University of Zurich[UZH]

ROBOTICS & PERCEPTION GROUP

Autonomous Inspection with Drones done Fast

Davide Scaramuzza

http://rpg.ifi.uzh.ch/

Today’s Global Commercial Drone Market: **24 Billion USD**

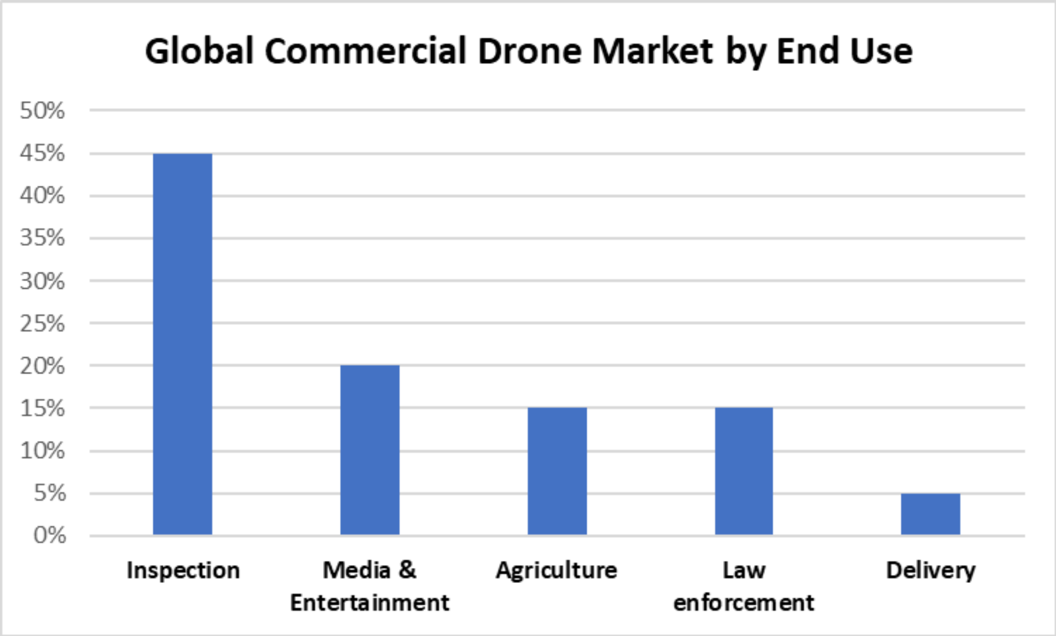
The global commercial drone market is expected to reach $500 billions by 2028

Inspection

Media & Entertainment

Agriculture

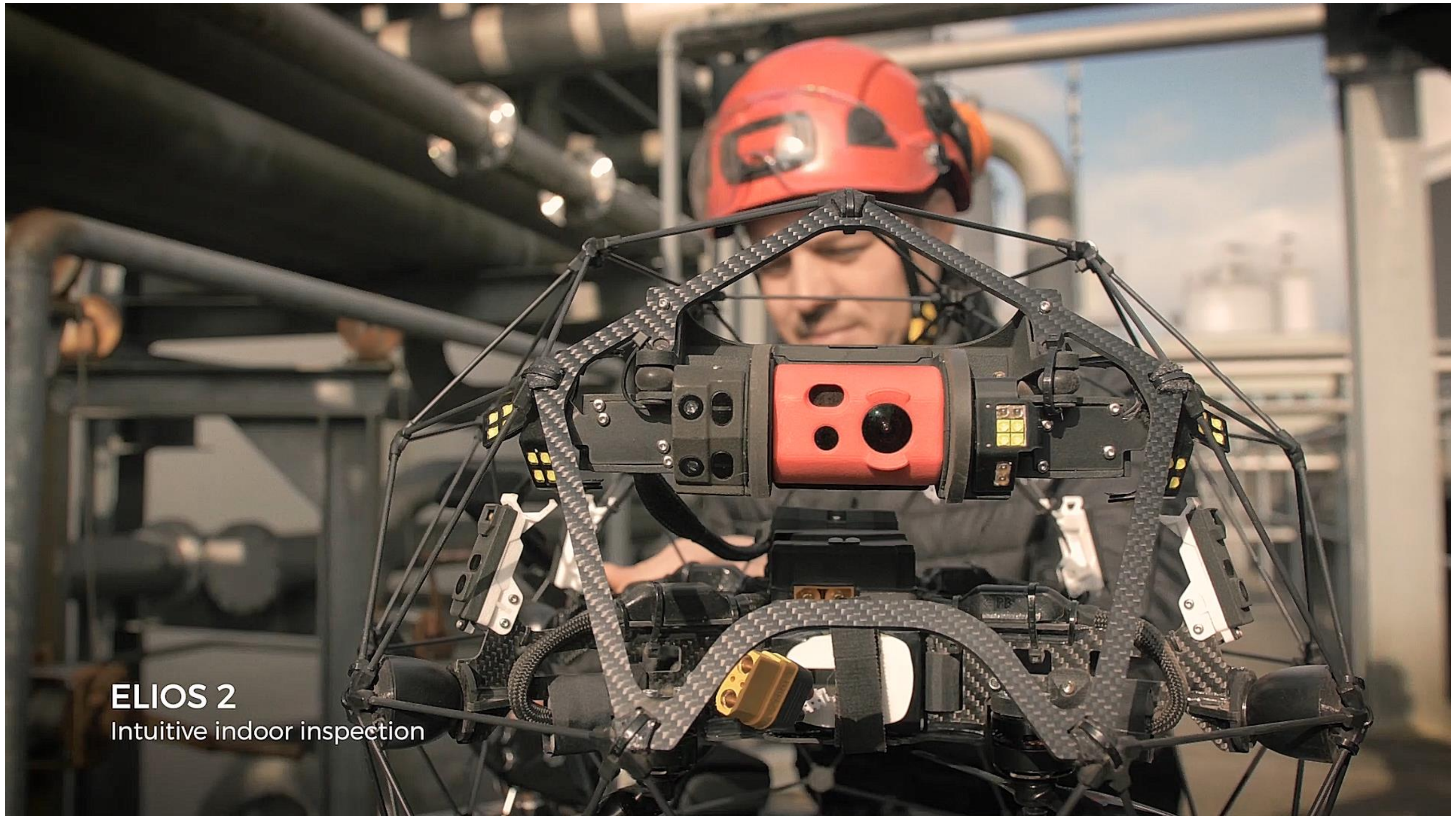
Law enforcement



Grand View Research, Commercial drone market size, share & trends analysis, 2021: Link

