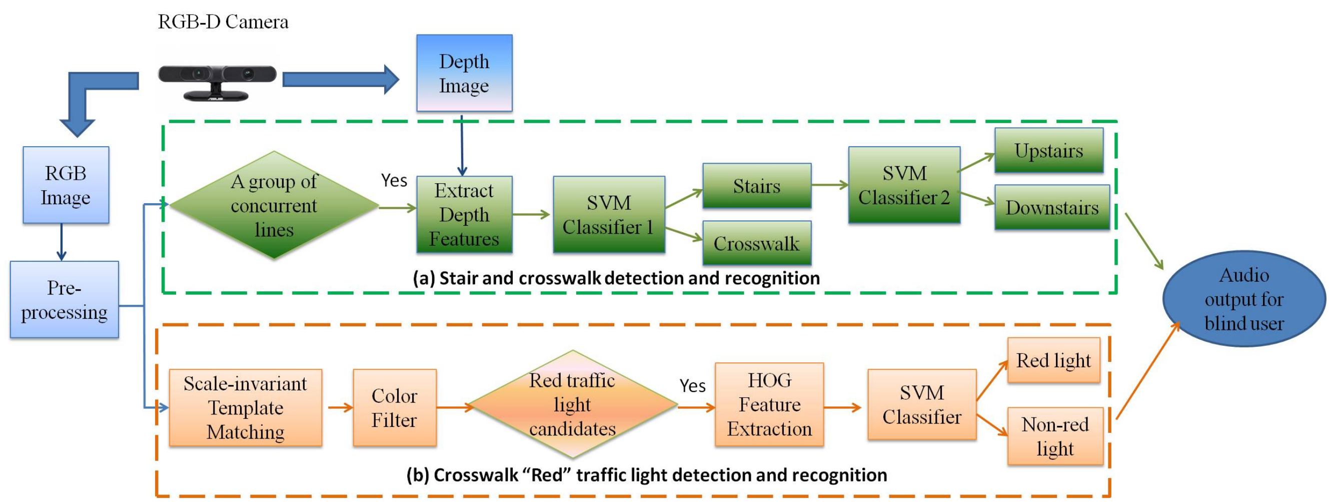

Figure 6. Flowchart of the proposed algorithm for stair, pedestrian crosswalk, and crosswalk "*Red*" traffic sign detection and recognition.

Table 3. Detection accuracy of stairs and pedestrian crosswalks

Classes	No. of Samples	Correctly Detected	Missed	Detection Accuracy
Stairs	106	103	3	97.2%
Crosswalks	52	41	11	78.9%
Negative samples	70	70	0	100%
Total	**228**	**214**	**14**	**93.9%**

Table 4. Detection and recognition accuracy of "*red*" and "*non-red*" crosswalk traffic signs

Classes	No. of Samples	Correctly Detected & Recognized	Accuracy
Red	80	74	92.50%

Non-red	102	99	97.06%
Total	**182**	**173**	**95.05%**

Figure 7. Example results of our proposed method of "*red*" crosswalk traffic sign recognition (marked in red boxes).

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