Certifiable Perception for Robots and Autonomous Vehicles

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November 13, 2019 | MIT Research and Development Conference

Robots & Autonomous Systems

ground

transportation


domestic


supply chain logistics


mining

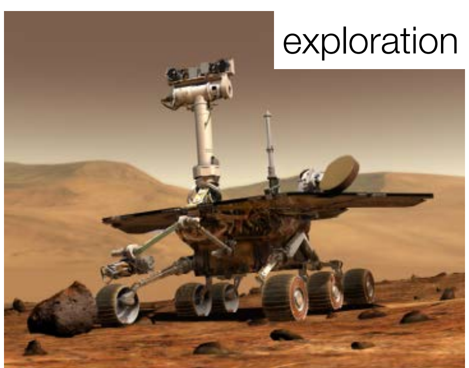
air

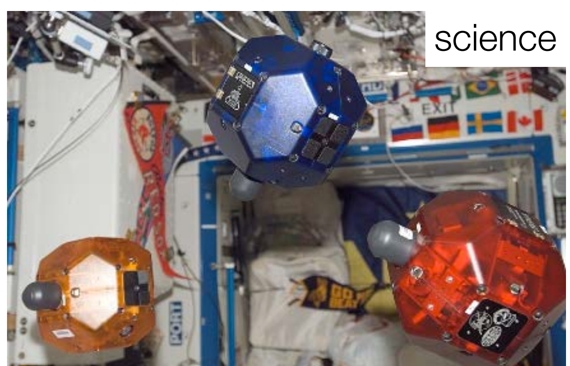

disaster response

precision agriculture

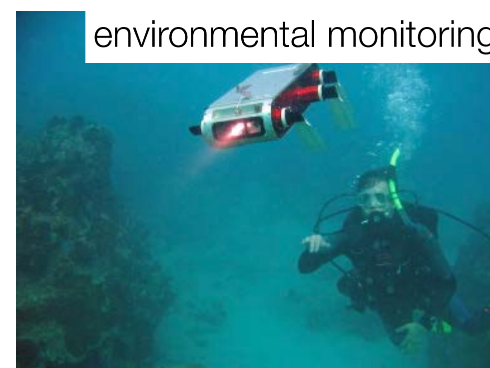

infrastructure inspection

space


exploration


science

and more …

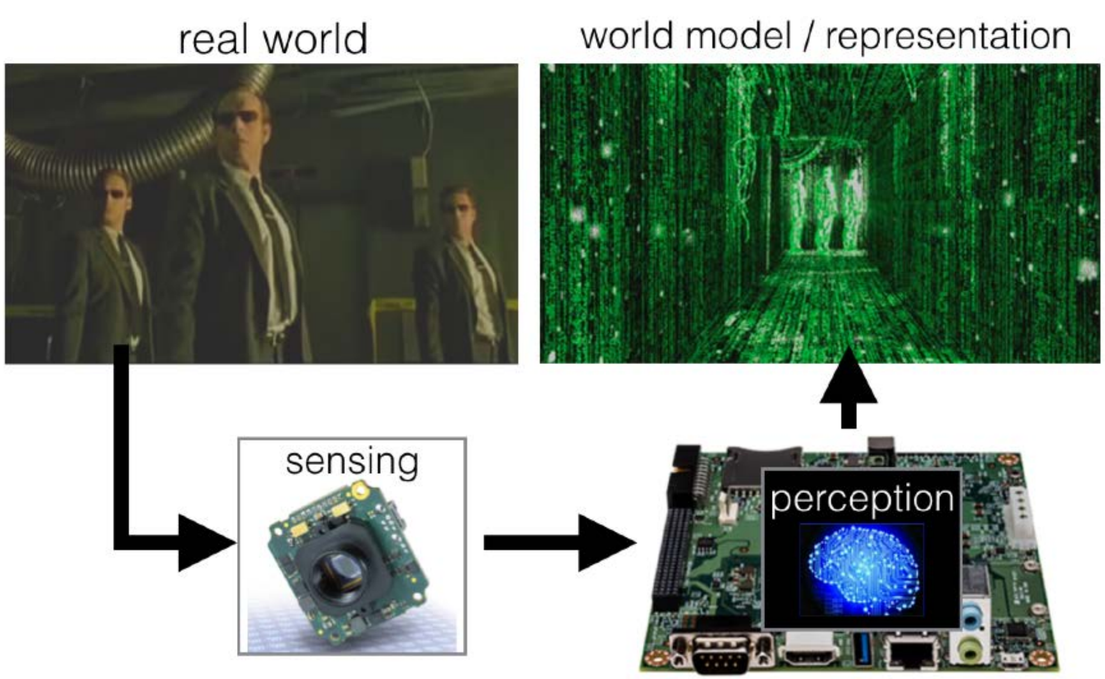

environmental monitoring

reasons for adoption: faster, better, safer, cheaper

SPARK Lab

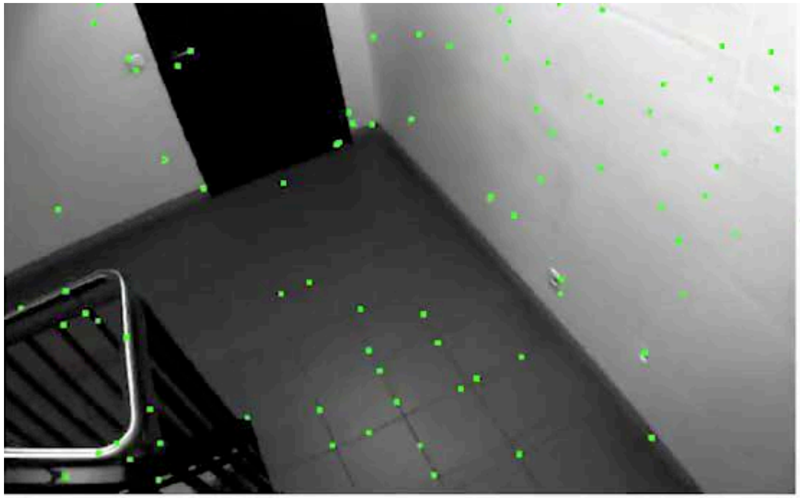
Sensing Perception
Autonomy and
Robot Kinetics

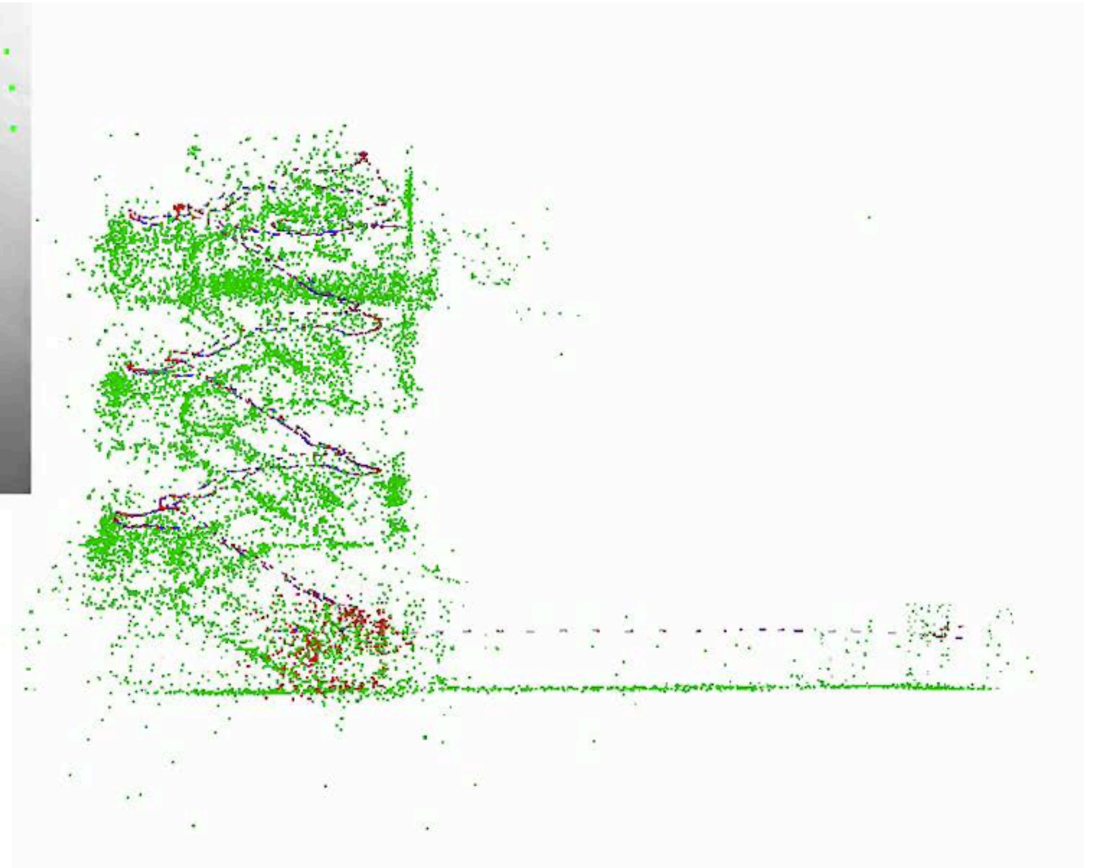
Mission: to develop theoretical understanding and practical algorithms to bridge the gap between human and robot *perception for autonomous navigation*

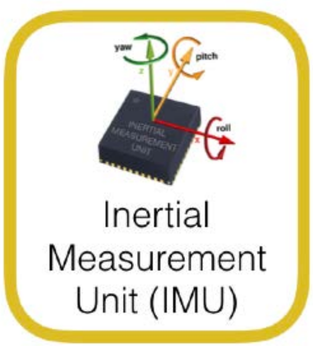


- **signal processing**
  (e.g., 2D computer vision)
- **state estimation**
  (e.g., localization & mapping)
- **probabilistic inference**
  (e.g., high-level understanding)
- **machine learning**
  (e.g., object detection)