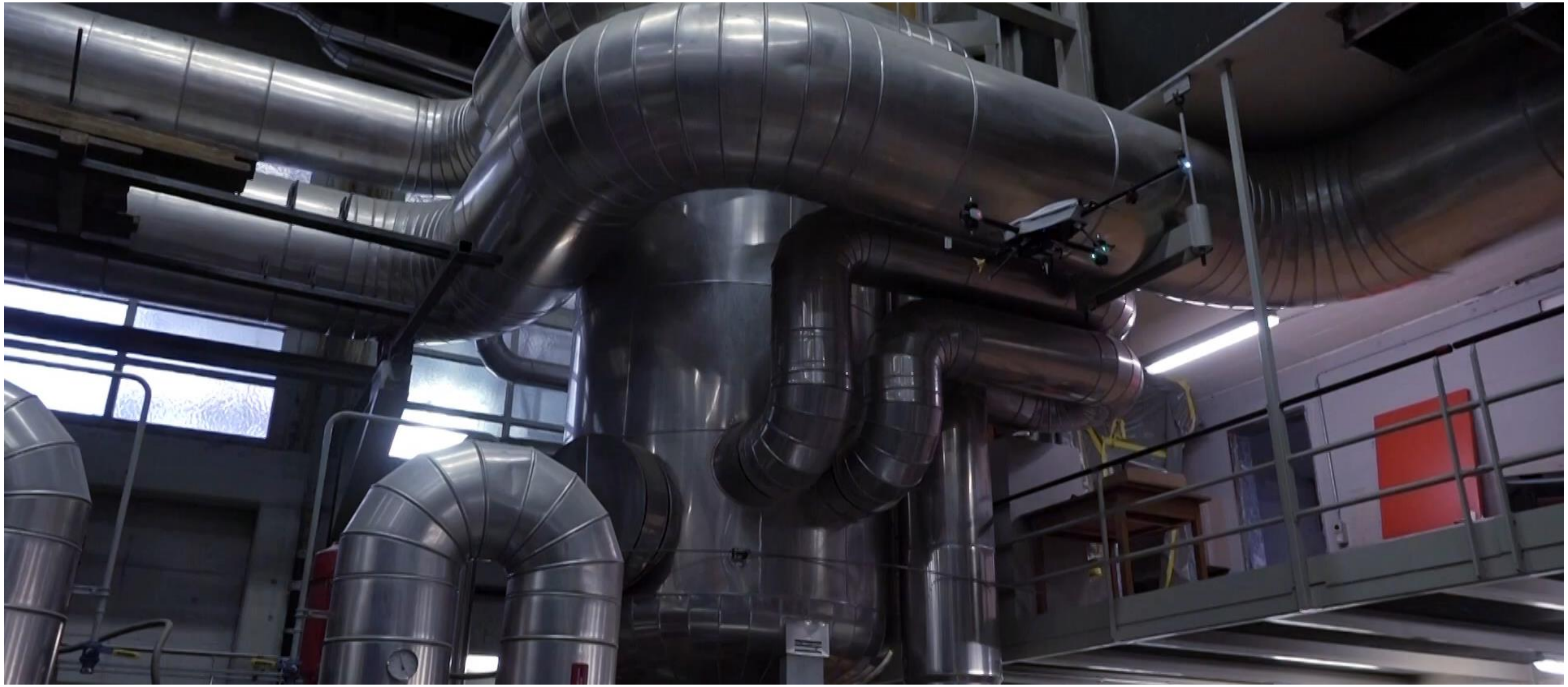
2

99% commercial drones is controlled by human pilots



Video from «Flyability», company based in Lausanne, Switzerland

99% commercial drones is controlled by human pilots



Voliro (2019) – Contact Inspection Drone (remote controlled).
Uses tiltable motors for omnidirectional navigation, scanning, drilling, and painting

Can drones do autonomous inspection and maintenance?

EU Project AERIAL-CORE (2020-2023)
Autonomous Inspection and Maintenance of Power Lines by Drones

