University of Zurich[UZH] | ETH zürich

Institute of Informatics – Institute of Neuroinformatics

ROBOTICS & PERCEPTION GROUP

Vision-based Agile Flight: Lessons Learned from the DARPA FLA program (2016-2018)

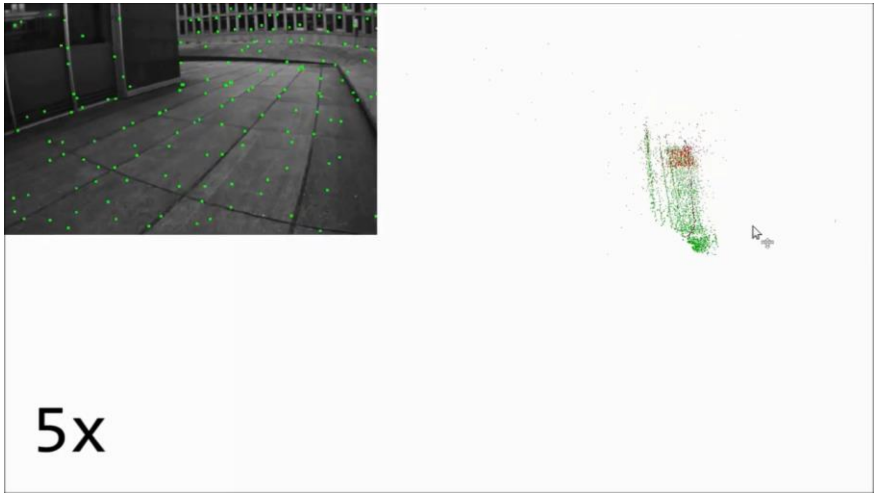
Davide Scaramuzza

- My lab homepage: http://rpg.ifi.uzh.ch/
- Publications: http://rpg.ifi.uzh.ch/publications.html
- Software & Datasets: http://rpg.ifi.uzh.ch/software_datasets.html
- YouTube: https://www.youtube.com/user/ailabRPG/videos

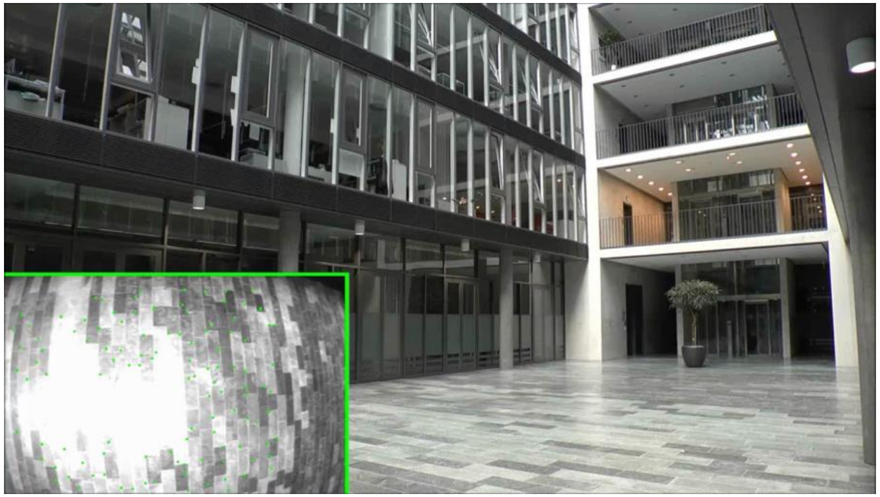
My Research Overview

Real-time, Onboard Computer Vision and Control for **Autonomous, Agile** Drone **Flight**