Example 1: Visual-Inertial Navigation





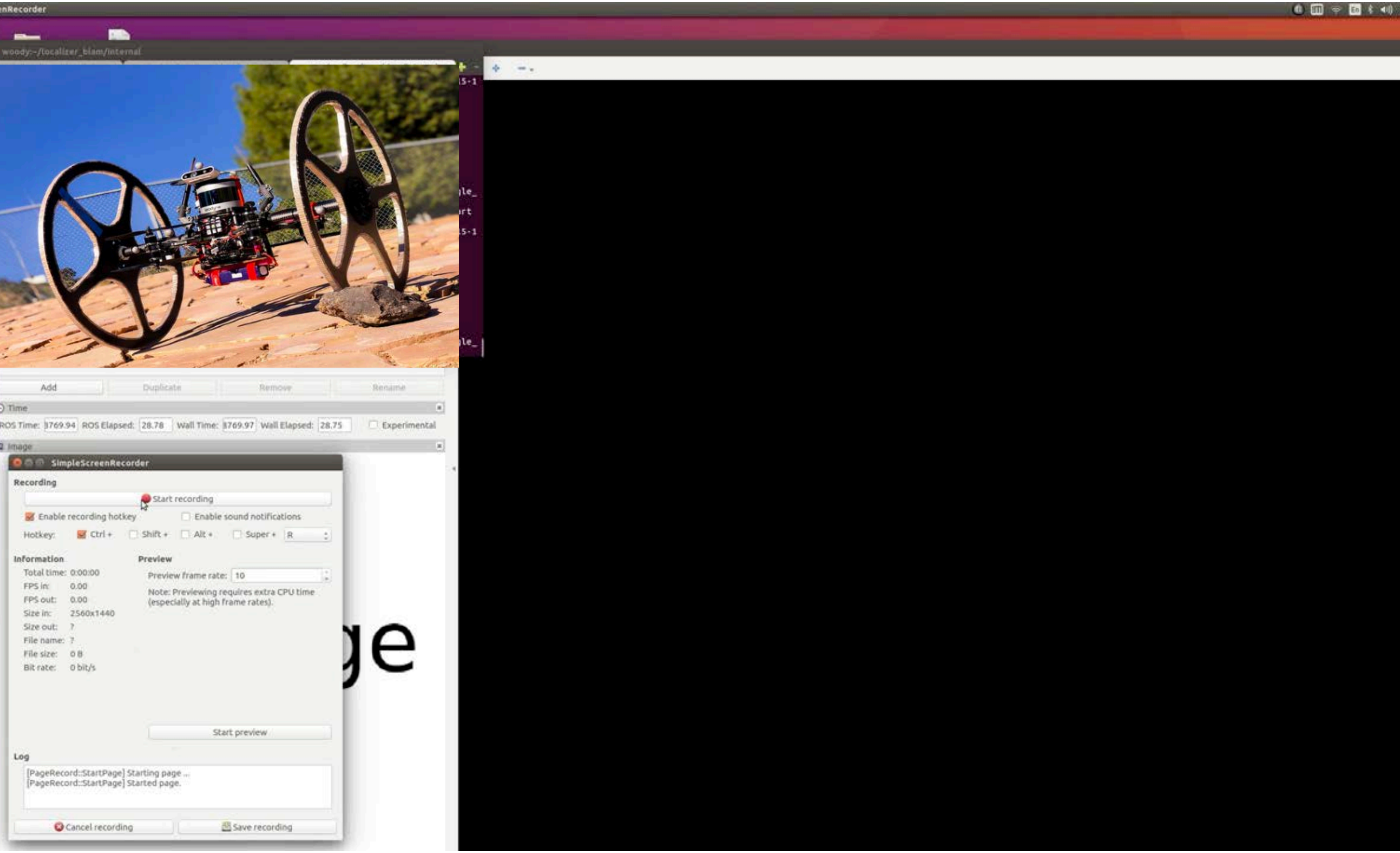


Localization in GPS-denied scenarios

- 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)

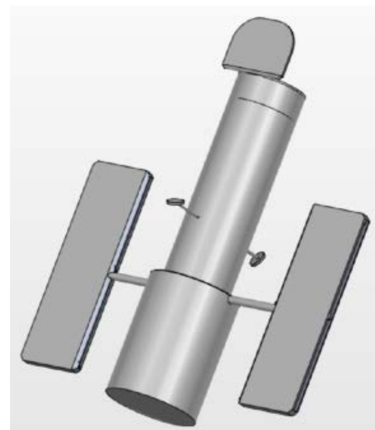
Example 2: Lidar-based Mapping



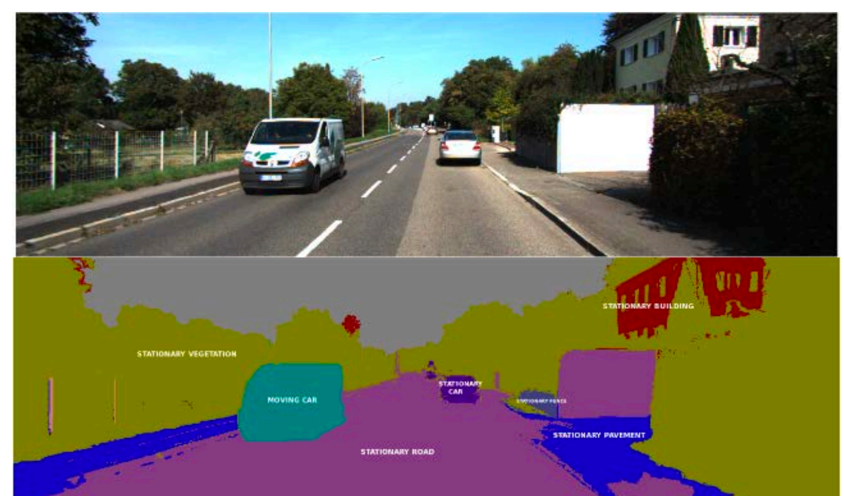
DARPA Subterranean Challenge, in collaboration with JPL

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



Outline

- Intro: Autonomy and Perception
- Grand Challenges
- Recent Results from SPARK

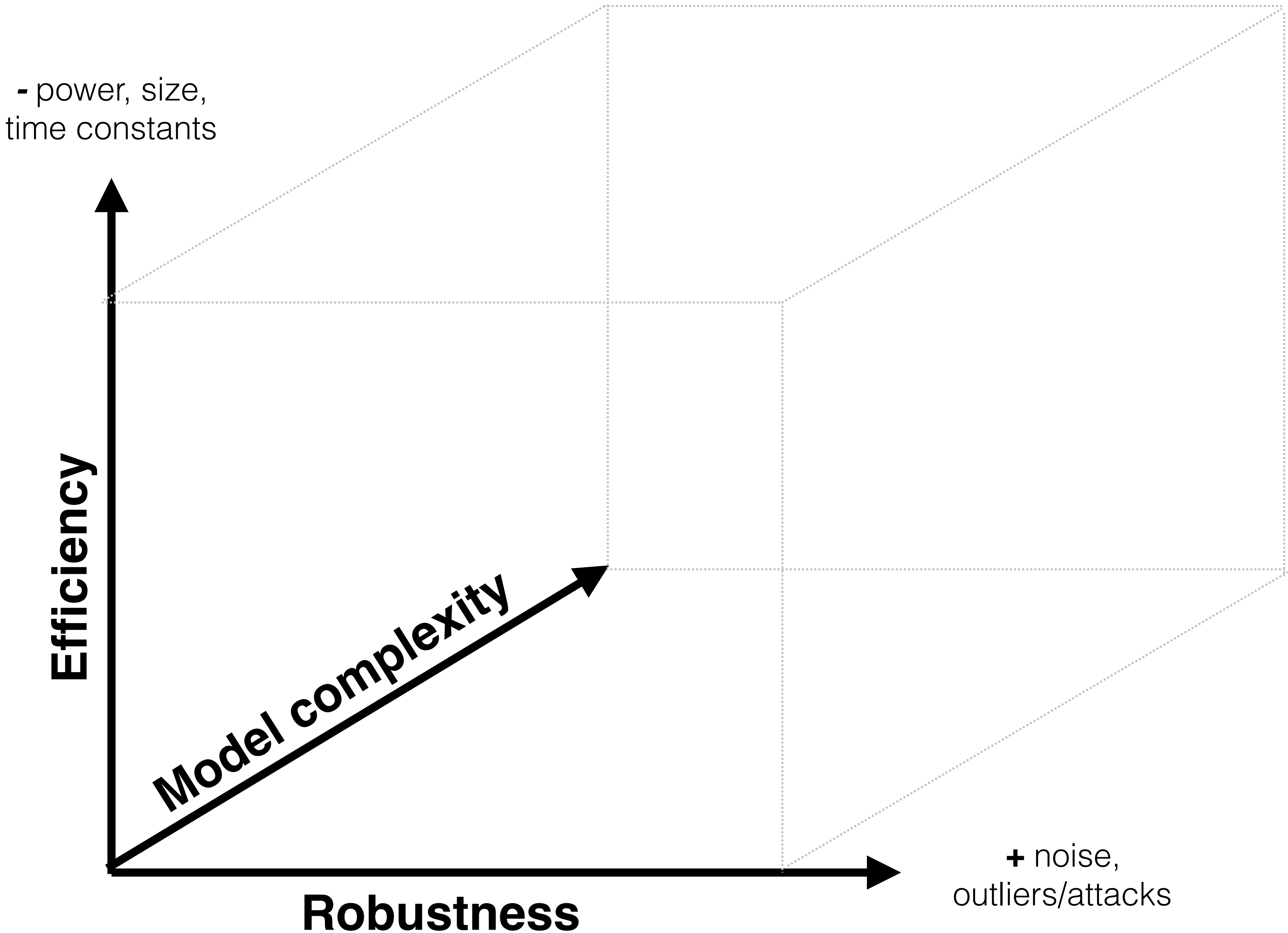
Perception Success… and its failures

Tesla Autopilot

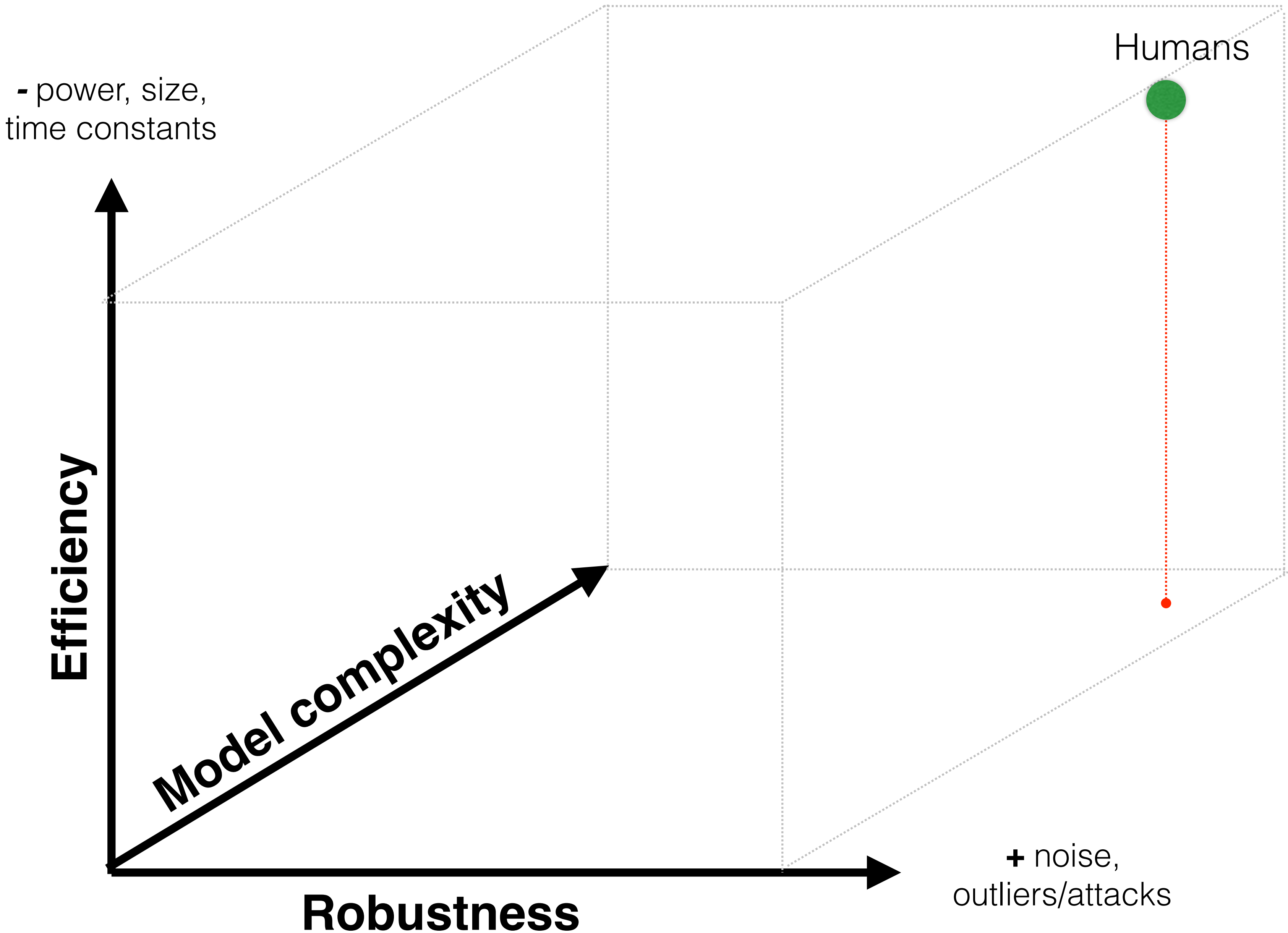
Images: Evtimov et al

Camouflage graffiti and art stickers cause a neural network to misclassify stop signs as speed limit 45 signs or yield signs.