https://aerial-core.eu/

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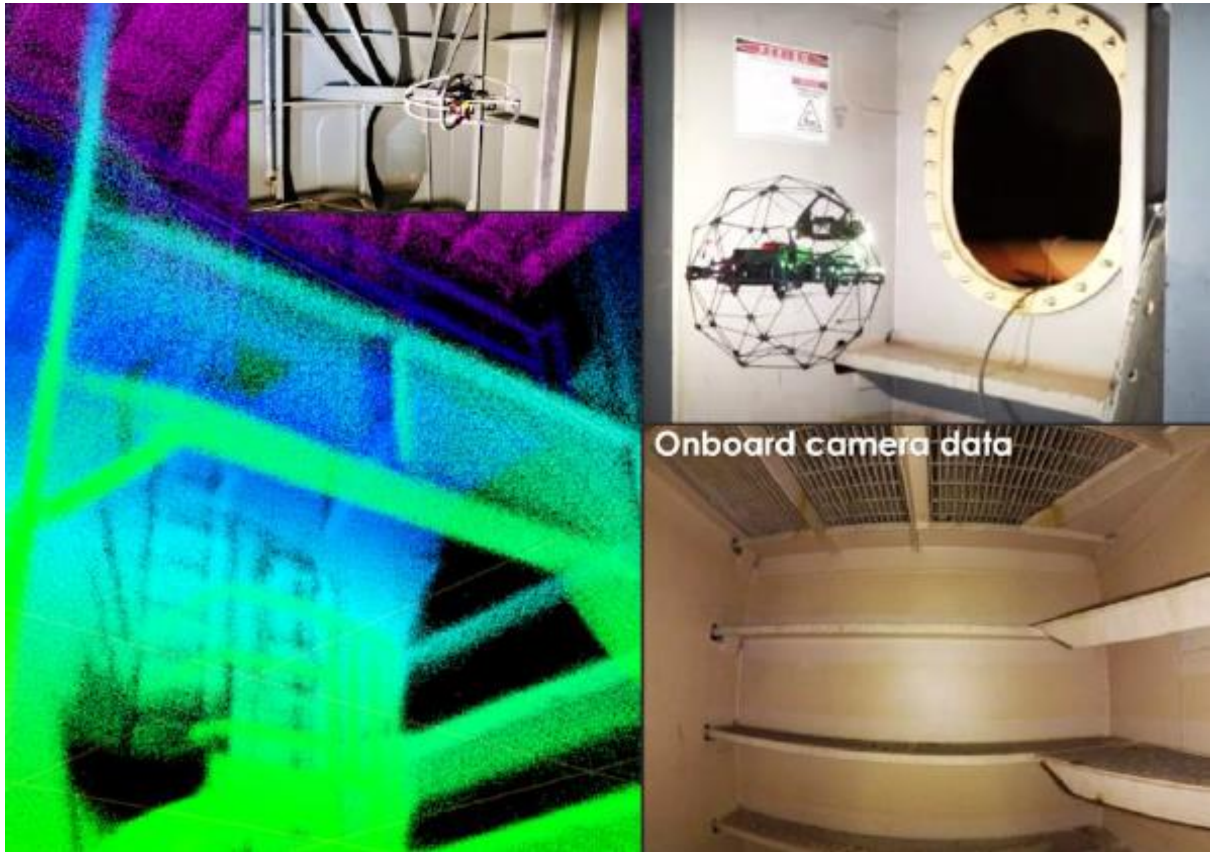
Autonomous Inspection and Maintenance of Power Lines by Drones

https://aerial-core.eu/

EU Project AutoAssess (2024-2027)
Autonomous Inspection of Ballast Tanks of Container Ships



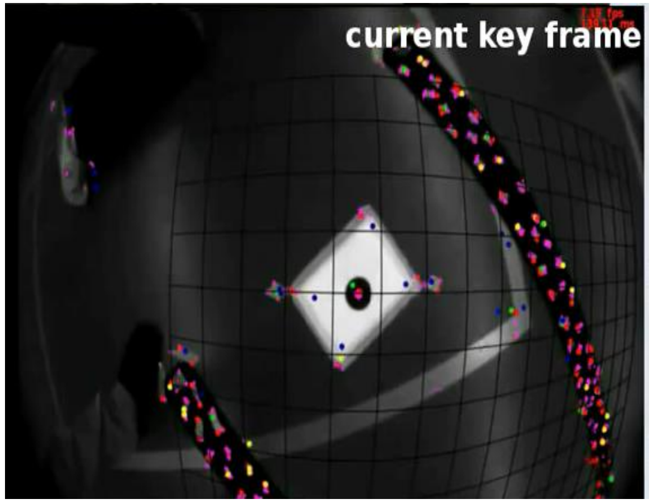
How can drones navigate autonomously?

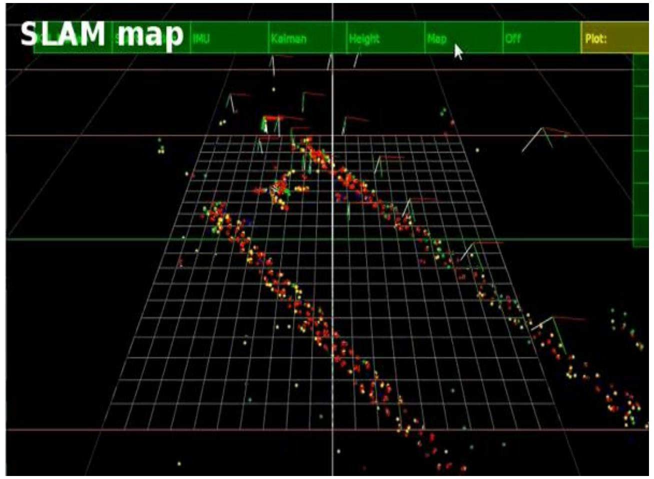
Using **cameras**

10

Vision-based Navigation

2009: First Vision-based Autonomous Flight

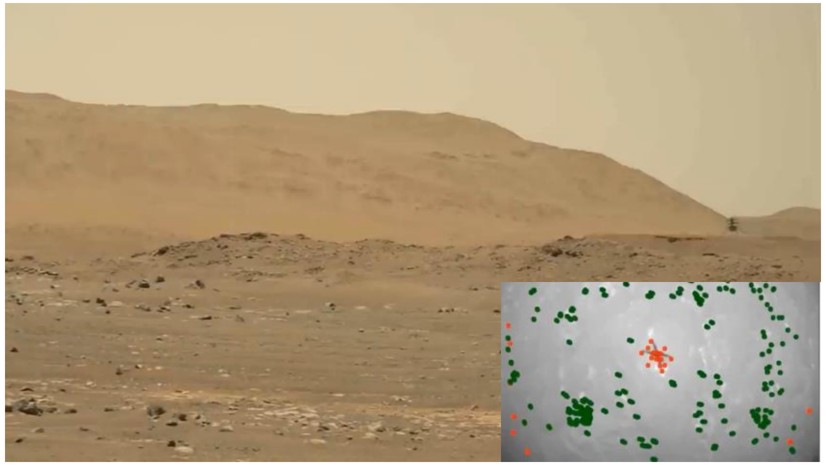




European Micro Aerial Vehicle competition, Sep. 9, 2009

Bloesch, Weiss, Scaramuzza, Siegwart, *Vision Based MAV Navigation in Unknown and Unstructured Environment*, ICRA'10
Weiss, Scaramuzza, Siegwart, *Monocular-SLAM–based Navigation for Autonomous Micro Helicopters in GPS-denied Environments,* JFR'11

