Siddharth Choudhary

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Research Interests

Computer Vision, Robotics, Machine Learning, High Performance Computing

Education

Georgia Institute of Technology, Atlanta, Georgia USA

Ph.D., Computer Science, August 2017

- Dissertation Topic: "Distributed Object based SLAM"
- Advisors: Professor Henrik I. Christensen, Professor Frank Dellaert

IIIT Hyderabad, Hyderabad, India

M.S. (By Research), Computer Science, August 2012

- Dissertation Topic: "Improving the Efficiency of SfM and its Applications"
- Advisor: Professor P J Narayanan

IIIT Hyderabad, Hyderabad, India

B.S., Computer Science (with Honours), August 2010

Honors and Awards

Recipient of National Science Foundation travel grants to attend international conferences like ICRA 2016, IROS 2015, ICRA 2015, IROS 2014 and IPAM Computer Vision Summer School 2013.

Recipient of CS 7001 Research Project Award for Fall 2012.

Recipient of Undergraduate Research Award for the year 2009-2010 and 2010-2011.

Included in the Deans List for the year 2007-2008 at IIIT Hyderabad.

Academic Experience

Georgia Institute of Technology, Atlanta, GA USA

Graduate Research Assistant **08/20/2012 - 08/05/2017**

Includes Ph.D. level research in multiple projects sponsored by the Army Research Lab and the Institute of Robotics and Intelligent Machines. Mentored multiple graduate students working towards their research thesis.

During the Ph.D, I primarily worked on a problem where a team of robots is deployed in an unknown environment and it has to collaboratively build a map of the area without a reliable infrastructure for communication. This work was sponsored through the US Army Research Labs Micro Autonomous Systems and Technology (MAST) Collaborative Technological Alliance (CTA) program.

To solve this problem I did research and development of techniques for distributed semantic SLAM (simultaneous localization and mapping) that allows each robot or mobile device to build its own semantic map while asking for minimal knowledge of the map of the teammates due to bandwidth constraints (in areas without a reliable infrastructure for communication).

The use of multiple cooperative robots or mobile devices has the potential to enable fast information gathering, and more efficient coverage and monitoring of large areas. In particular, distributed SLAM, i.e., the cooperative construction of a model of the environment explored by the robots or mobile devices, is fundamental to geotag sensor data (e.g., for pollution monitoring, surveillance and search and rescue), and to gather situational awareness. For military applications, multi-robot

systems promise more efficient operation and improved robustness to adversarial attacks. In civil applications (e.g., pollution monitoring, surveillance, search and rescue), the use of several inexpensive, heterogeneous, agile platforms is an appealing alternative to monolithic single robot systems.

For my thesis, I designed and developed a technique that allows each robot or mobile device to build its own object level map while asking for minimal knowledge of the map of the teammates. In particular, I made the following three major contributions:

- I researched and developed a distributed algorithm based on Distributed Gauss-Seidel to estimate the 3D trajectories of multiple cooperative robots from relative pose measurements. This approach has several advantages. It requires minimal information exchange, which is beneficial in the presence of communication and privacy constraints. It has an anytime flavor: after few iterations, the trajectory estimates are already accurate, and they asymptotically convergence to the centralized estimate. The DGS approach scales well to large teams of uptown 50 robots, is resistant to noise and it has a straightforward implementation. We test the approach in simulations and field tests, demonstrating its advantages over related techniques.
- I researched and developed an approach for distributed SLAM which uses object landmarks in a distributed mapping framework. I showed that this approach further reduces the information exchange among robots (as compared to feature based DGS), results in a compact, human understandable map, and has lower computational complexity as compared to low-level feature based distributed mapping.
- Finally, I extended the previous work to the case where object models are previously unknown and are modeled jointly with Distributed Object-based SLAM. I showed that this approach further reduces the memory required to store the object models while maintaining the accuracy at the same level as the state of art RGB-D mapping approaches.

The resulting research work was published and presented as a part of leading international robotics conferences and journals like IEEE International Conference on Robotics and Automation (ICRA), IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), International Symposium on Experimental Robotics (ISER) and the International Journal of Robotics Research (IJRR). This work culminated with a live demonstration in a military facility as a part of the US Army Research Lab's Micro Autonomous Systems and Technology (MAST) Capstone demo.

Teaching Assistant **01/01/2015 - 04/01/2015**
Co-taught undergraduate level course for the Introduction to Robotics and Perception course. Shared responsibility for lectures, exams, homework assignments, and grades.

- CS-3630 Introduction to Robotics and Perception, Spring 2015.

Teaching Assistant **01/01/2016 - 04/01/2016**
Co-taught graduate level course for the Pattern Recognition course. Shared responsibility for lectures, exams, homework assignments, and grades.