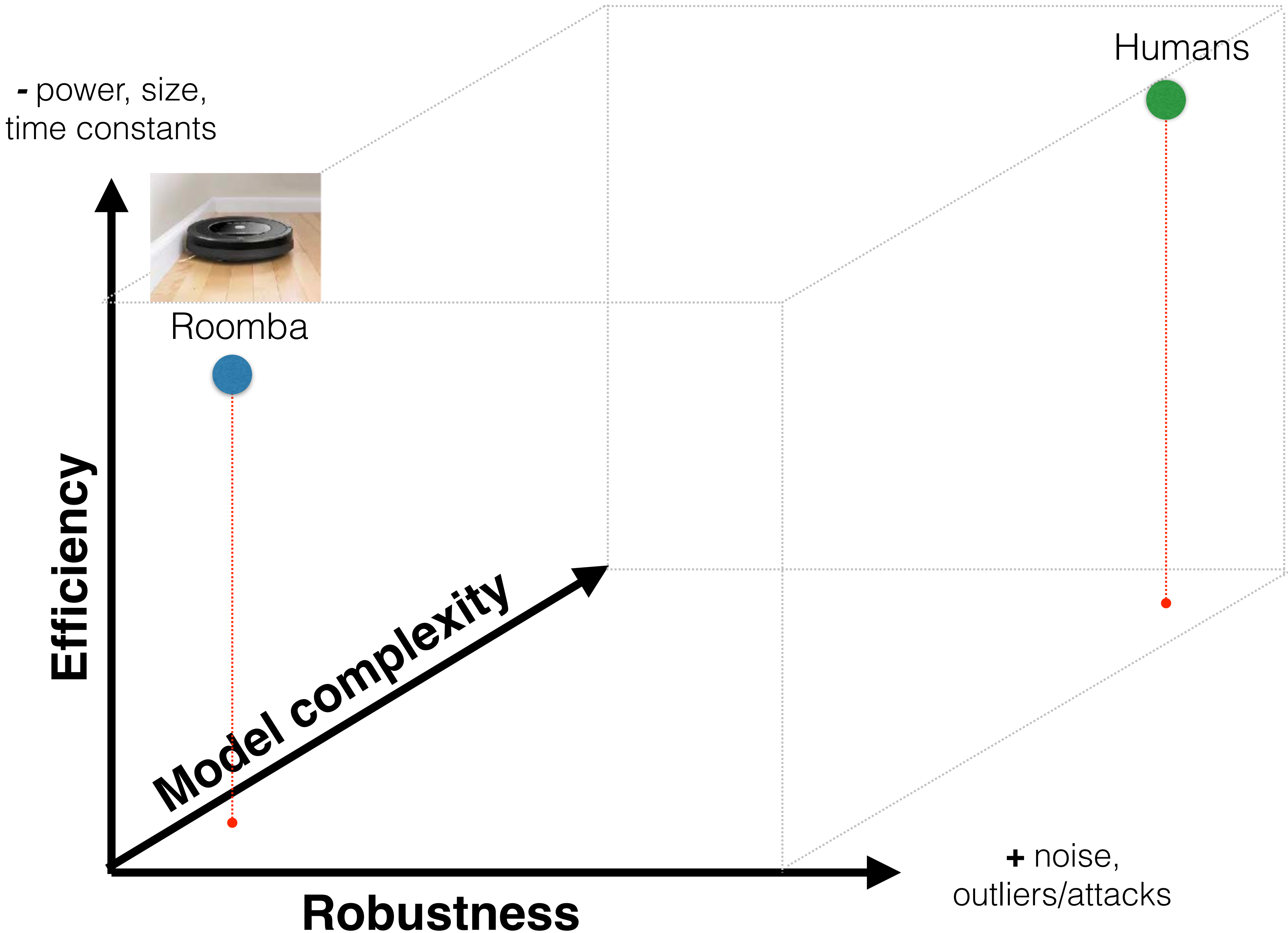
Axes of complexity



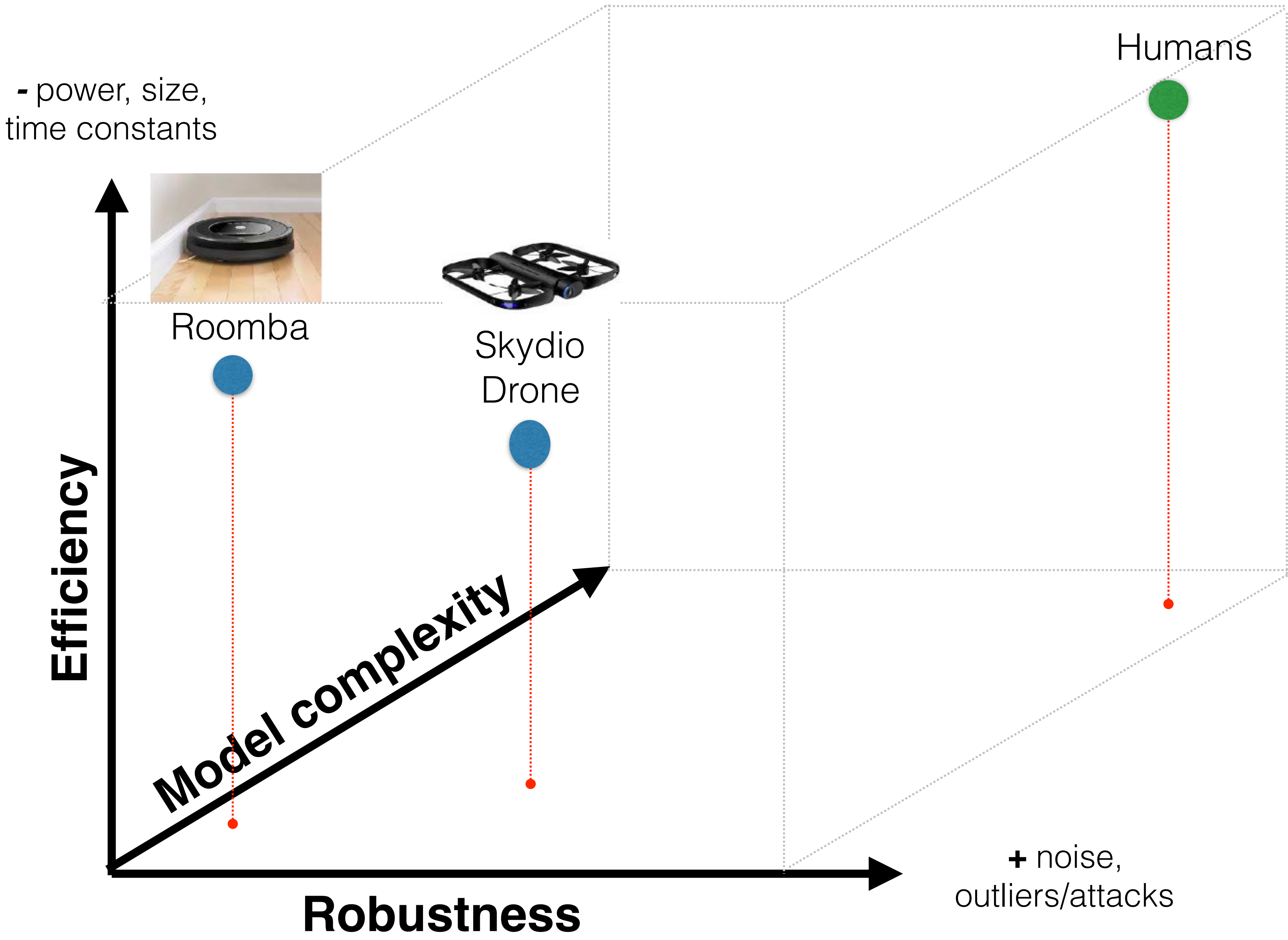
Axes of complexity



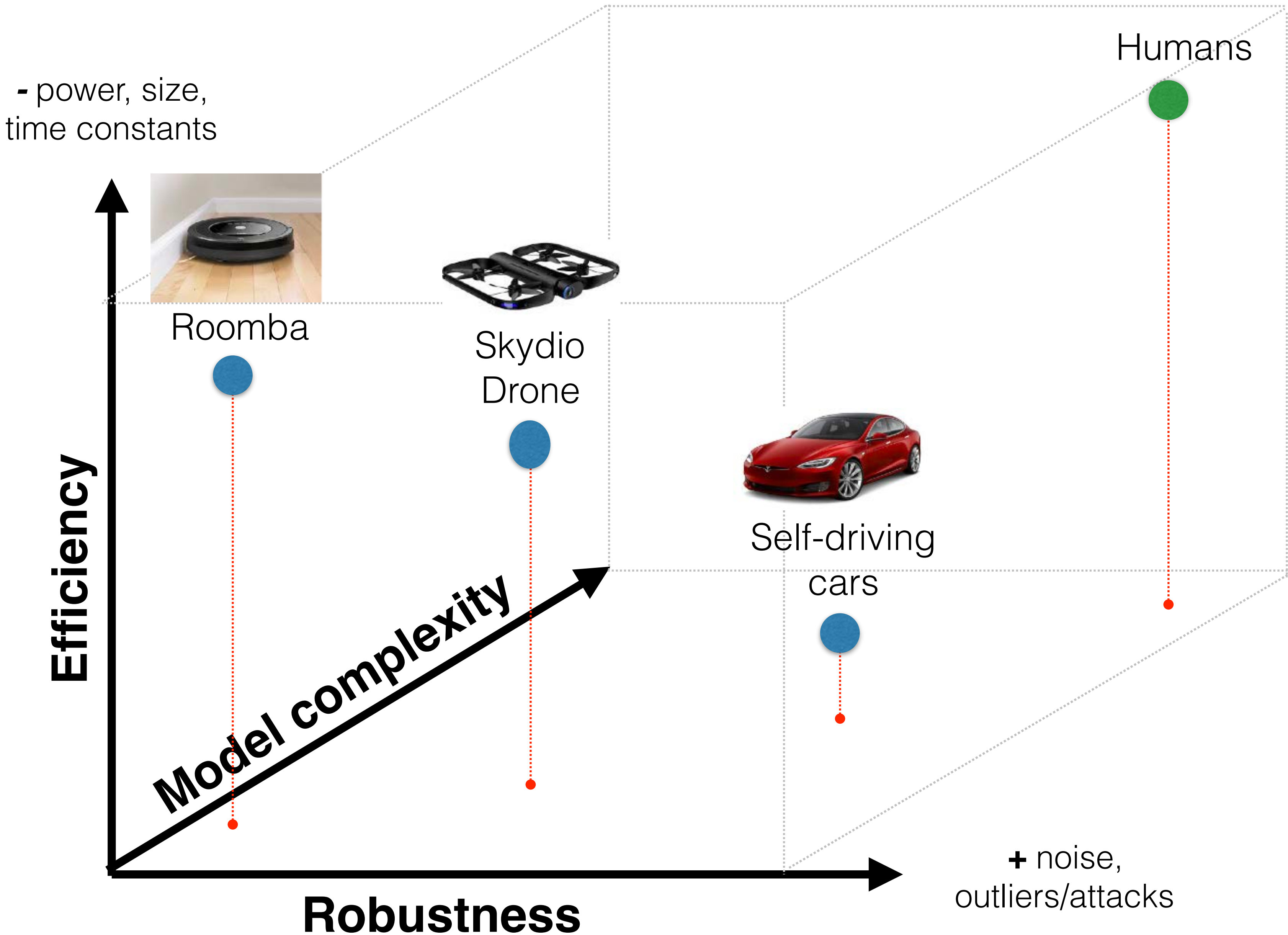
Axes of complexity



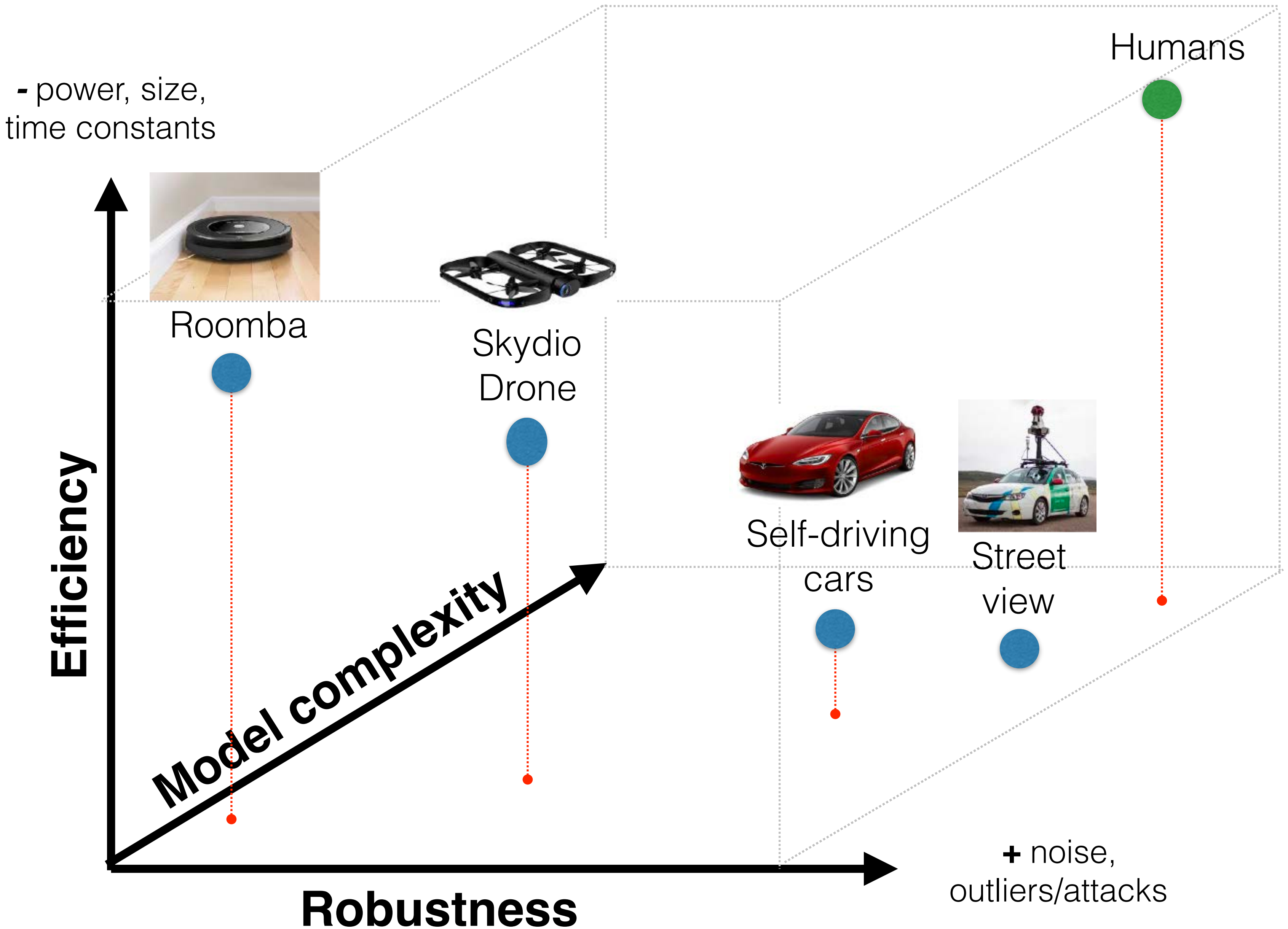
Axes of complexity



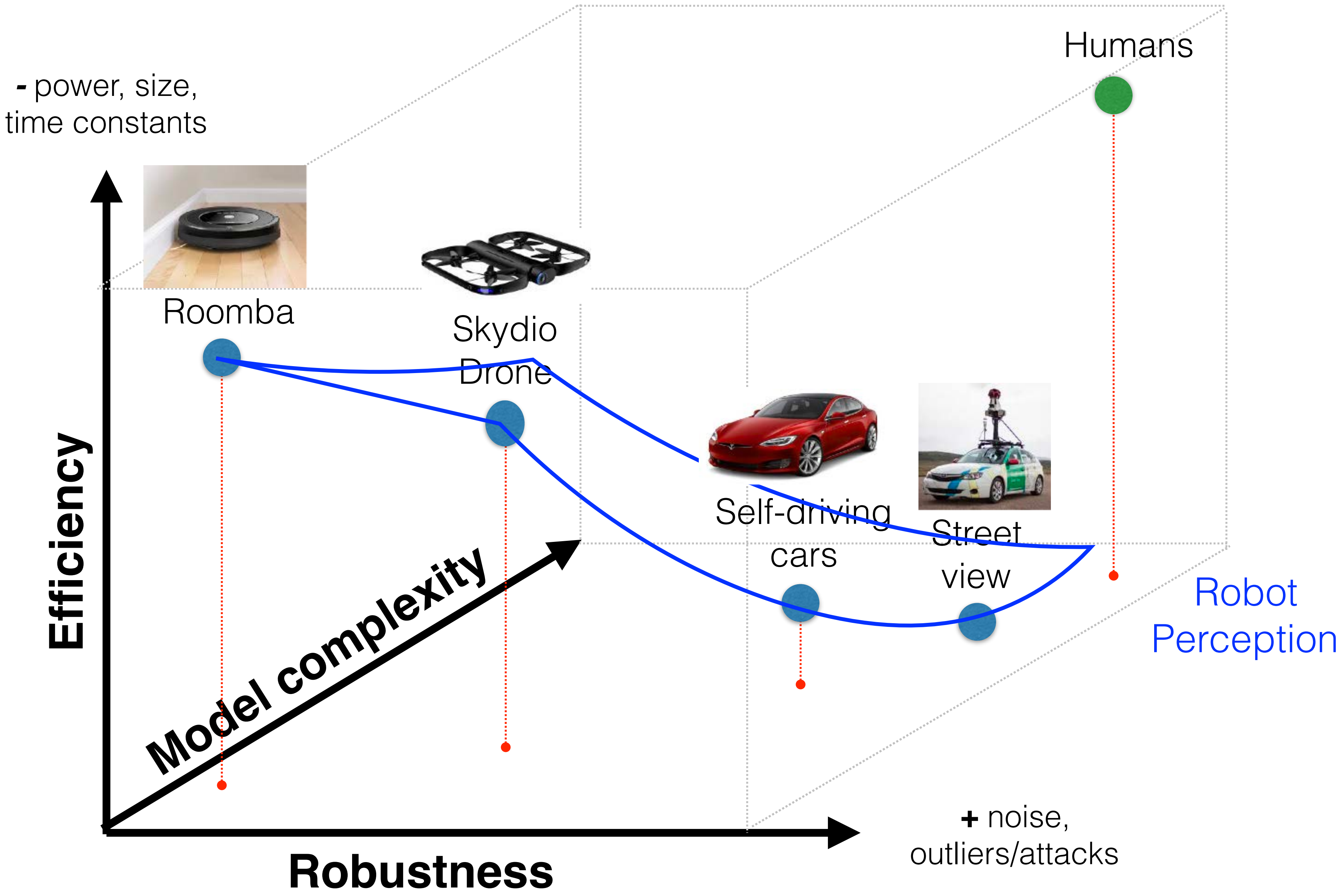
Axes of complexity



Axes of complexity