Today



NASA Mars Helicopter

SKYDIO: Bridge inspection

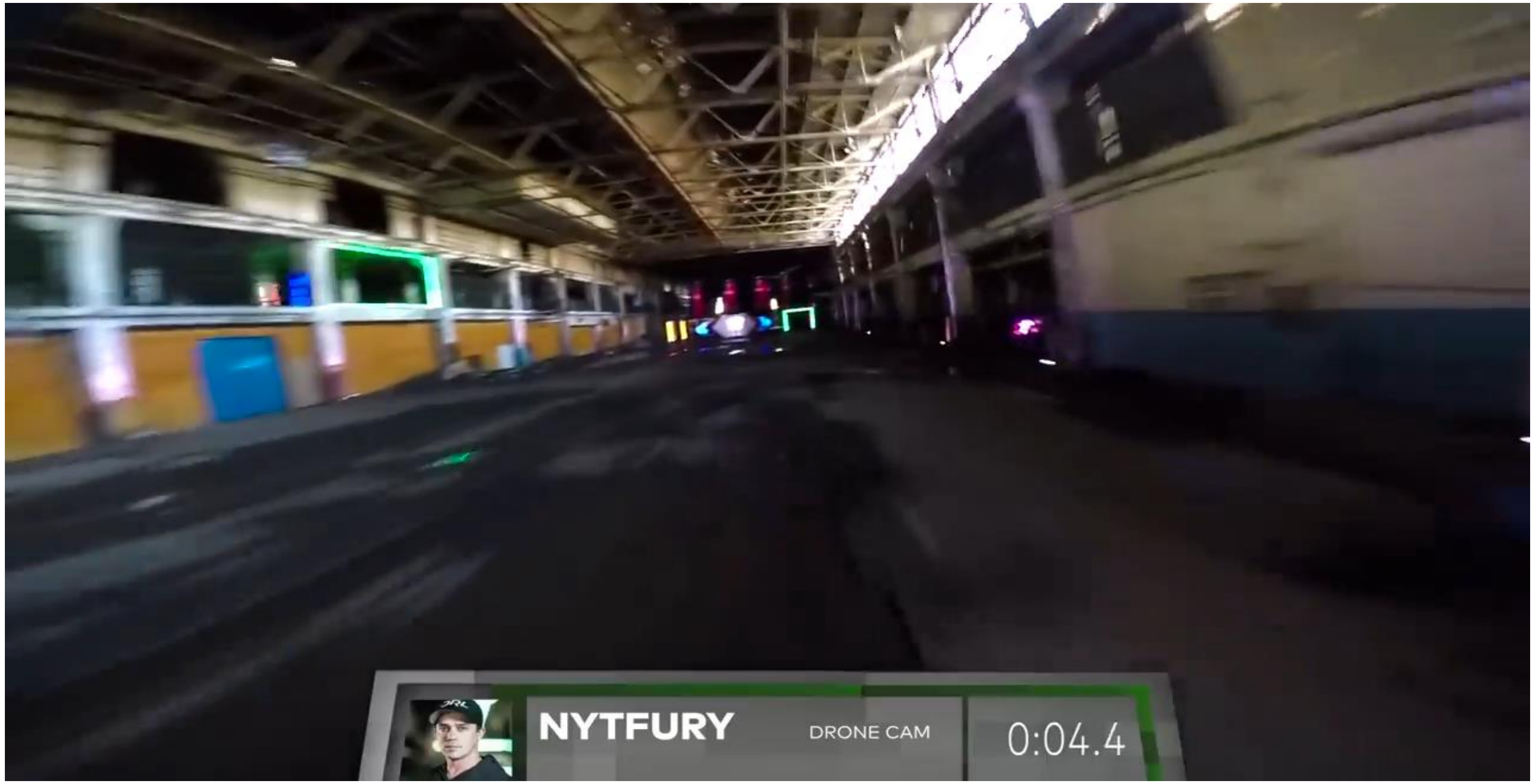
VERITY: inventory management

SUIND: crop spraying

Vision is making flying robots more autonomous,
but **human pilots are still preferred** in most applications

Autonomous drones are still far from human-pilot performance
regarding **agility**, **versatility**, **robustness**

What does it take to fly **as agile as** or better than **human pilots**?



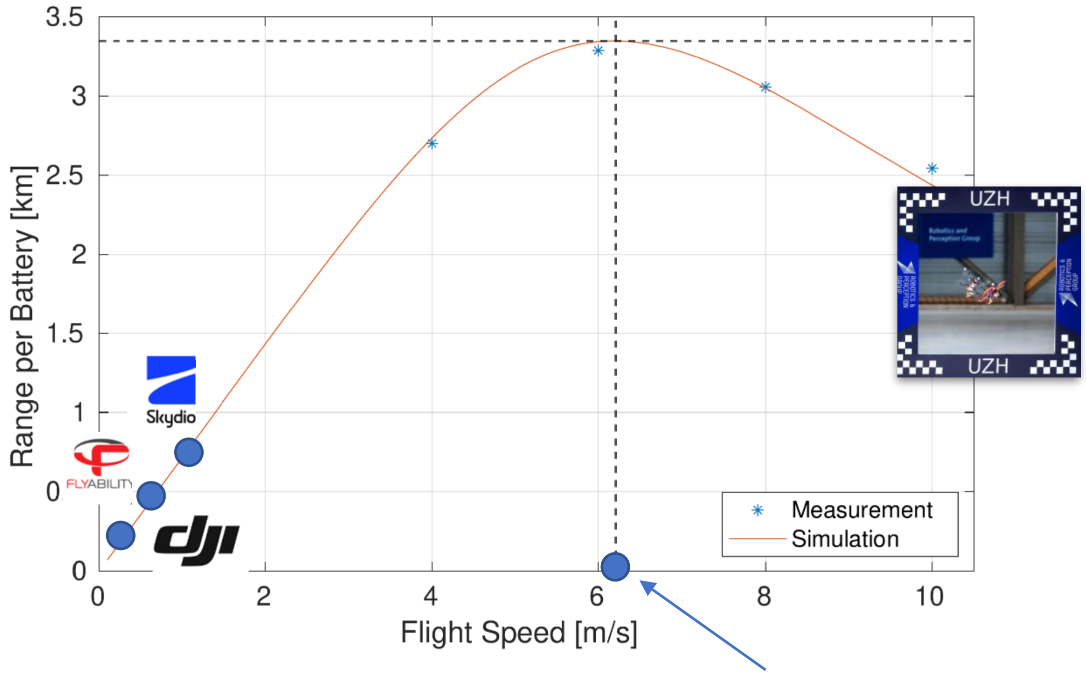
WARNING! This drone is NOT autonomous; it is operated by a human pilot.