- CS-7616 Pattern Recognition, Spring 2016.

IIIT Hyderabad, Hyderabad, India

Research Assistant **08/01/2009 - 08/01/2012**
Includes Masters level research in multiple projects sponsored by the Government of India.

I primarily worked on research and development of technique to improve to the efficiency of structure from motion algorithms.

The first algorithm that I focused on is the problem of image localization and feature triangulation. Image localization is the problem of estimating the camera pose given a query image and a 3D reconstructed model of the world. Feature triangulation is the problem of estimating the 3D coordinates of a given 2D point in the image. In order to improve the efficiency of image local-

ization, I encoded the visibility information between and among points and cameras created using structure from motion as visibility probabilities. The conditional visibility probability of a set of points on a point (or a set of cameras on a camera) can be used to select points (or cameras) based on their dependence or independence. I used it to efficiently solve the problems of image localization and feature triangulation. I showed how the conditional probability can be combined with other measures to prioritize a set of points (or cameras) for matching and use it for fast guided search of points for the image localization problem. I also defined the problem of feature triangulation as the estimation of 3D coordinate of a given 2D feature using the SfM data. This approach can guide the search to quickly identify a subset of cameras in which the feature is visible.

Other than image localization and feature triangulation, bundle adjustment is a key component of the structure from motion pipeline and often its slowest and the most computational resource intensive. It hasnt been parallelized effectively so far. I also a developed a hybrid implementation of sparse bundle adjustment on the GPU (graphics processing unit) using CUDA (Compute Unified Device Architecture), with the CPU (central processing unit) working in parallel. The algorithm is decomposed into smaller steps, each of which is scheduled on the GPU or the CPU. I developed efficient kernels for the steps and make use of existing libraries for several steps. My implementation outperforms the CPU implementation significantly, achieving a speedup of 30-40 times over the standard CPU implementation for datasets with upto 500 images on an Nvidia Tesla C2050 GPU.

The research done during this time was published and presented as a part of the European Conference on Computer Vision (ECCV) in 2010 and 2012 and The Eighth Indian Conference on Vision, Graphics and Image Processing (ICVGIP) in 2012.

Teaching Assistant **08/01/2009 - 12/01/2009**
Co-taught undergraduate level course for the Information Technology workshop teaching basics of scripting languates and linux OS.

- CS-3001 IT Workshop I, Fall 2009.

Industrial Experience

Magic Leap, Sunnyvale CA
Lead Computer Vision Researcher/Engineer **09/01/2018 - Present**

- Lead Architect and Developer for **3D Object Recognition feature** deployed in ML-19. The pipeline was designed and built from scratch.
- Object Recognition algorithm is scalable in a large number of concurrent users, number of objects or size of map while maintaining a lower memory footprint.
- Led the team through research and development phase to deliver Object Recognition for ML19 OTA 1.
- Collaborated across other teams like Data, Cloud and Deep Learning teams to build evaluation and visualization tools.
- Object Recognition is a key feature for ML19 and one of the most requested feature for ML2 from developer feedback.
- Research paper is under submission at CVPR 2020 Workshop on AR/VR. Patent filed as well.

Senior Computer Vision Researcher/Engineer **10/09/2017 - 09/01/2018**

- **Learned Keyframe Selection**: Designed and implemented a PointNet based neural network which learns a frame embedding given sparse feature descriptors to improve retrieval for localization. Improved the localization recall with respect to Bag of Words algorithm by 10-30% while reducing the memory requirement to store each keyframe by 75%. Optimized the network resulting in similar computational requirement as Bag of Words. Patent pending.

- **Cross Reality System**: Worked on improving cloud based and on-device localization using learned keyframe selection and improved 3D-2D correspondence estimation. Involved in the algorithm development of cloud based and on-device localization system. Patent Pending.
- **Scalable Infrastructure for SLAM Research**: Designed and implemented a scalable infrastructure to extract data from various stages in the SLAM pipeline along with ground-truth. This enabled scalable training and evaluation of various SLAM related machine learning algorithms.

Fyusion Inc., San Francisco CA

Research Intern **06/01/2016 - 08/21/2016**

- Research and development of algorithm to estimate the trajectory and stabilize loopy fyuses using factor graphs.
- Developed loop closure algorithm to handle loopy fyuses.

Point Cloud Library, CA

Summer of Code Scholar **05/01/2011 - 08/01/2011**

- Developed a generic interface for all the search functions in Point Cloud Library
- Developed a fast Octree implementation on GPU.

DrishtiCare, Hyderabad, India

Research Intern **05/01/2010 - 08/01/2010**

Research and development of medical image analysis algorithms for early detection of Diabetic Retinopathy.