Visual-Inertial SLAM

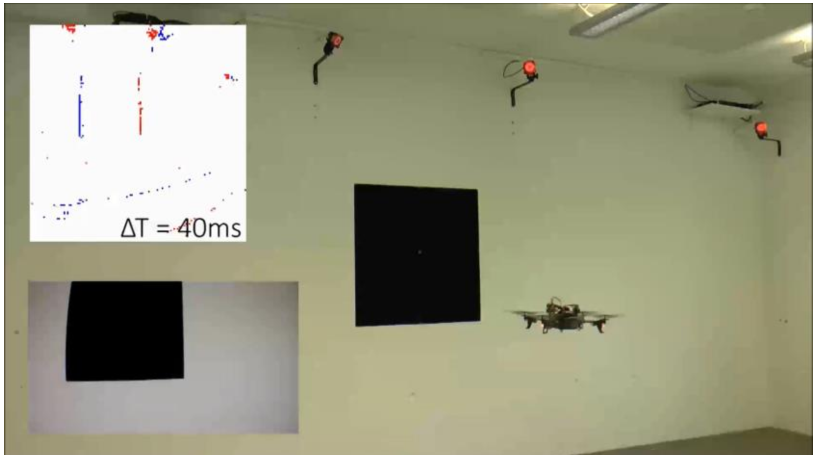


Autonomous Flight



Learning-aided Autonomous Navigation

Event-based Vision for Low-latency Control



Motivation: Flying Robots to the Rescue!

“DARPA FLA” Program (June 2015 – June 2018)

- **Minimalistic** high-speed navigation in cluttered environments.
- Autonomous flight at speeds up to **20 m/s (72 km/h) without GPS**.
- Pushing innovation **in high-speed perception, planning, and control**.
- **Indoor, outdoor,** and hybrid testing environments.

Vijay Kumar
UPenn

Davide Scaramuzza
University of Zurich & ETH

Toby Delbruck
IniVation

Brian Gerkey
OSRF (Open-Source Robotics Foundation)

“DARPA FLA” Program (June 2015 – June 2018)

Video: https://youtu.be/6eeetSVHXPk

Mohta, Loianno, Scaramuzza, Daniilidis, Taylor, Kumar, Fast, Autonomous Flight in GPS-denied and Cluttered Environments, *Journal of Field Robotics*, 35 (1), 2018. PDF

My Dream Robot: Fast, Lightweight, Autonomous (FLA)

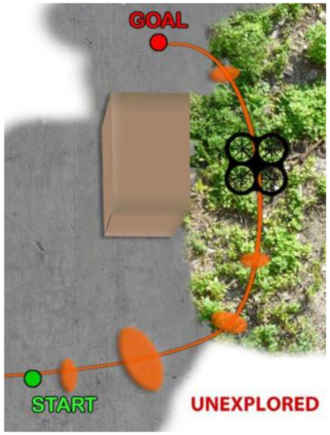
WARNING: These drones are computer generated ☺