Human pilots take years to become **agile**

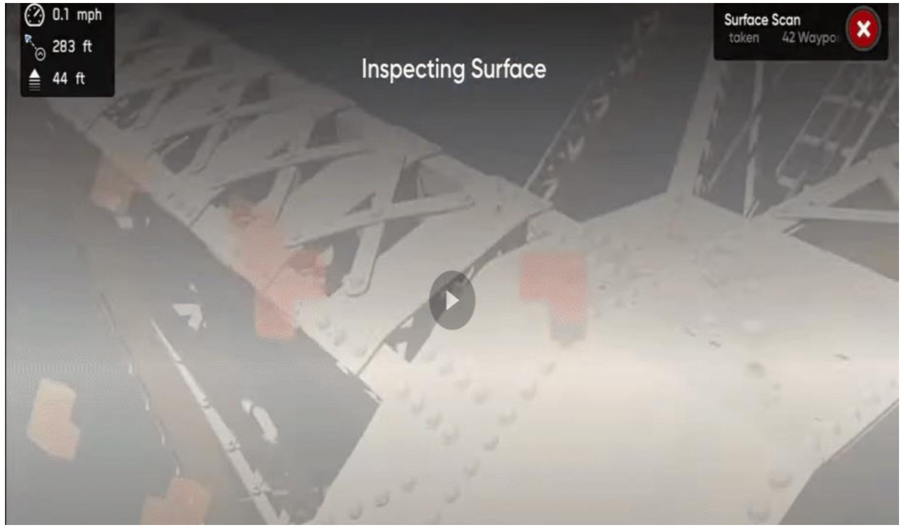
Pfeiffer, Scaramuzza (2021) *Human-piloted drone racing: Perception and control*, **RAL'21**

Why Agile? To Increase Productivity

- Multi-rotor drone's **battery** limited to **30 minutes**
- By flying **faster**, they can fly **farther** [1]



Optimal speed



Current inspection drones fly slow:

- Safety/Robustness
- Motion Blur
- Frequent Battery Replacement

[1] Bauersfeld, Scaramuzza, *Range, Endurance, and Optimal Speed Estimates for Multicopters*, IEEE RAL, 2022. PDF.

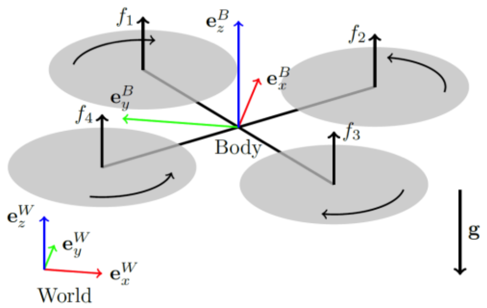
Vision-based Drone Control Architecture

Images
IMU

Perception → Planning → Control → **Commands**

✓ State estimation:
- Position
- Orientation
- Velocity

✓ Local 3D map



Vision-based Drone Control Architecture

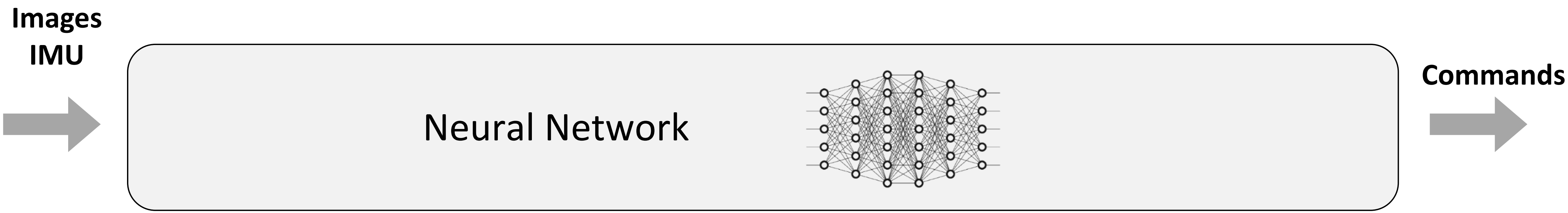
Images
IMU

→ Perception → Planning → Control →

Commands

Fragile to imperfect perception and unmodelled effects, and slow

Can we Learn a Navigation Policy?



Key issues with this architecture:

- **Too sample inefficient** to be trained on a physical drone
- Limited **interpretability**

How can we augment the traditional robotic cycle with learning-based methods?