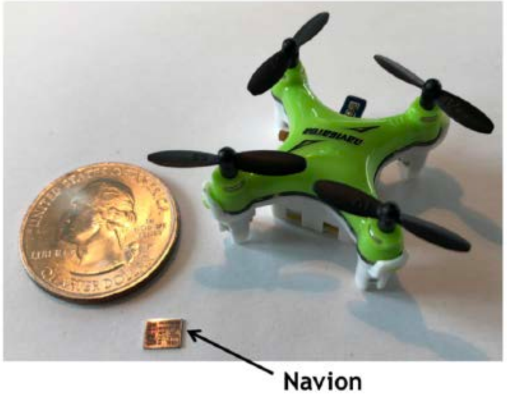
Axes of complexity



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

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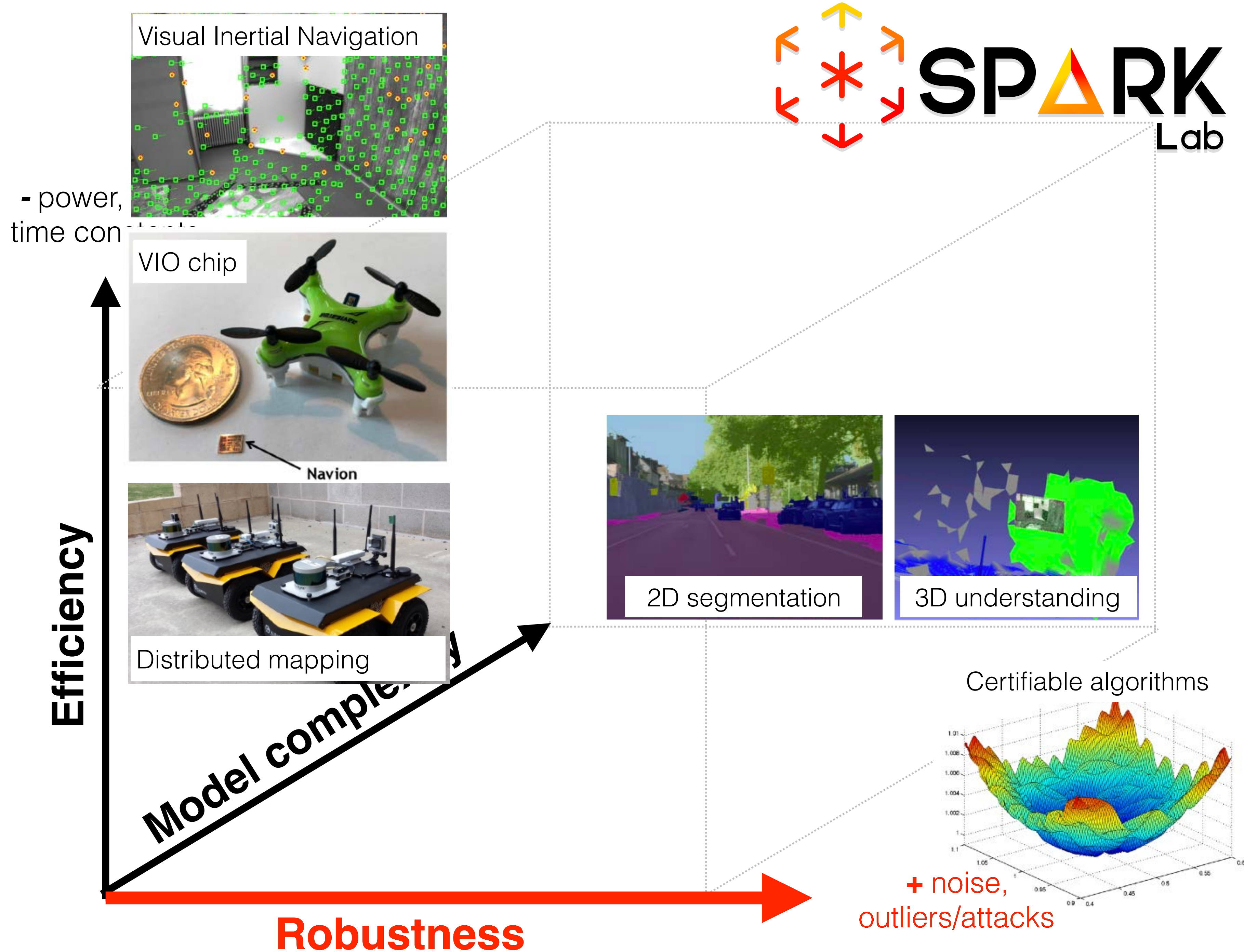
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3D understanding
Certifiable algorithms
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Robustness