https://www.youtube.com/watch?v=JDvcBuRSDUU

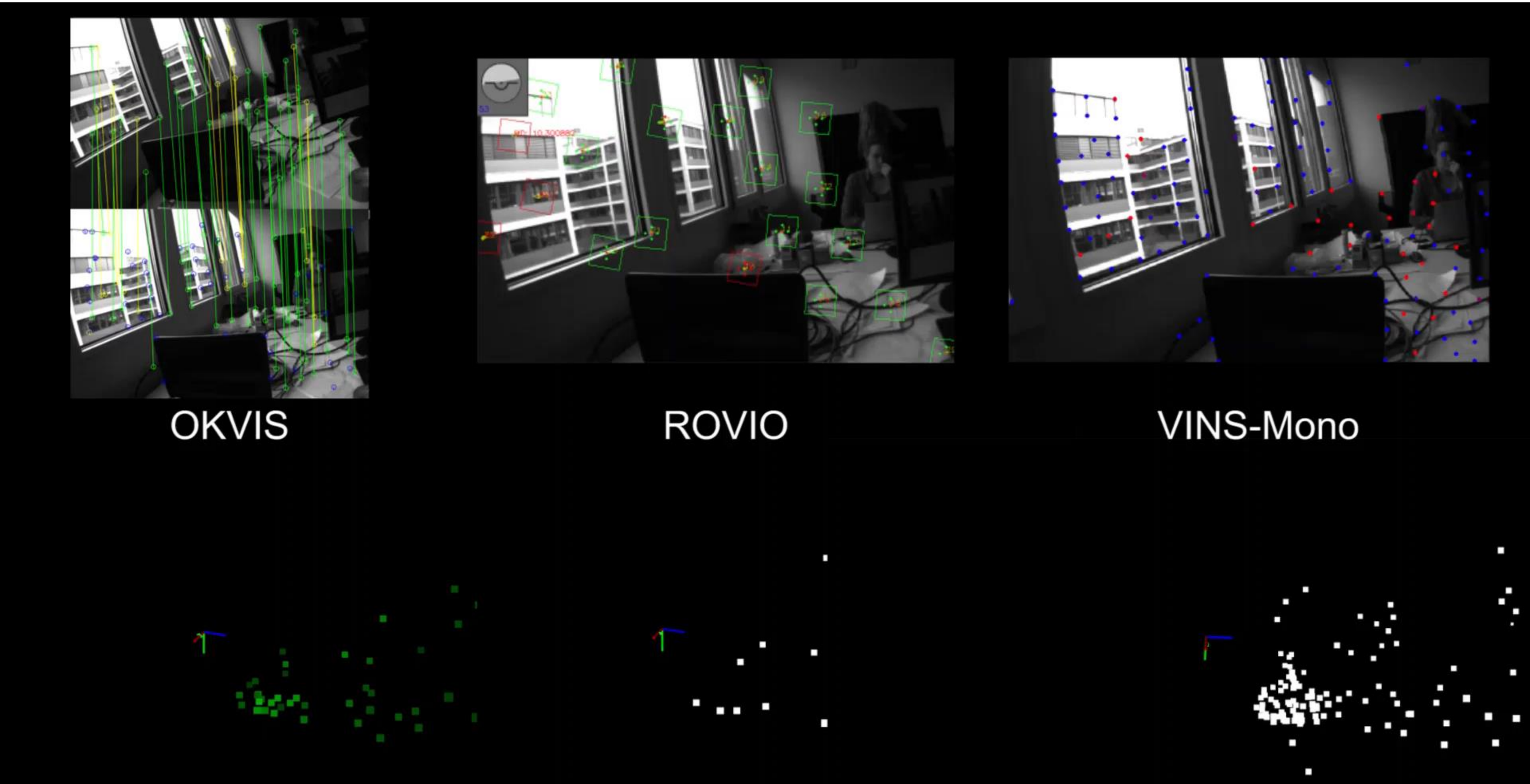
Current Open Challenges

Perception algorithms are **mature but not robust**

- Problems with **low texture, HDR scenes, motion blur**
- Unlike mocap systems, **localization accuracy** depends on **distance & texture**
- Algorithms and sensors have **big latencies** (50-200 ms) → need faster sensors
- Need **accurate models** of the **sensors** and the **environment**
- **Control & Perception** are often **considered separately** (e.g., perception, state estimation, and planning are treated as separate blocks)



Today, visual-inertial odometry systems based on standard cameras fail in high-speed scenarios and high dynamic range scenes.