Key Questions

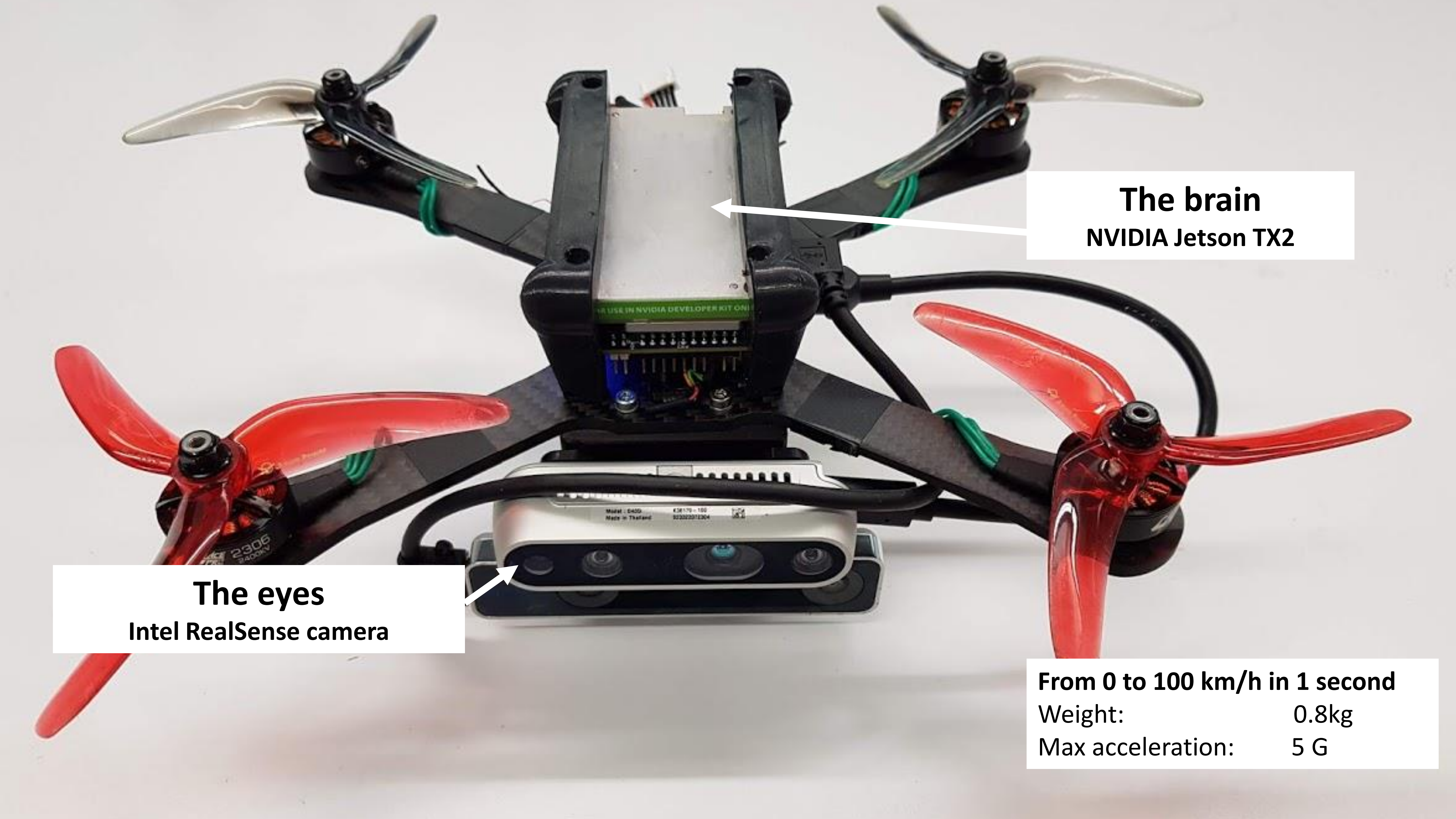
- Should we train it with or without supervision?
- How do we get enough training data? Can we learn in simulation?
- How do we address the simulation to reality gap?

Tasks

Autonomous Drone Acrobatics

Navigation in the wild

Autonomous Drone Racing


The brain
NVIDIA Jetson TX2
The eyes
Intel RealSense camera
From 0 to 100 km/h in 1 second
Weight: 0.8kg
Max acceleration: 5 G

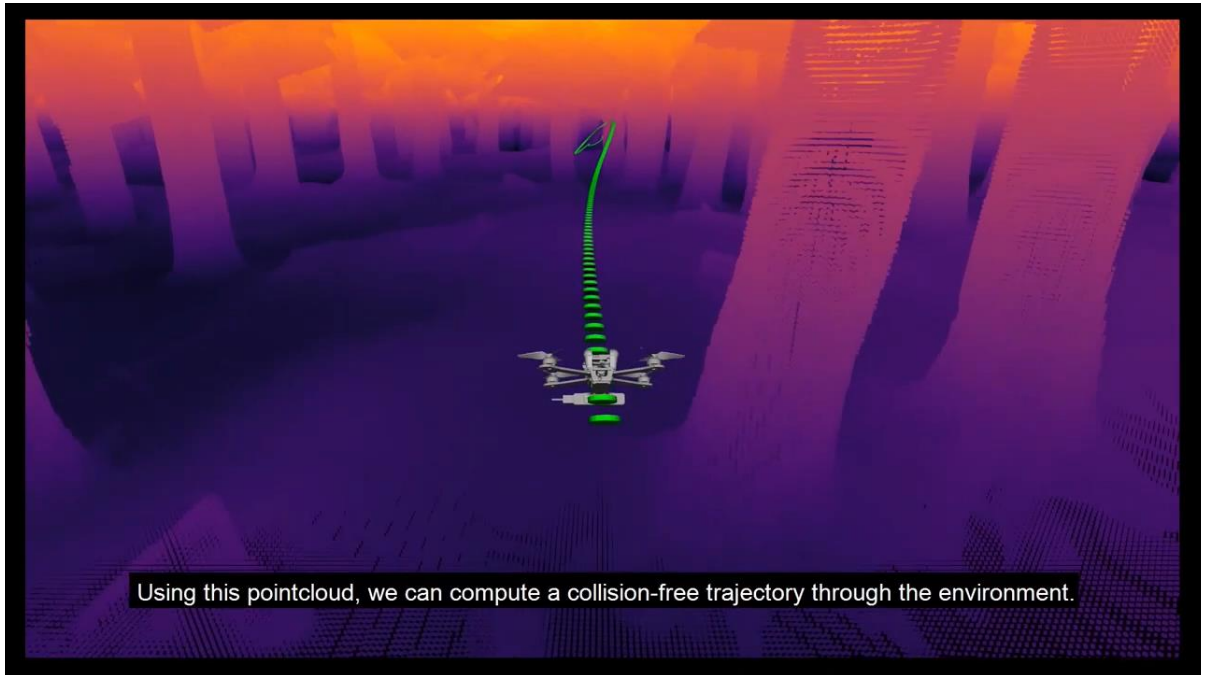
Thanks to Machine Learning we reached unprecedented agility