Robust Perception

Standard estimation:

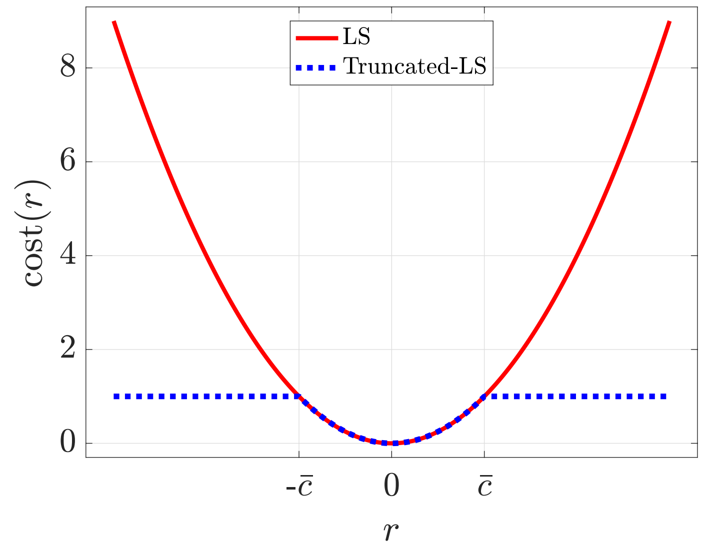
$$\arg\min_{x \in \mathbb{X}} \sum_{i \in \mathcal{M}} \|r_i(x, y_i)\|^2$$

Measurements/data

Estimate

Residual

Robust Perception

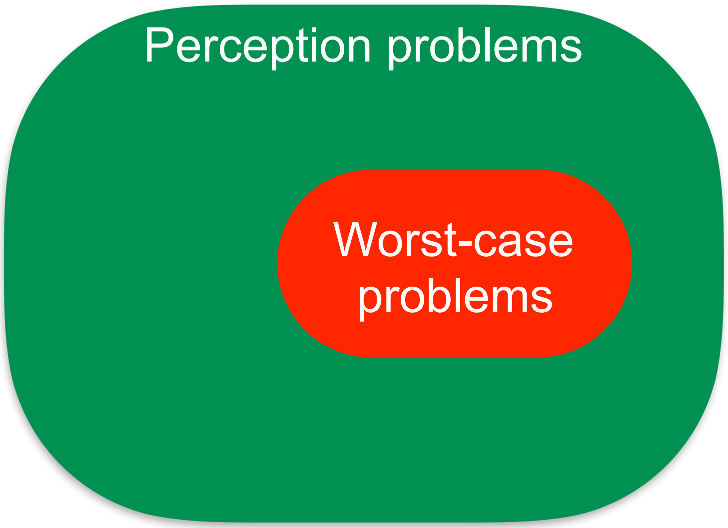


Outlier-robust estimation:

$$\arg\min_{\substack{x \in \mathbb{X}, \\ \theta_i \in \{0,1\}, \forall i}} \sum_{i \in \mathcal{M}} \theta_i \| r_i(x, y_i) \|^2 + (1 - \theta_i) \bar{c}^2$$

- 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.

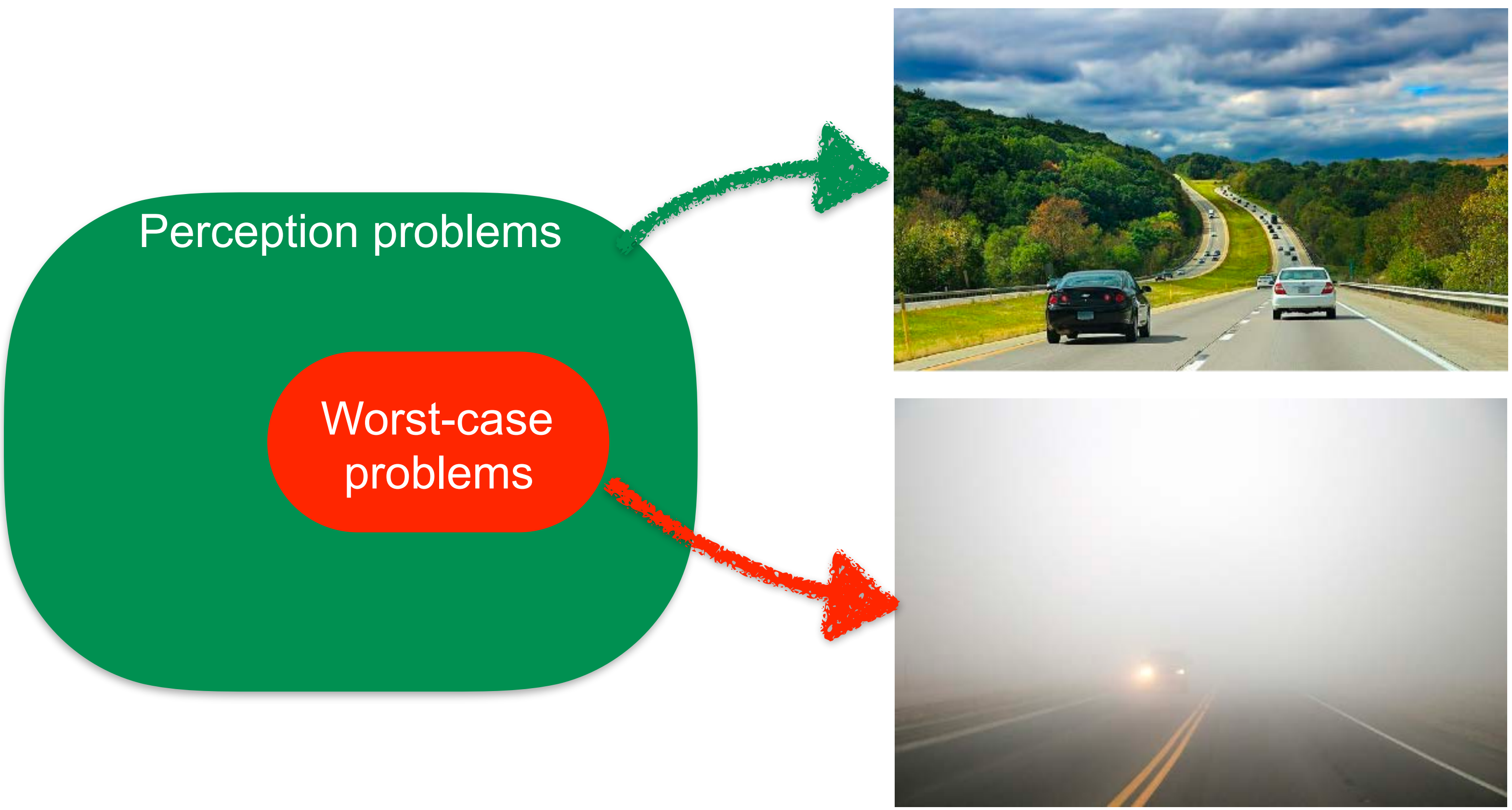


Tzoumas, Antonante, Carlone. Outlier-robust spatial perception: Hardness, general-purpose algorithms, and guarantees. IROS, 2019.

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 once which are impossible to solve in polynomial time)

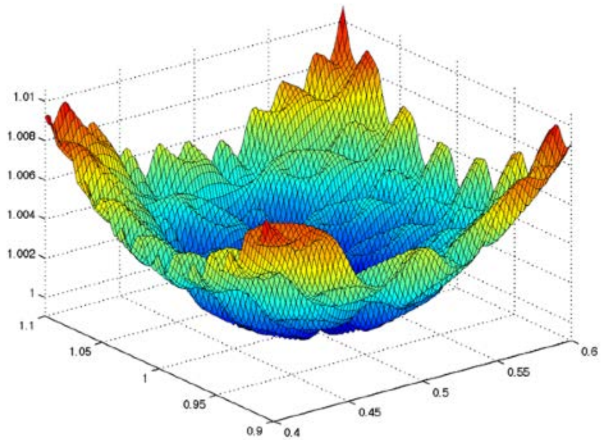


A New Perspective: Certifiable Algorithms

Robust perception

(non-convex, combinatorial)

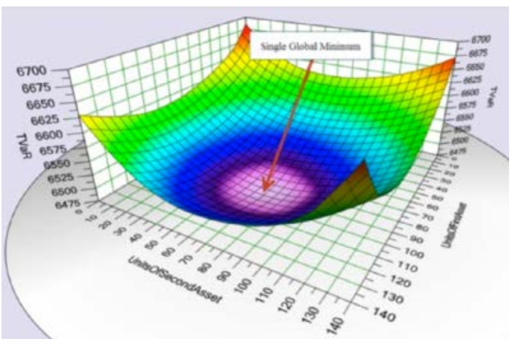
$$\arg\min_{\substack{x\in\mathbb{X},\\ \theta_i\in\{0,1\},\forall i}} \sum_{i\in\mathcal{M}} \theta_i \|r_i(x,y_i)\|^2 + (1-\theta_i)\bar{c}^2$$



Convex relaxation

(convex, easy to solve)

$$\begin{aligned}
\min_{Z\succeq 0} \quad & \operatorname{tr}(\boldsymbol{Q}\boldsymbol{Z}) \\
\textit{subject to} \quad & \operatorname{tr}([\boldsymbol{Z}]_{qq}) = 1 \\
& [\boldsymbol{Z}]_{q_i q_i} = [\boldsymbol{Z}]_{qq}, \forall i = 1,\ldots,N \\
& [\boldsymbol{Z}]_{q q_i} = [\boldsymbol{Z}]_{q q_i}^{\mathsf{T}}, \forall i = 1,\ldots,N \\
& [\boldsymbol{Z}]_{q_i q_j} = [\boldsymbol{Z}]_{q_i q_j}^{\mathsf{T}}, \forall 1 \le i < j \le N
\end{aligned}$$



certificate

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.

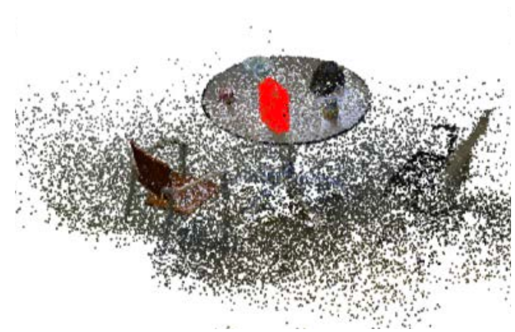
Yang and Carlone. A Polynomial-time Solution for Robust Registration with Extreme Outlier Rates. RSS 2019.
Yang and Carlone. A quaternion-based certifiably optimal solution to the Wahba problem with outliers. ICCV, 2019.