Video: https://youtu.be/0hDGFFJQfmA

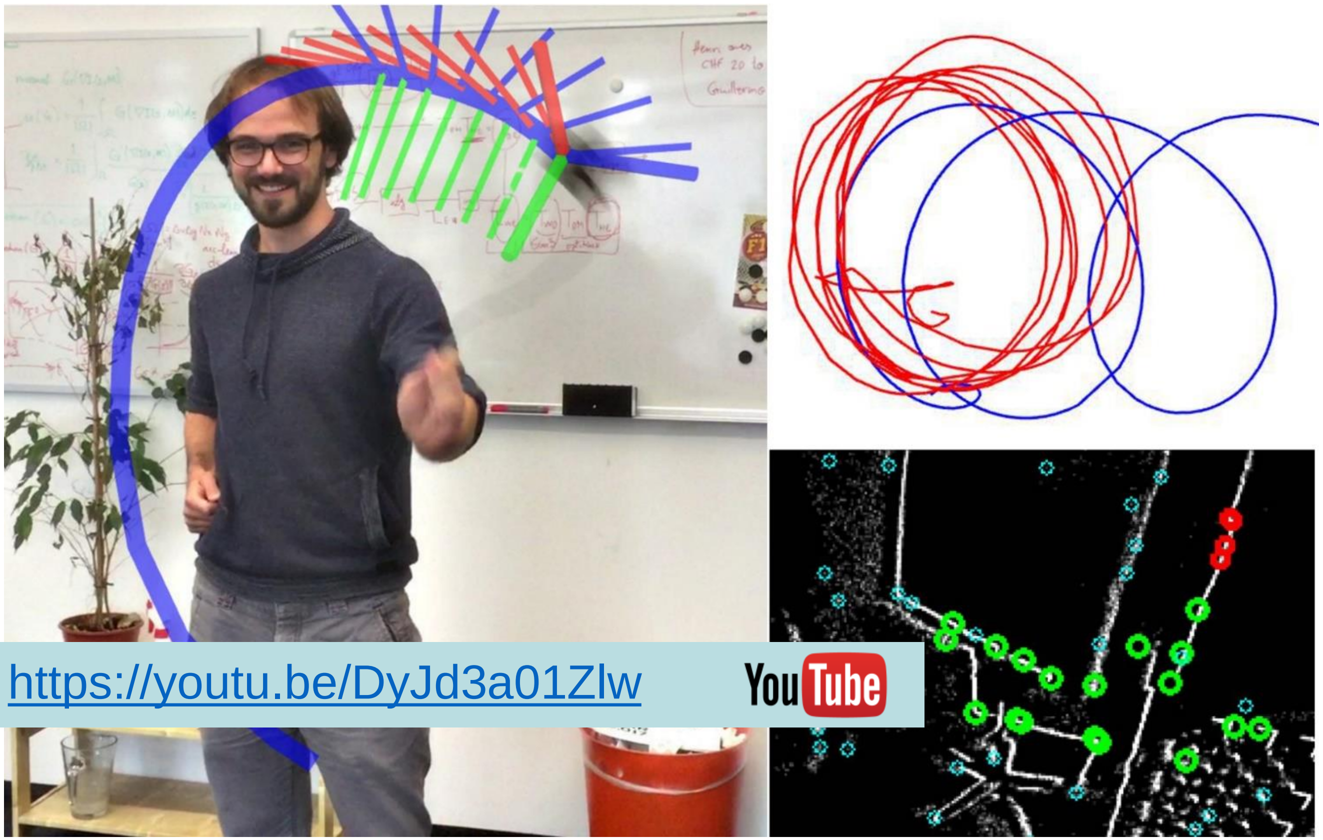
Ultimate SLAM?
Combining Events, Images, and IMU for Robust Visual SLAM in HDR and High Speed Scenarios

Vidal, Rebecq, Horstschaefer, Scaramuzza

IEEE RAL – ICRA 2018

PDF
YouTube
ICRA18 Video Pitch
Project Webpage

UltimateSLAM is the first VSLAM system that can combines the complementary advantages of an **event camera**, a **standard camera** and an **IMU** to achieve **robust SLAM operation** in **high-speed conditions** and **high dynamic range (HDR) scenes**.

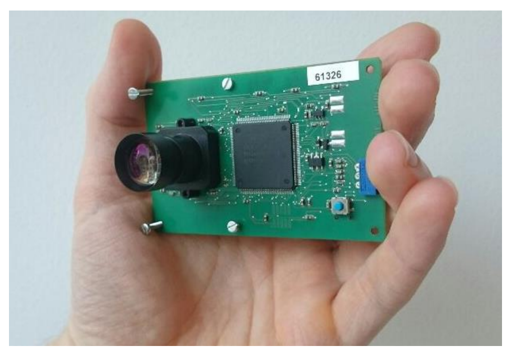


Video: https://youtu.be/DyJd3a01Zlw YouTube

Rosinol et al., Ultimate SLAM? Combining Events, Images, and IMU for Robust Visual SLAM in HDR and High Speed Scenarios, IEEE RAL'18, [PDF]()

What is an event camera?

- Novel sensor that **measures only motion** in the scene (i.e. motion-activated edge detector)
- Low-latency (~ 1 μs)
- No motion blur
- High dynamic range (140 dB instead of 60 dB)



