Certifiable Perception for Robots and Autonomous Vehicles

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Robots & Autonomous Systems

ground transportation domestic supply chain logistics mining

disaster response precision agriculture infrastructure inspection

exploration science

environmental monitoring

reasons for adoption: faster, better, safer, cheaper
Mission: to develop theoretical understanding and practical algorithms to bridge the gap between human and robot perception for autonomous navigation.

- signal processing (e.g., 2D computer vision)
- state estimation (e.g., localization & mapping)
- probabilistic inference (e.g., high-level understanding)
- machine learning (e.g., object detection)
Example 1: Visual-Inertial Navigation

Localization in GPS-denied scenarios
- localize robot (and map unknown environment) using camera and IMU

Forster, Carlone, Dellaert, Scaramuzza, On-Manifold Preintegration for Real-Time Visual-Inertial Odometry, TRO’17 (best paper award)
Example 2: Lidar-based Mapping

DARPA Subterranean Challenge, in collaboration with JPL
Example 3: Object Detection, Pose Estimation

• **Object pose estimation in point clouds:**
  • **Registration problem:** find rigid transformation (position, rotation) that aligns two point clouds

• **Related problems:**
  • Image-based object pose estimation
  • Image segmentation
• Intro: Autonomy and Perception

• Grand Challenges

• Recent Results from SPARK
Perception Success… and its failures

Images: Evtimov et al.
Camouflage graffiti and art stickers cause a neural network to misclassify stop signs as speed limit 45 signs or yield signs.
Ages of complexity

- power, size, time constants

Efficiency

Model complexity

Robustness

+ noise, outliers/attacks
Axe of complexity

Robustness

- power, size, time constants

Efficiency

Model complexity

+ noise, outliers/attacks

Humans
Axes of complexity

- power, size, time constants

Roomba

Humans

- noise, outliers/attacks

Model complexity

Efficiency

Robustness
Axes of complexity

- **Robustness**: power, size, time constants
- **Efficiency**: + noise, outliers/attacks

Humans

Roomba

Skydio Drone

Axes of complexity

Efficiency

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Self-driving cars

Humans

+ noise, outliers/attacks
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Roomba

Skydio Drone

Self-driving cars

Street view

Axes of complexity

Efficiency

Model complexity

Robustness
Axes of complexity

- power, size, time constants

Humans

Robot Perception

Efficiency

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Roomba

Skydio

Drone

Self-driving cars

Street view

Humans
Key Challenges

– **Certifiable performance**: how to establish rigorous performance guarantees on correctness and robustness of perception systems?
  • **Example**: can we design a perception system with lower failure rate than an expert human?

– **Efficient real-time performance**: can we design algorithms that execute in real-time on embedded platforms with tight resource constraints (power, size, weight, cost)?
  • **Example**: drones, small sats, self-driving cars

– **Perception for cognitive robotics**: can we design perception algorithms that replicate advanced reasoning in humans to support complex tasks?
  • **Example**: human-level understanding of the environment for collaborative robotics
Outline

- Intro: Autonomy and Perception
- Grand Challenges
- Recent Results from SPARK
Robustness
Efficiency
Model complexity

Visual Inertial Navigation

- power, size, time constants

VIO chip

Navion

Distributed mapping

2D segmentation

3D understanding

Certifiable algorithms

+ noise, outliers/attacks
Robust Perception

Standard estimation:

$$\arg \min_{x \in X} \sum_{i \in \mathcal{M}} \| r_i(x, y_i) \|^2$$

Measurements/data

Estimate

Residual

Cost function

$$\text{cost}(r)$$
Robust Perception

Outlier-robust estimation:

\[
\arg\min_{x \in X, \{\theta_i\} \in \{0,1\}^M, \forall i} \sum \theta_i \|r_i(x, y_i)\|^2 + (1 - \theta_i) \bar{c}^2
\]

- Rejects outliers, computes least squares solution of inliers

**Theorem (Inapproximability):**

Outlier rejection is inapproximable. In the worst case, there is no polynomial-time algorithm that can compute a near-optimal solution.

A New Perspective: Certifiable Algorithms

Certifiably robust algorithms: efficient algorithms that can assess their performance in each problem instance:

• perform well and certify correctness in common instances
• detect and declare failure in worst case problems (the ones which are impossible to solve in polynomial time)
**Theorem (Certification of robustness)**: If the solution $Z^*$ of the convex relaxation has rank 1, then $Z^*$ can be factored into $Z^* = x^T x$, and $x$ is the optimal solution of the original (combinatorial, non-convex) problem.
Certifiable Perception Algorithms

- **Key contribution:** the first efficient and certifiably robust algorithm for object pose estimation in liar scans (able to tolerate 99% outliers)

![Diagram with data points and outlier ratios]

95.44% outliers 97.37% outliers 96.87% outliers

- TEASER (proposed) is best approach
- *second best is Branch-&-Bound (exponential time)

Certifiable Perception Algorithms

Real-time Localization and Mapping

collaboration with JPL & Caltech

Lidar-based Object Localization

Proposed

RANSAC

Camera-based Object Localization

Proposed

Baseline


Robustness

Efficiency

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Certifiable algorithms

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2D segmentation

3D understanding
Beyond Geometry

Autonomy requires the robot to obtain a high-level understanding of the environment (geometry, objects & semantics, …)
Releasing Kimera

Real-time metric-semantic visual-inertial SLAM

Releasing Kimera

Kimera-VIO tracks sparse 3D landmarks for fast and accurate state estimation.

Back to Robustness…

solving 2D semantic segmentation failures:
2D semantic segmentation is doomed to fail…
Back to Robustness…

solving 2D semantic segmentation failures:
2D semantic segmentation is doomed to fail…
Back to Robustness…

solving 3D reconstruction failures
Robustness

Efficiency

Model complexity

- power, time constants

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Certifiable algorithms

+ noise, outliers/attacks
Efficient Real-time Perception

algorithm-and-hardware design

visual attention for robotics

• **Key contribution (in collaboration with Karaman and Sze):** the Navion Chip for visual-inertial navigation
  • uses 3 orders of magnitude less energy with respect to a state-of-the-art implementation on a workstation
  • ensures a comparable accuracy
Conclusion

- **Perception** is a key ingredient of autonomy
- Safety critical applications require robust perception
- **Certifiable algorithms** provide a practical approach to get provably robust performance
- **High-level understanding** enables autonomy applications and can further enhance robustness

Thank you!
Teaching Perception and Autonomy

6.141/16.405j - Robotics: Science And Systems
- Intro to robotics
- Coding: ROS and python
- Hands-on labs

- Geometric control
- 3D vision
- Coding: ROS and C++
- Optimization
- Hands-on labs