- The learned policy is **more robust against sensor noise** than traditional baselines
- Up to **2x faster** than traditional approaches

This AI-controlled drone is fully autonomous and uses onboard vision and computation

Loquercio, Kaufmann, Ranftl, Mueller, Koltun, Scaramuzza, *Learning High Speed Flight in the Wild*, **Science Robotics, 2021**
Kaufmann et al., *Deep Drone Acrobatics*, **RSS 2020. Best Paper Award Finalist**

…by training only in in simulation (zero shot)



Loquercio, Kaufmann, Ranftl, Mueller, Koltun, Scaramuzza, *Learning High Speed Flight in the Wild*, **Science Robotics, 2021**
Kaufmann et al., *Deep Drone Acrobatics*, **RSS 2020. Best Paper Award Finalist**

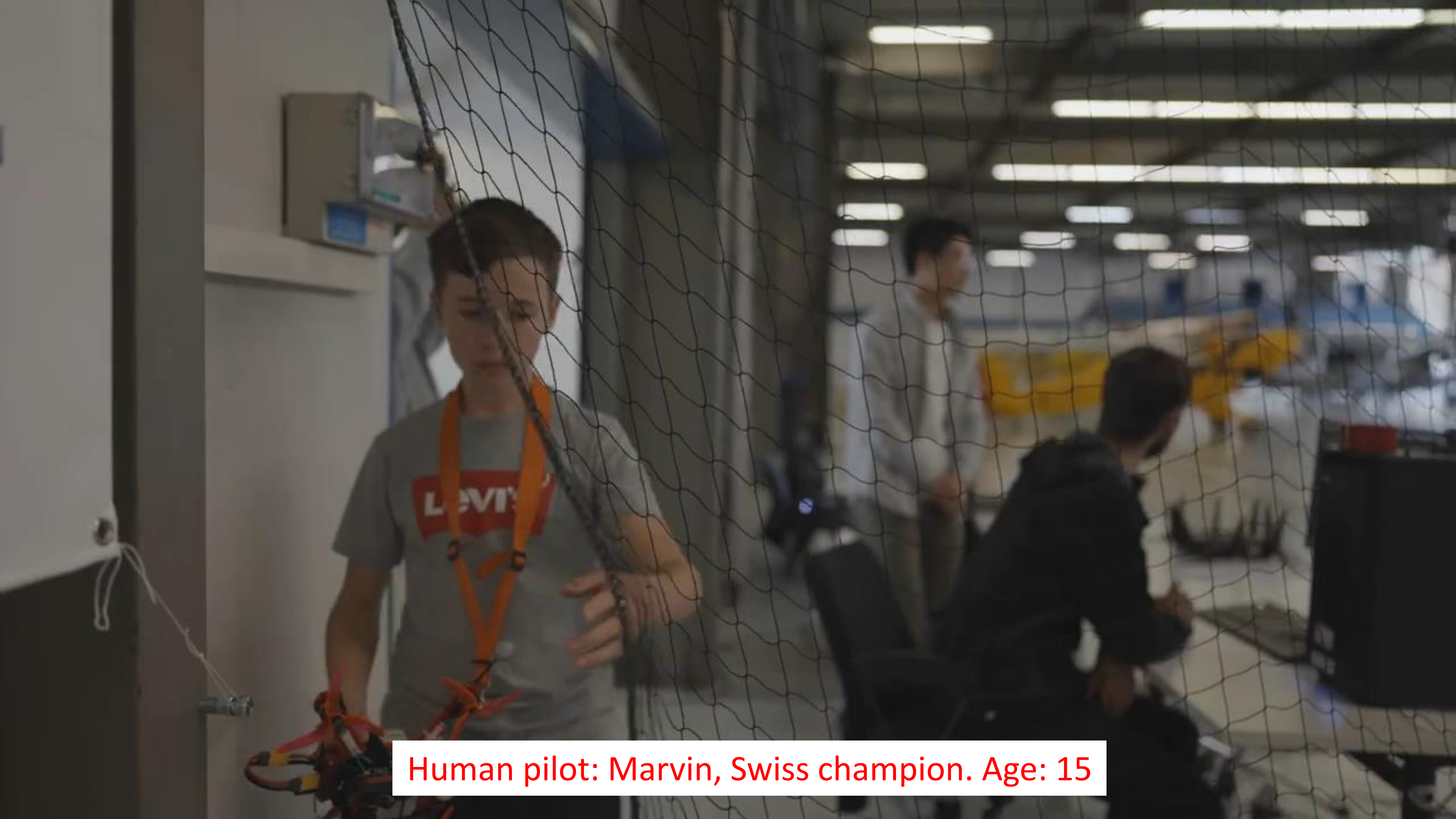
Open Challenge

- The presented approaches still rely on **labeled expert data**
- **What if we cannot create such an expert?**

Autonomous Drone Acrobatics

Navigation in the wild

Autonomous Drone Racing



Human pilot: Marvin, Swiss champion. Age: 15

Can we outrace the best human pilot?

After 7 years of work, in June 2022, we invited the world champions of drone racing