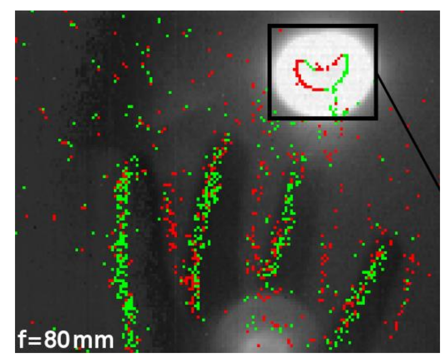
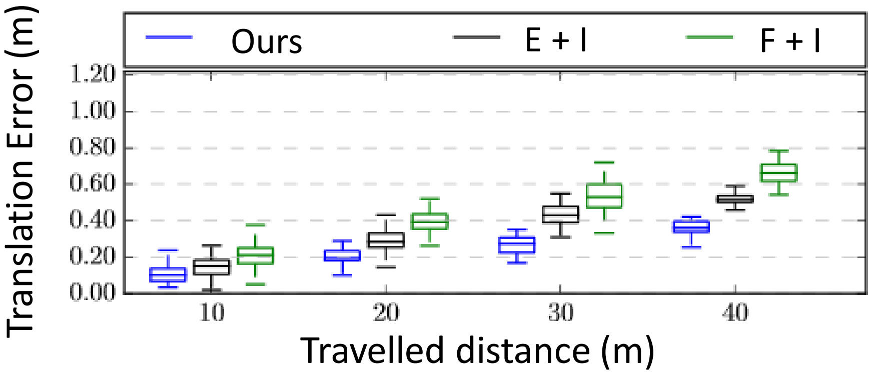
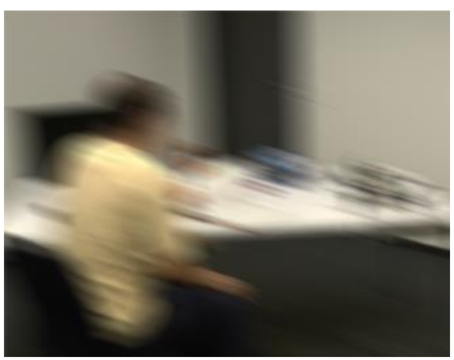


Image of solar eclipse captured by a DVS, without black filter!

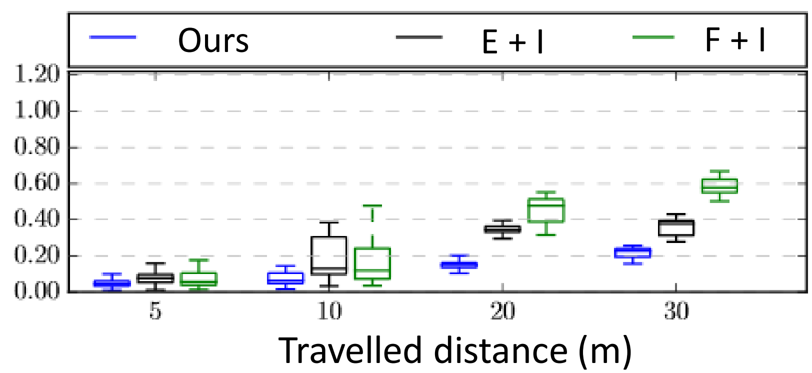
85% accuracy improvement over standard frame-based visual-inertial odometry