PUBLICATIONS (UNDER REVIEW)

S. Choudhary, S. Mahendran et al. Multiuser, Scalable 3D Object Detection in the AR Cloud. In CVPR Workshop on Computer Vision for AR/VR, Seattle, WA, June 15, 2020.

PUBLICATIONS (PEER REVIEWED)

T. Cieslewski, S. Choudhary, D. Scaramuzza. Minimizing Data Exchange in Decentralized Visual SLAM. IEEE International Conference on Robotics and Automation Workshop on Robot Teammates Operating in Dynamic, Unstructured Environments (RT-DUNE), Brisbane, Australia, May 21-25, 2018.

T. Cieslewski, S. Choudhary, D. Scaramuzza. Data-Efficient Decentralized Visual SLAM. IEEE International Conference on Robotics and Automation, Brisbane, Australia, May 21-25, 2018. pp: 2466-2473

S.Choudhary. Distributed Object based SLAM. Ph.D. Thesis. Georgia Institute of Technology. August 2017. uri: http://hdl.handle.net/1853/59177

S. Choudhary, L. Carlone, C. Nieto, J. Rogers, H. I. Christensen, F. Dellaert. Distributed Mapping with Privacy and Communication Constraints: Lightweight Algorithms and Object-based Models. The International Journal of Robotics Research 2017. vol: 36-12. pp: 1286-1311.

S. Choudhary, L. Carlone, C. Nieto, J. Rogers, H. I. Christensen, F. Dellaert. Distributed trajectory estimation with privacy and communication constraints: A two-stage distributed Gauss-Seidel approach. IEEE International Conference on Robotics and Automation 2016, Stockholm, Sweden, May 16-21, 2016. pp: 5261-5268

V. Murali, C. Nieto, S. Choudhary, H. I. Christensen. Active planning based extrinsic calibration of exteroceptive sensors in unknown environments. IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2016, Daejeon, South Korea, October 9-14, 2016. pp: 2498-2505

S. Choudhary, L. Carlone, C. Nieto, J. Rogers, Z. Liu, H. I. Christensen, F. Dellaert. Multi Robot Object-Based SLAM. International Symposium on Experimental Robotics, ISER 2016, Tokyo, Japan, October 3-6, 2016. pp: 729-741

S. Choudhary, V. Indelman, H. I. Christensen, F. Dellaert. Information based Reduced Landmark SLAM. IEEE International Conference on Robotics and Automation, ICRA 2015, Seattle, WA, USA, 26-30 May, 2015. pp: 4620-4627

S. Choudhary, L. Carlone, C. Nieto, J. Rogers, Z. Liu, H. I. Christensen, F. Dellaert. Exactly sparse memory efficient SLAM using the multi-block alternating direction method of multipliers. 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2015, Hamburg, Germany, September 28 - October 2, 2015. pp: 1349-1356

C. Nieto, S. Choudhary, J. G. Rogers, J. Twigg, V. Murali, H. I. Christensen. Object guided autonomous exploration for mobile robots in indoor environments. Proc. SPIE 9084 Unmanned Systems Technology XVI. 2014. International Society for Optics and Photonics

S. Choudhary, A.J.B. Trevor, H. I. Christensen, F. Dellaert. SLAM with object discovery, modeling and mapping. 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, USA, September 14-18, 2014. pp: 1018-1025

S. Choudhary. Improving the Efficiency of SfM and its Applications. Masters Thesis. July 2012. uri: `http://web2py.iiit.ac.in/research_centres/publications/view_publication/mastersthesis/147`

K. Kothapalli, D. S. Banerjee, P. J. Narayanan, S. Sood, A. K. Bahl, S. Sharma, S. Lad, K. K. Singh, K. K. Matam, S. Bharadwaj, R. Nigam, P. Sakurikar, A. Deshpande, I. Misra, S. Choudhary, S. Gupta. CPU and/or GPU: Revisiting the GPU Vs. CPU Myth. CoRR 2013. vol: abs/1303.2171

S. Choudhary, P. J. Narayanan. Visibility Probability Structure from SfM Datasets and Applications. 12th European Conference on Computer Vision, Florence, Italy, October 7-13, 2012. pp: 130-143

A. Deshpande, S. Choudhary, P. J. Narayanan, K. K. Singh, K. Kundu, A. Singh, A. Kumar Geometry directed browser for personal photographs. The Eighth Indian Conference on Vision, Graphics and Image Processing, ICVGIP '12, Mumbai, India, December 16-19, 2012

S. Choudhary, S. Gupta, P. J. Narayanan. Practical Time Bundle Adjustment for 3D Reconstruction on the GPU. Trends and Topics in Computer Vision - ECCV 2010 Workshops, Heraklion, Crete, Greece, September 10-11, 2010. pp: 423-435

Patent Pending

A. Mohan et al. Cross reality system. US Patent US20200051328A1, Filed October 2019.

Additional patent applications filed for scalable 3D object recognition system running in the AR Cloud.