Certifiable Perception Algorithms

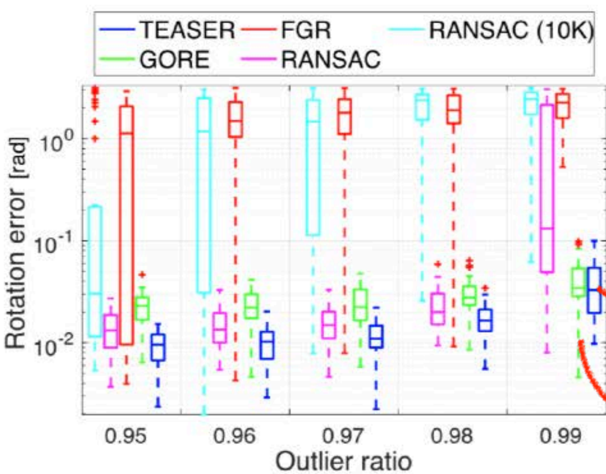
– **Key contribution:** the first efficient and certifiably robust algorithm for object pose estimation in liar scans (able to tolerate 99% outliers)

95.44% outliers

97.37% outliers



96.87% outliers



*TEASER (proposed) is best approach

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

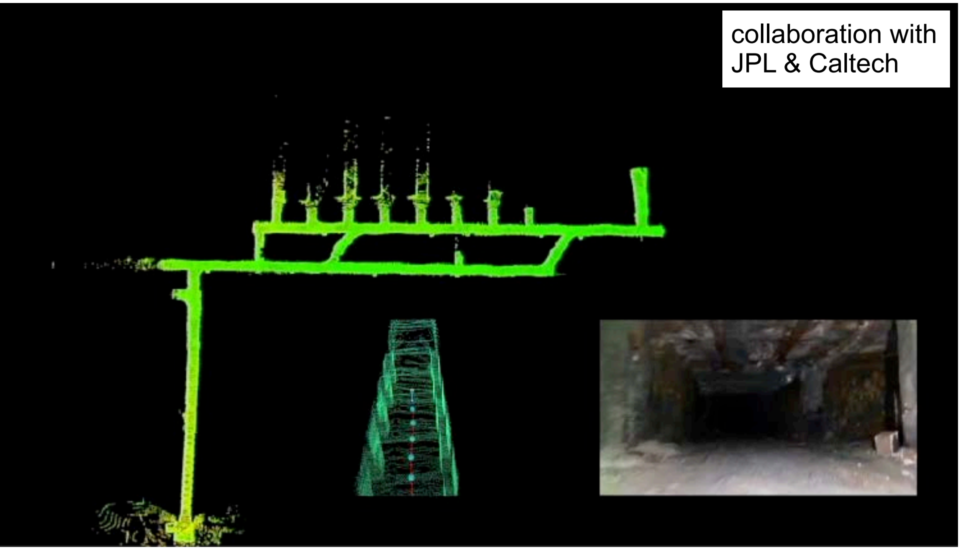
Yang and Carlone. A Polynomial-time Solution for Robust Registration with Extreme Outlier Rates. RSS 2019.
Yang and Carlone. A quaternion-based certifiably optimal solution to the Wahba problem with outliers. ICCV, 2019.

Stanford Bunny

80% outliers

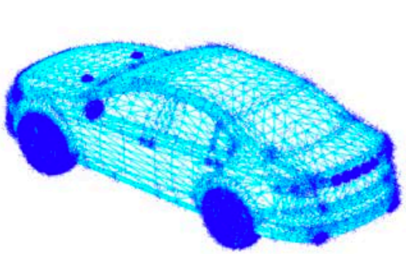
Certifiable Perception Algorithms

Real-time Localization and Mapping

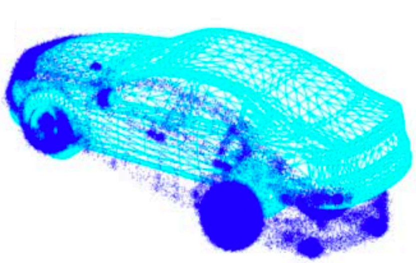


Lidar-based Object Localization

Proposed



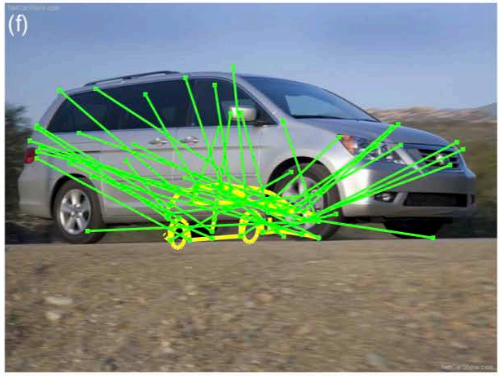
RANSAC



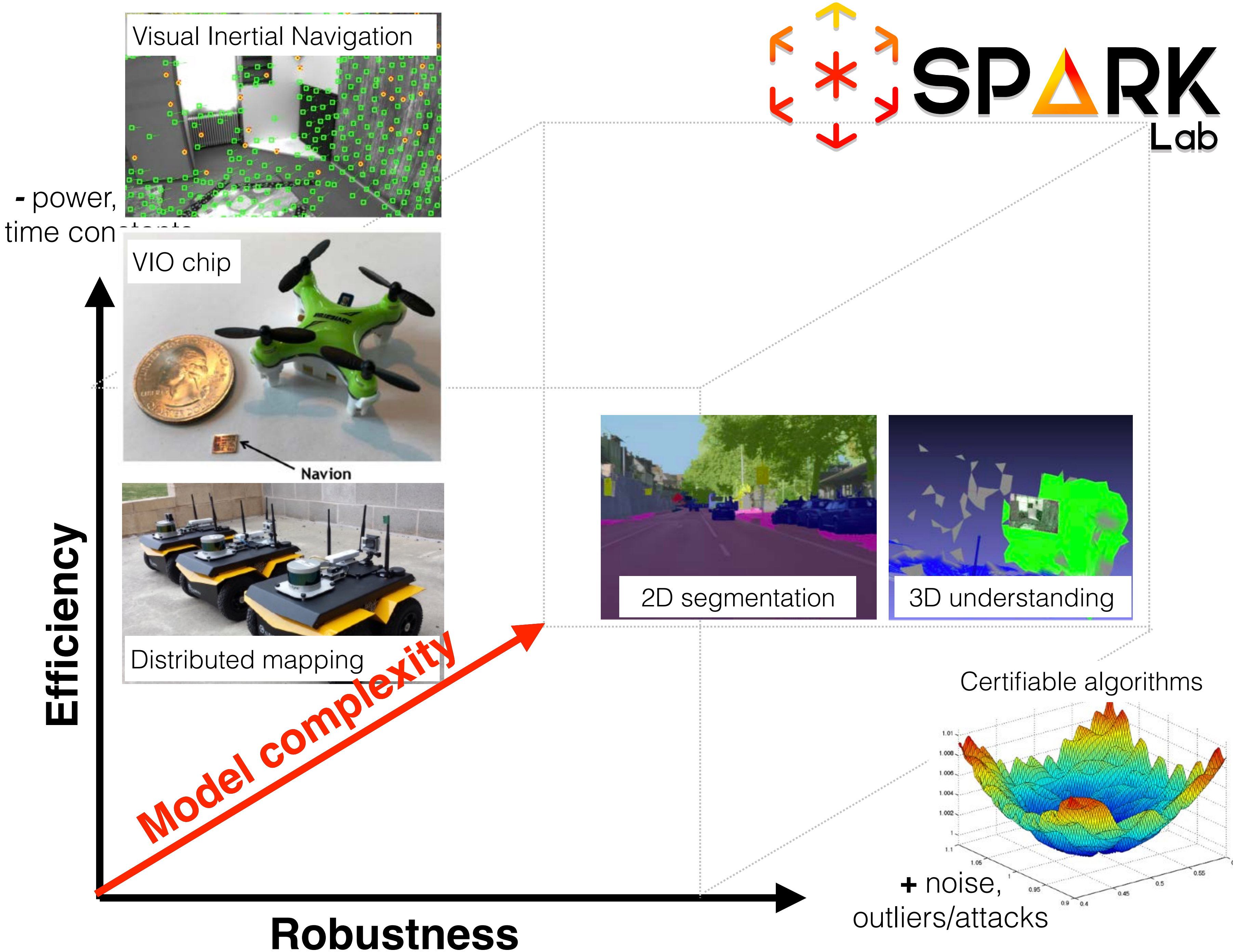
Camera-based Object Localization

Proposed

Baseline

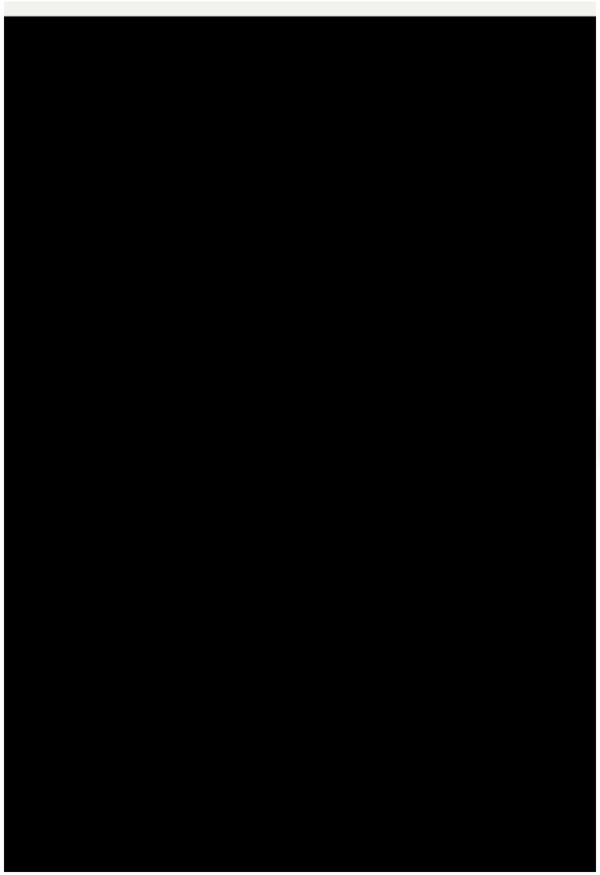


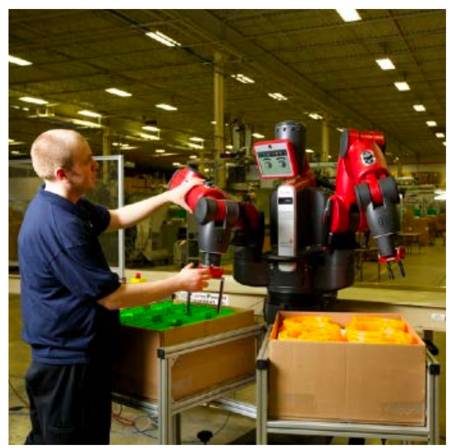
Yang, Antonante, Tzoumas, Carlone. Graduated non-convexity for robust spatial perception: From non-minimal solvers to global outlier rejection. Arxiv, 2019.
Lajoie, Hu, Beltrame, Carlone, Modeling Perceptual Aliasing in SLAM via Discrete Continuous Graphical Models, RAL 2019.