High-speed sequence



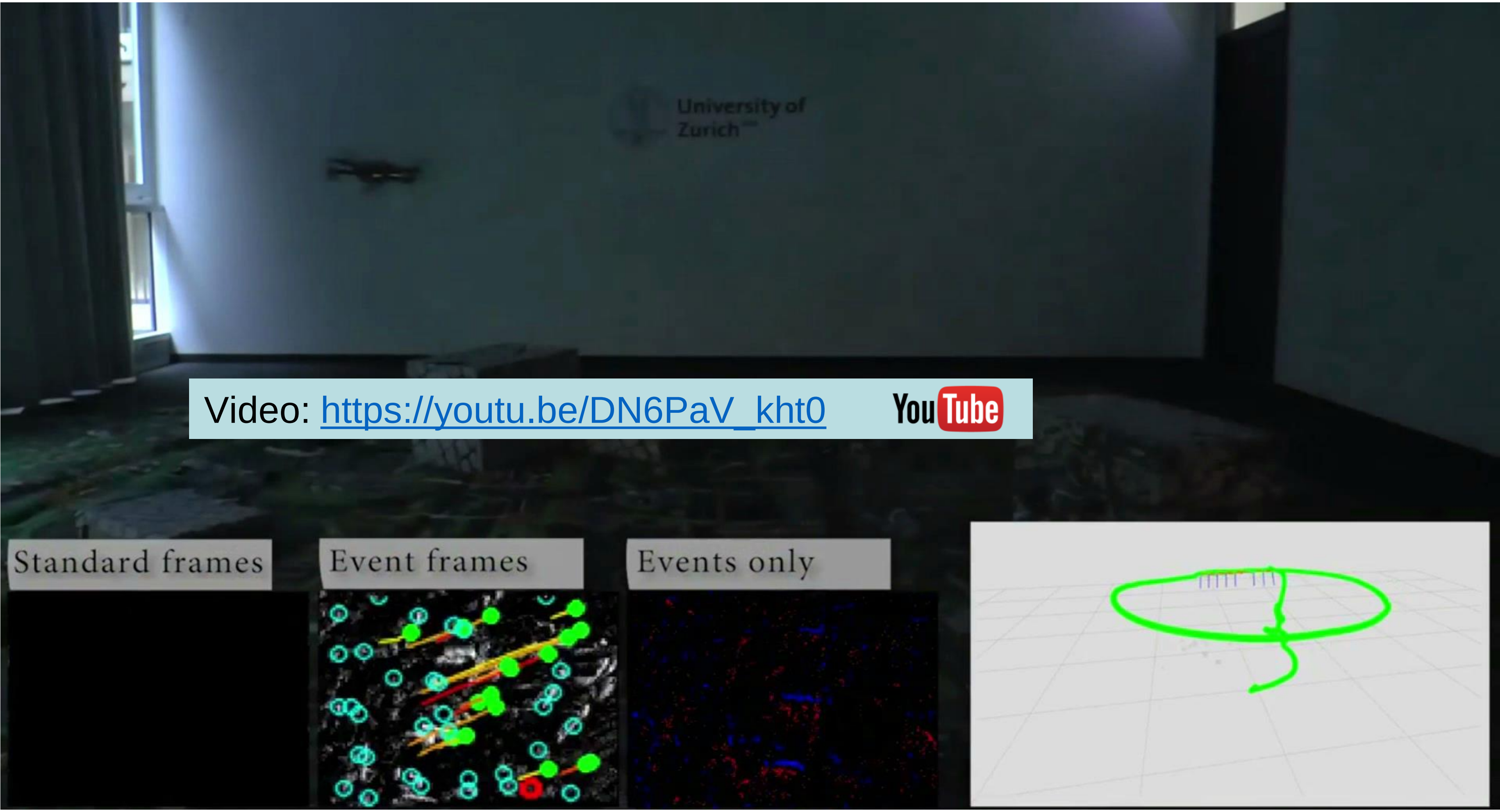


HDR sequence



Rosinol et al., Ultimate SLAM? Combining Events, Images, and IMU for Robust Visual SLAM in HDR and High Speed Scenarios, IEEE RAL'18, [PDF]

1st Autonomous Quadrotor Flight with an event camera (UltimateSLAM running fully onboard)



Video: https://youtu.be/DN6PaV_kht0

Rosinol et al., Ultimate SLAM? Combining Events, Images, and IMU for Robust Visual SLAM in HDR and High Speed Scenarios, IEEE RAL'18, PDF