Invited Talks

Conference on Computer Vision and Pattern Recognition, Long Beach, California

Tutorial on Perception at Magic Leap **June 16, 2019**

Talk on localization, deep keyframe selection, semantics and other future directions that is being worked on at Magic Leap.

IEEE International Conference on Robotics and Automation, Brisbane, Australia

Data-Efficient Decentralized Visual SLAM **May 21-26, 2018**

Presented a state-of-the-art decentralized visual SLAM system based on optimized based on data association scales linearly with the robot count and uses highly compact place representations. For optimization, a state-of-the-art decentralized pose-graph optimization method is used. It exchanges a minimum amount of data which is linear with trajectory overlap

Apple, Seattle, Washington

Distributed Object based SLAM **August 24, 2017**
Gave an overview of my Ph.D. thesis work on Distributed Object based SLAM. Presented a new approach that allows each mobile device to build its own object level map while asking for minimal knowledge of the map of the teammates.

iRobot, Bedford, Massachusetts

Distributed Object based SLAM **August 7, 2017**
Gave an overview of my Ph.D. thesis work on Distributed Object based SLAM. Presented a new approach that allows each mobile device to build its own object level map while asking for minimal knowledge of the map of the teammates.

SRI International, Princeton, New Jersey

Distributed Object based SLAM **July 18, 2017**
Gave an overview of my Ph.D. thesis work on Distributed Object based SLAM. Presented a new approach that allows each mobile device to build its own object level map while asking for minimal knowledge of the map of the teammates.

Magic Leap, Sunnyvale, California

Distributed Object based SLAM **June 30, 2017**
Gave an overview of my Ph.D. thesis work on Distributed Object based SLAM. Presented a new approach that allows each mobile device to build its own object level map while asking for minimal knowledge of the map of the teammates.

International Symposium on Experimental Robotics, Tokyo, Japan

Multi Robot Object-based SLAM **October 6, 2016**
Presented a multi robot SLAM approach that uses 3D objects as landmarks for localization and mapping.

IEEE International Conference on Robotics and Automation, Stockholm, Sweden

Distributed trajectory estimation with privacy and communication constraints **May 16-21, 2016**
Presented a distributed algorithm to estimate the 3D trajectories of multiple cooperative robots from relative pose measurements using Distributed Gauss Seidel.

IEEE International Conference on Robotics and Automation, Seattle, WA, USA

Information based Reduced Landmark SLAM **May 26-30, 2015**
Presented an information-based approach to select a reduced number of landmarks and poses for a robot to localize itself and simultaneously build an accurate map.

IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, USA

SLAM with object discovery, modeling and mapping **Sept 14-18, 2014**
Presented an approach for online object discovery and object modeling, and extend a SLAM system to utilize these discovered and modeled objects as landmarks to help localize the robot in an online manner.

European Conference on Computer Vision, Heraklion, Crete, Greece

Practical Time Bundle Adjustment for 3D Reconstruction on GPU **Sept 10-11, 2010**
Presented a hybrid implementation of sparse bundle adjustment on the GPU using CUDA, with the CPU working in parallel which outperforms the CPU implementation significantly, achieving a speedup of 30-40 times over the standard CPU implementation.

Academic Duties

- Conference reviewer for IEEE International Conference on Robotics and Automation since 2015.
- Conference reviewer for IEEE/RSJ International Conference on Intelligent Robots and Systems since 2014.
- Journal reviewer for IEEE Transactions of Robotics.
- Journal reviewer for IEEE Robotics and Automations letters.
- Journal reviewer for International Journal for Robotics Research.
- Program Committee member of Robotics Science and Systems conference in 2016.
- Member of the Organizing committee for the tutorial on Perception at Magic Leap at the 2019 Conference on Computer Vision and Pattern Recognition.
- Member of the Organizing committee for the tutorial on Into the MagicVerse at the 2020 Conference on Computer Vision and Pattern Recognition.

Professional Memberships

- Member of the IEEE Robotics and Automation Society.
- Member of the Computer Vision foundation.
- Member of the Army Research Lab's Micro Autonomous Systems and Technology (MAST) consortium.

Computer Skills

- Languages: C, C++, Python, MATLAB, CUDA.
- Libraries/Frameworks: OpenCV, GTSAM, PCL, ROS, Eigen, Boost, PyTorch, Numpy, SciPy
- Operating Systems: Unix/Linux, Windows.

References

- Prof. Henrik Christensen
- Prof. Frank Dellaert
- Prof. Luca Carlone
- Prof. John Lenoard
- Prof. Davide Scaramuzza
- Prof. P J Narayanan