SPARK
Lab
Visual Inertial Navigation
- power,
time con
VIO chip
Navion
Distributed mapping
Efficiency
Model complexity
Robustness
2D segmentation
3D understanding
Certifiable algorithms
+ noise,
outliers/attacks

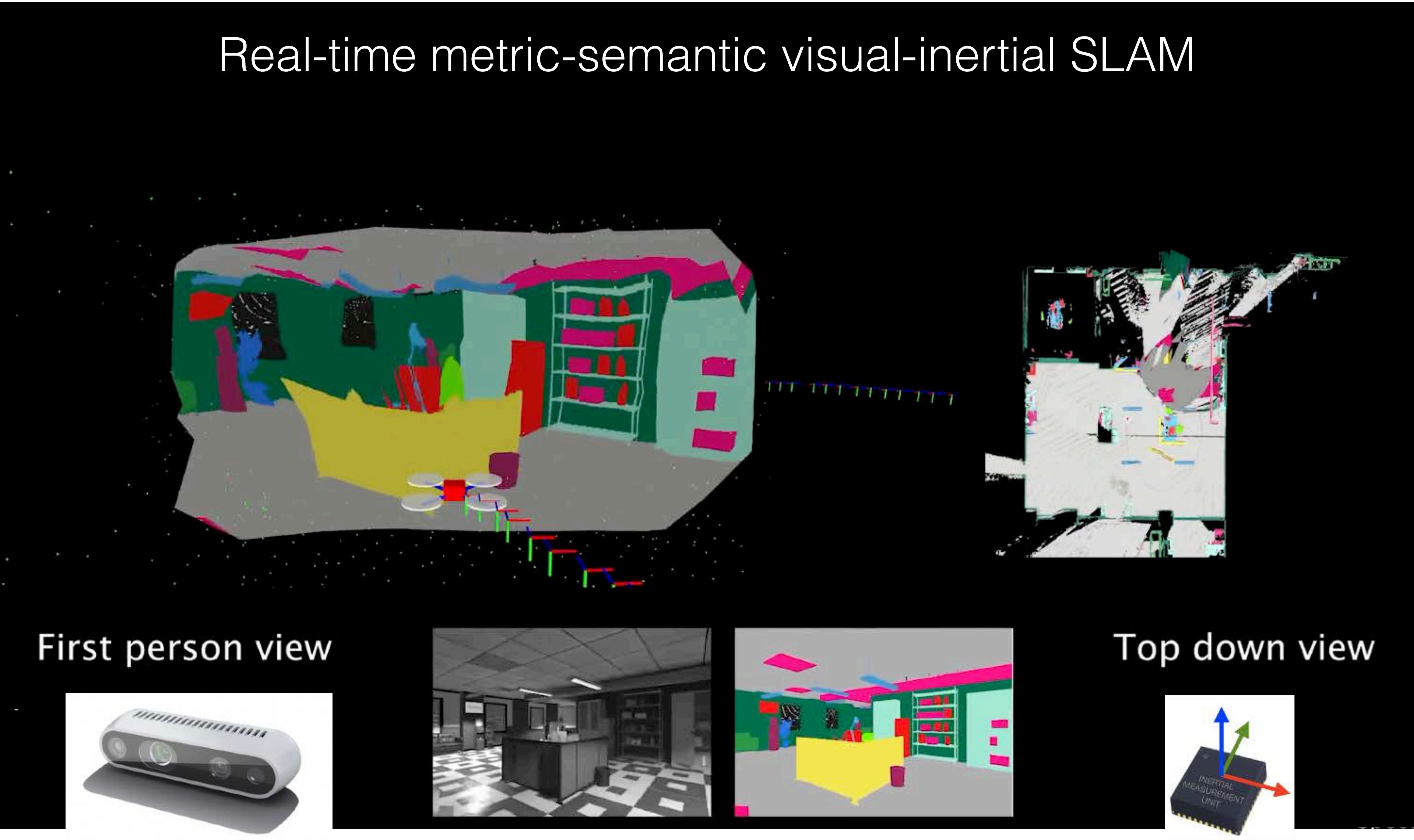
Beyond Geometry





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

Releasing Kimera



Rosinol, Abate, Chang, Carlone. Kimera: an open-source library for real-time metric-semantic localization and mapping. Arxiv, 2019.

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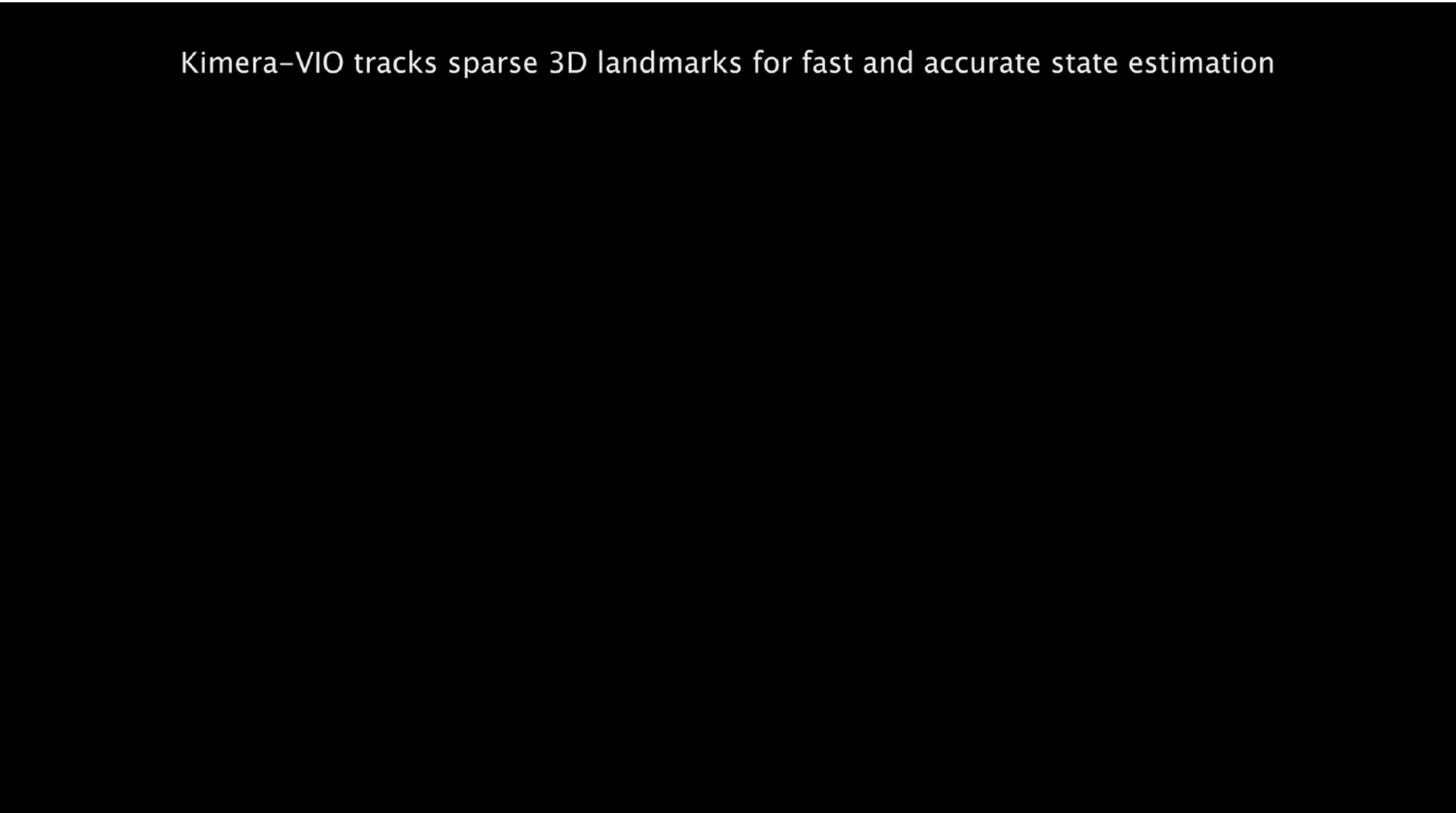
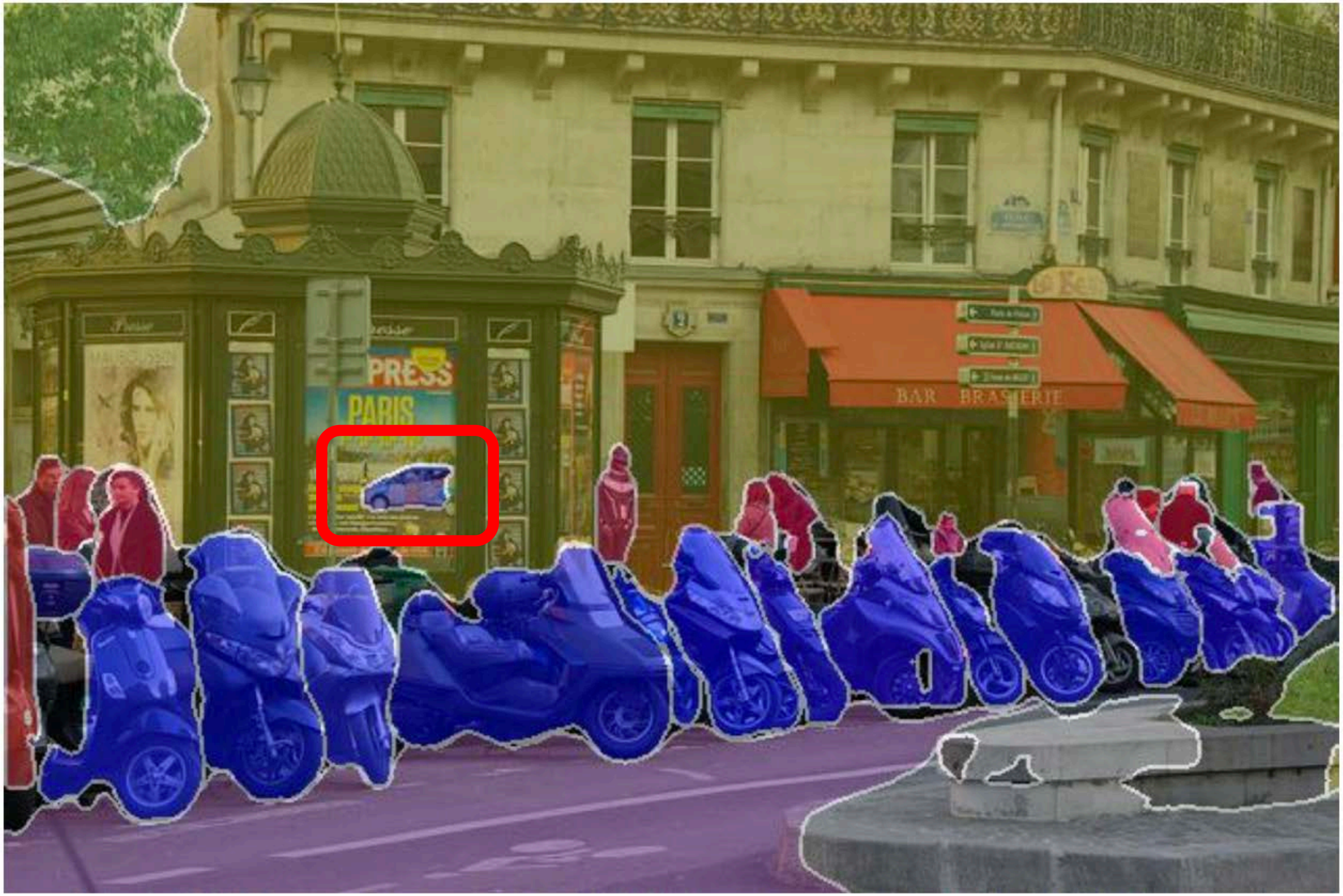


Rosinol, Abate, Chang, Carlone. Kimera: an open-source library for real-time metric-semantic localization and mapping. Arxiv, 2019.