DroNet:
Learning to Fly by Driving

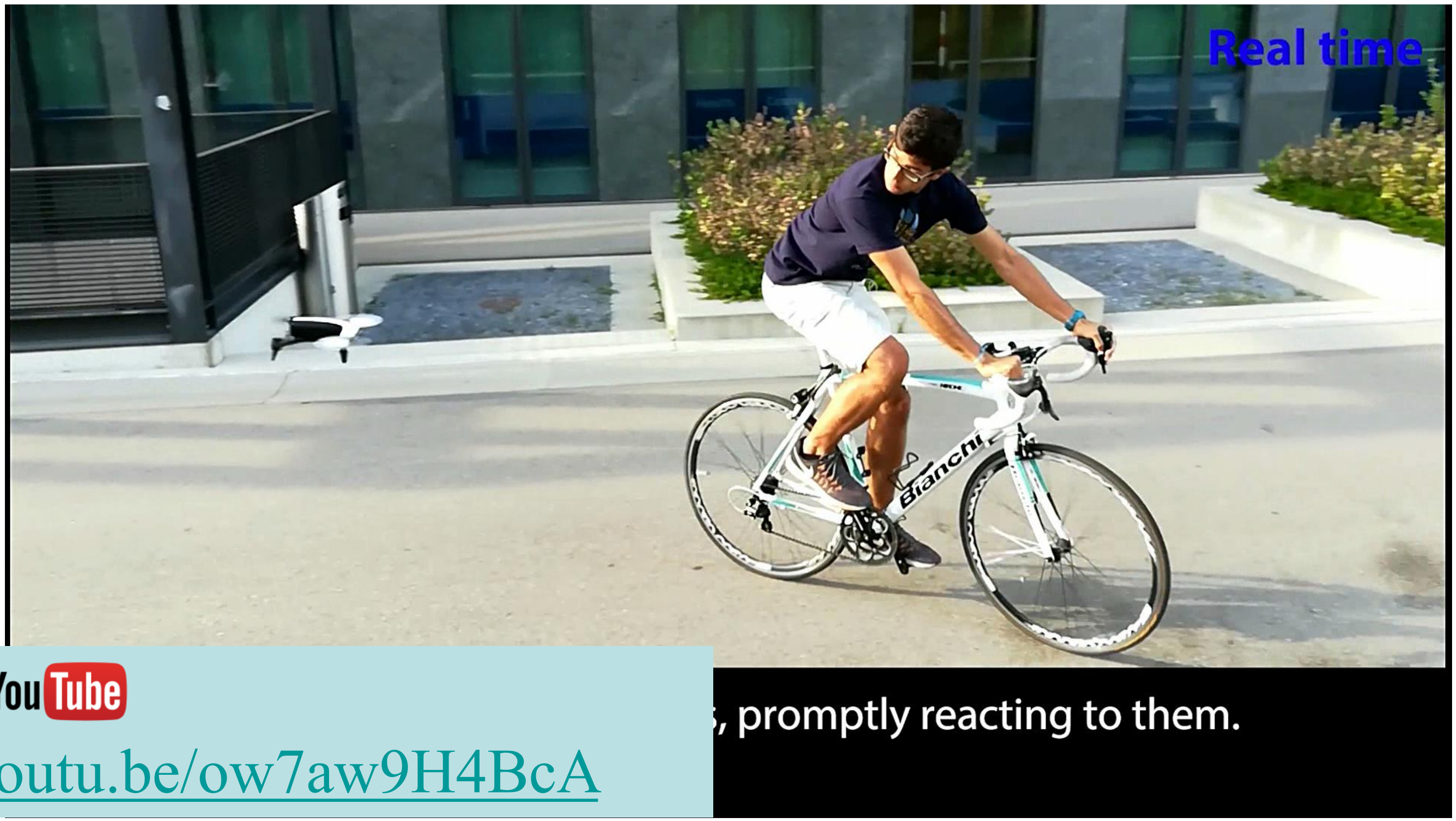
Loquercio, Maqueda, Del Blanco, Scaramuzza

IEEE RAL – ICRA 2018

PDF

DroNet: Learning to Fly by Driving

- DroNet learns to follow streets autonomously, without interaction
- The hardest problem in Machine Learning is **data collection**
- **Our idea: learn to fly autonomously by mimicking cars and bicycles!**



Video: YouTube
https://youtu.be/ow7aw9H4BcA

[Loquercio, DroNet: Learning to Fly by Driving, IEEE RAL'18
PDF. **Featured on IEEE Spectrum, MIT Technology Review,**
and **Discovery Channel Global**

Code & Datasets:
http://rpg.ifi.uzh.ch/dronet.html

PAMPC: Perception-Aware Model Predictive Control for Quadrotors

Davide Falanga*, Philipp Foehn*, Peng Lu, and Davide Scaramuzza

.04811v1 [cs.RO] 13 Apr 2018

***Abstract*— We present a perception-aware model predictive control framework for quadrotors that unifies control and planning with respect to action and perception objectives. Our framework leverages numerical optimization to compute trajectories that satisfy the system dynamics and require control inputs within the limits of the platform. Simultaneously, it optimizes perception objectives for robust and reliable sensing by maximizing the visibility of a point of interest and minimizing its velocity in the image plane. Considering both perception and action objectives for motion planning and control is challenging due to the possible conflicts arising from their respective requirements. For example, for a quadrotor to track a reference trajectory, it needs to rotate to align its thrust with the direction of the desired acceleration. However, the perception objective might require to minimize such rotation to maximize the visibility of a point of interest. A model-based optimization framework, able to consider both perception and action objectives and couple them through the system dynamics, is therefore necessary. Our perception-aware model predictive control framework works in a receding-horizon fashion by iteratively solving a non-linear optimization problem. It is capable of running in real-time, fully onboard our lightweight, small-scale quadrotor using a low-power ARM computer, together with a visual-inertial odometry pipeline. We validate our approach in experiments demonstrating (I) the contradiction between perception and action objectives, and (II) improved behavior in extremely challenging lighting conditions.**

SUPPLEMENTARY MATERIAL

This paper is accompanied by a video showcasing the conducted experiments: http://rpg.ifi.uzh.ch/pampc

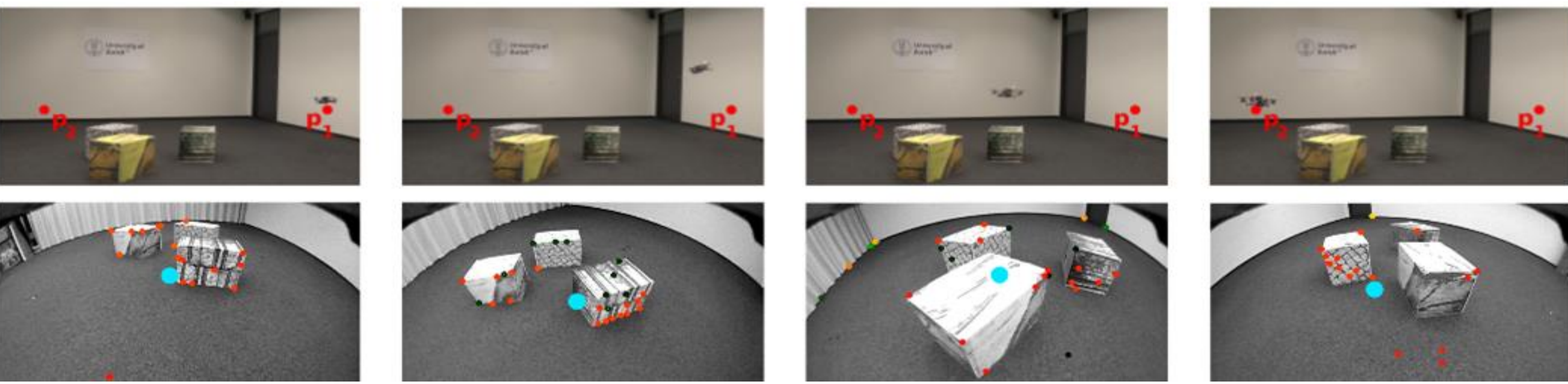
Fig. 1: An example application of our PAMPC, where a quadrotor is asked to fly at $3\,\mathrm{m/s}$ around a region of interest while keeping it visible in the field of view of its camera.

systems with onboard vision, since the motion of a camera can negatively affect the quality of the estimation, posing hard bounds on the agility of the robot. On the other hand, perception can benefit from the robot motion if it is planned considering the necessities and the limitations of onboard vision. For example, to pass through a narrow gap while localizing with respect to it using an onboard camera, it is necessary to guarantee that the gap is visible at all times. Similarly, to navigate through an unknown environment, it is necessary to guarantee that the camera always points towards texture-rich regions.

To fully leverage the agility of autonomous quadrotors, it

PAMPC: Perception Aware Model Predictive Control

- Manipulates trajectories to **increase visibility of points of interest**
  - Example hover-to-hover: increased thrust → lower pitch + more altitude → better visibility
- Controls **heading to look towards point of interest**
- **Robustly tracks reference jumps or trajectories**
- Execution time: **3.5ms on a single core** of a low-power ARM processor (Qualcomm Snapdragon or Odroid). Runs online with **100Hz**



Falanga, Foehn, Peng, Scaramuzza, *PAMPC: Perception-Aware Model Predictive Cotrol,* [Arxiv](). [Code]().

PAMPC: Perception Aware Model Predictive Control

Open Source:
MPC: https://github.com/uzh-rpg/rpg_quadrotor_mpc

Video: YouTube
https://youtu.be/9vaj829vE18

Falanga, Foehn, Peng, Scaramuzza, *PAMPC: Perception-Aware Model Predictive Cotrol,* Arxiv. Code.

Thanks!

- My lab homepage: http://rpg.ifi.uzh.ch/
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- Software & Datasets: http://rpg.ifi.uzh.ch/software_datasets.html
- YouTube: https://www.youtube.com/user/ailabRPG/videos