Back to Robustness…

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



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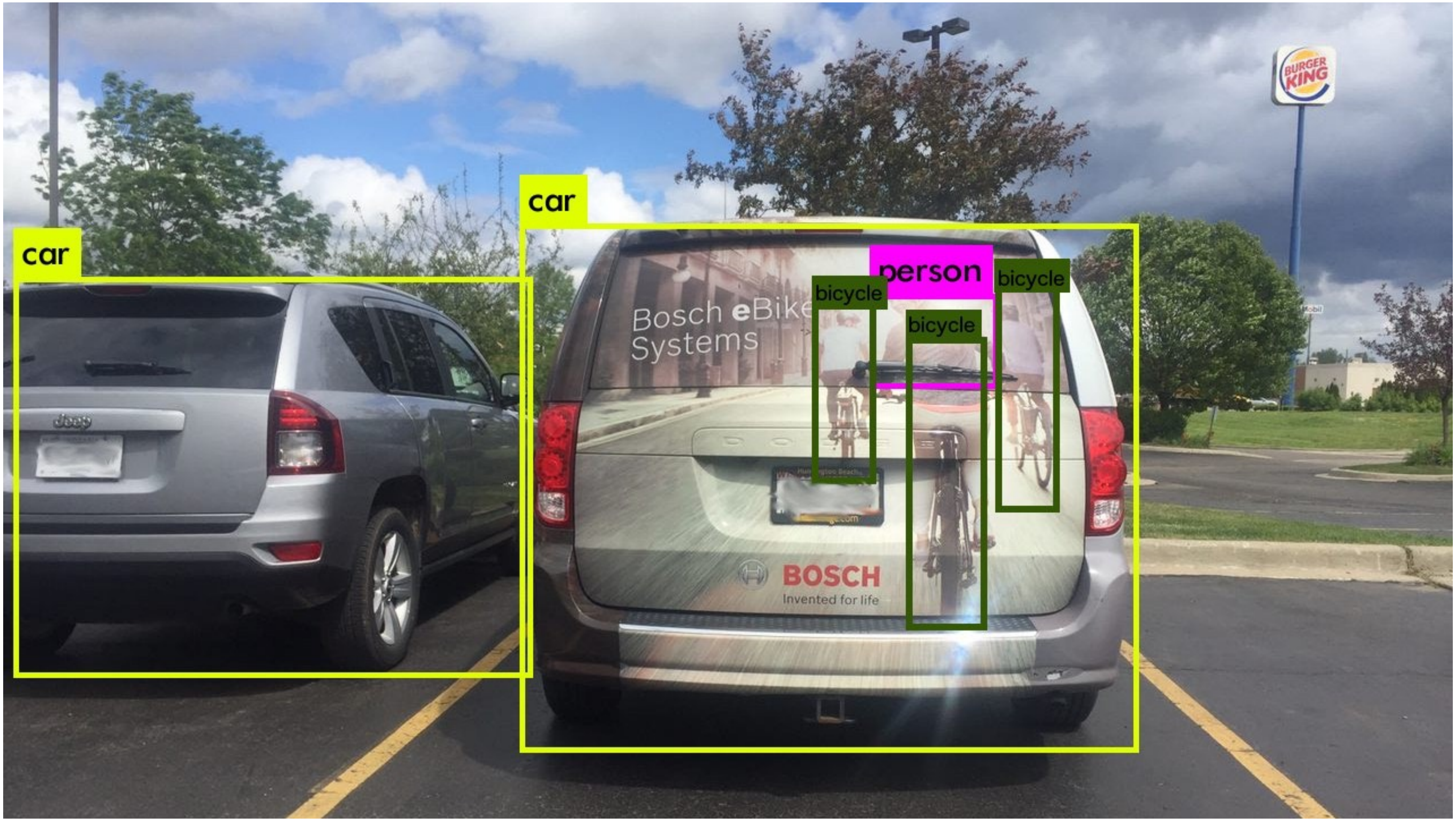
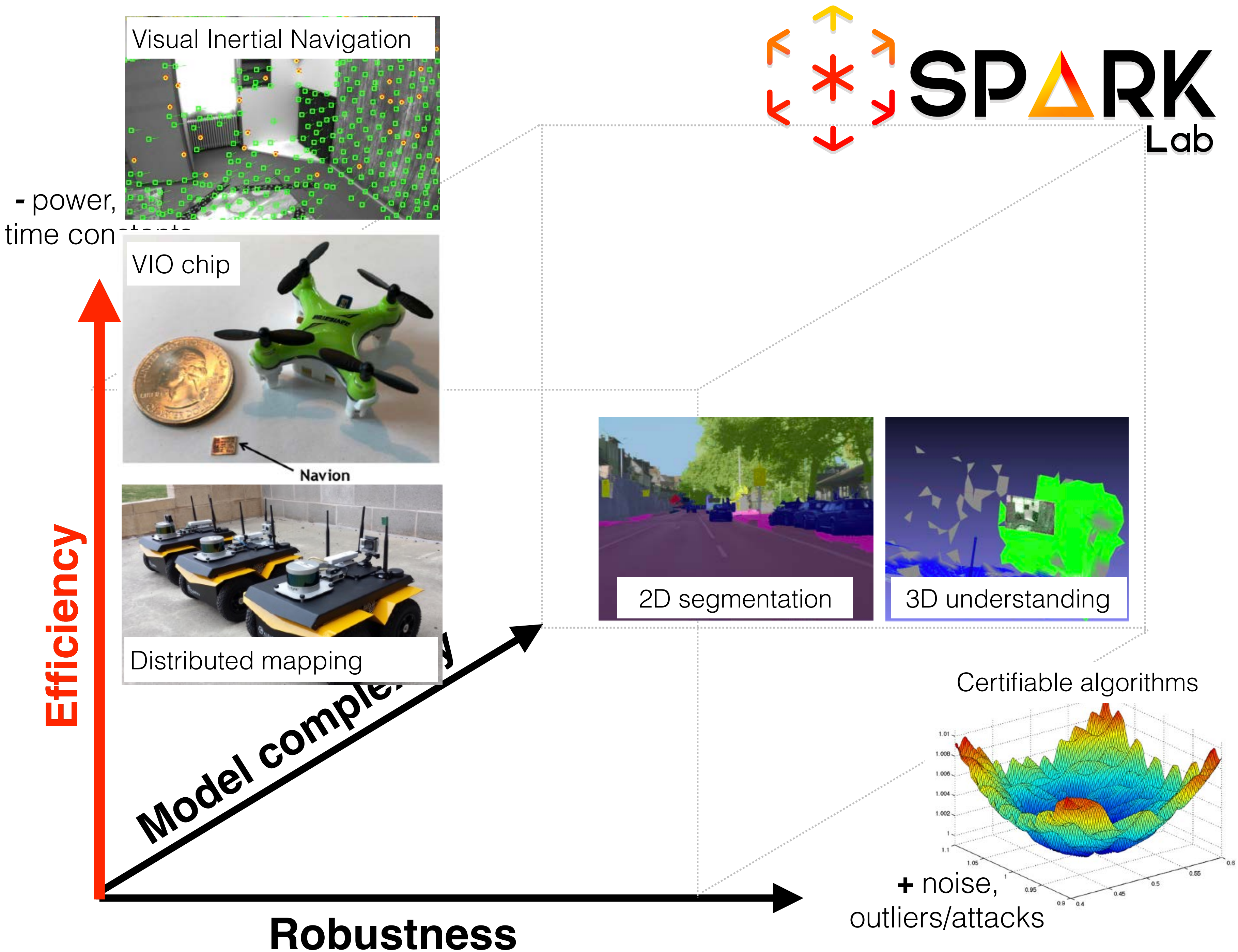


Back to Robustness…

solving 3D reconstruction failures



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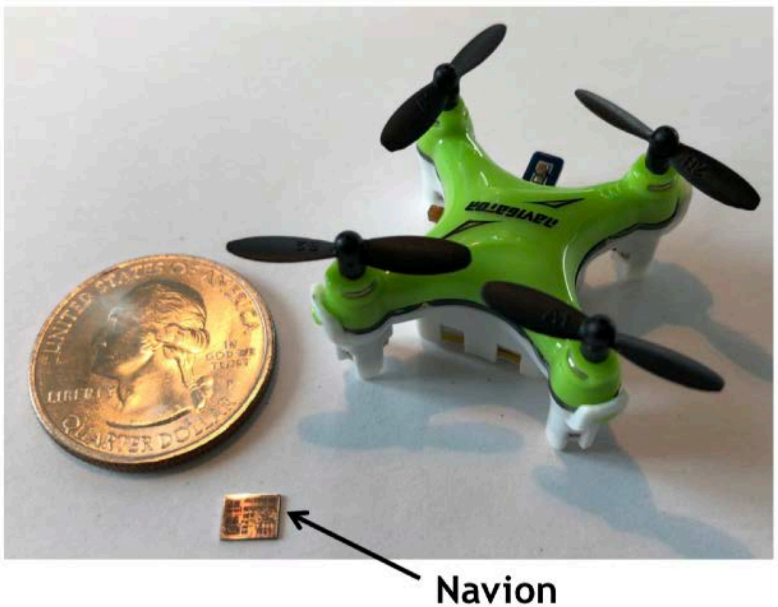
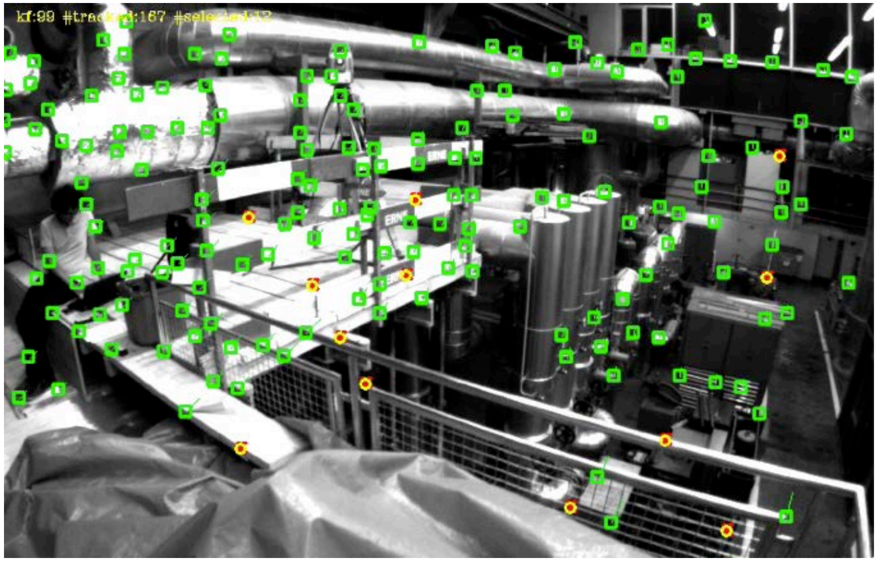
Efficient Real-time Perception

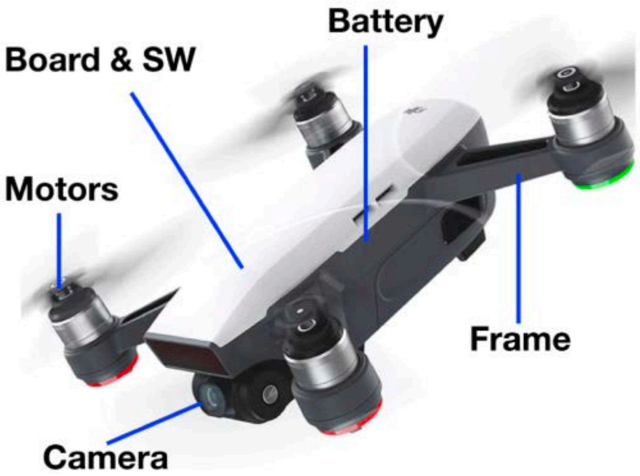
algorithm-and-hardware design



visual attention for robotics



robot co-design

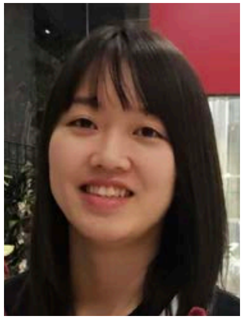


- **Key contribution (in collaboration with Karaman and Sze)**: the Navion Chip for visual-inertial navigation
  - uses 3 orders of magnitude less energy with respect to a state-of-the-art implementation on a workstation
  - ensures a comparable accuracy

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!

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DARPA

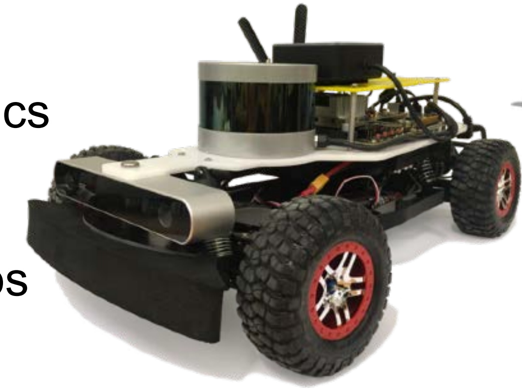
Google

Ford Go Further

Teaching Perception and Autonomy

6.141/16.405j - Robotics: Science And Systems

- Intro to robotics
- Coding: ROS and python
- Hands-on labs



16.S398 - Visual Navigation for Autonomous Vehicles

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