Alex Vanover

DRL World Champion

Thomas Bitmatta

MultiGP International World Champion

Marvin Schaepper

Swiss Drone League Champion

AI Drone

Both human and AI drones were identical

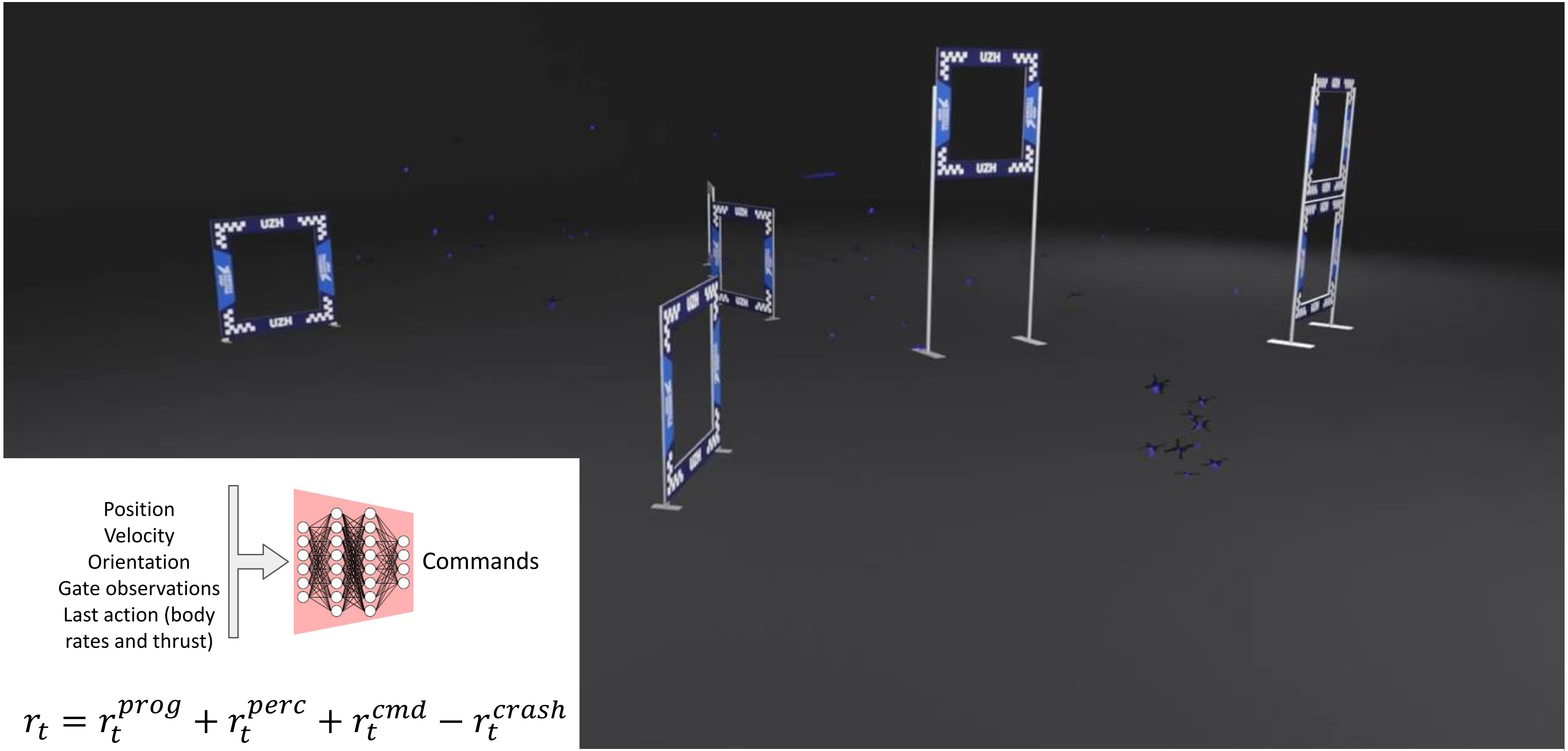
Kaufmann, Bauersfeld, Loquercio, Mueller, Koltun, Scaramuzza,
Champion-Level Drone Racing using Deep Reinforcement Learning, **Nature, 2023**

Drone Racing

Autonomous Drone	World's Best Human Pilots
"Swift"	A. Vanover, T. Bitmatta, M. Schaepper

Kaufmann, Bauersfeld, Loquercio, Mueller, Koltun, Scaramuzza,
Champion-Level Drone Racing using Deep Reinforcement Learning, **Nature, 2023**

Trained with RL in Simulation and refined with Data Collected in the Real World

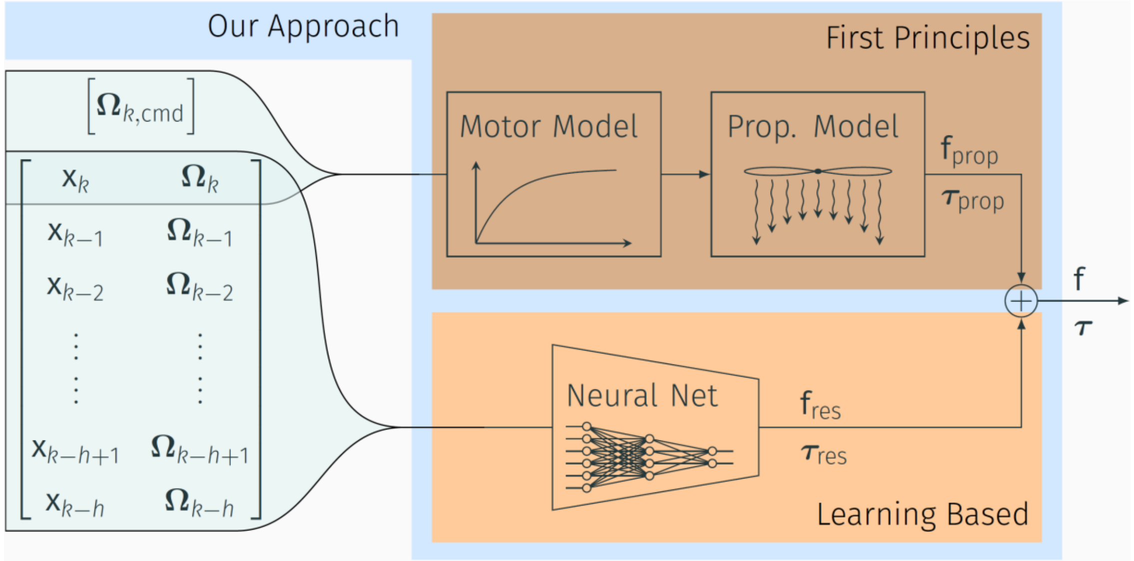


$$r_t = r_t^{prog} + r_t^{perc} + r_t^{cmd} - r_t^{crash}$$

Kaufmann, Bauersfeld, Loquercio, Mueller, Koltun, Scaramuzza,
Champion-Level Drone Racing using Deep Reinforcement Learning, **Nature, 2023**

Modeling Aerodynamic Effects

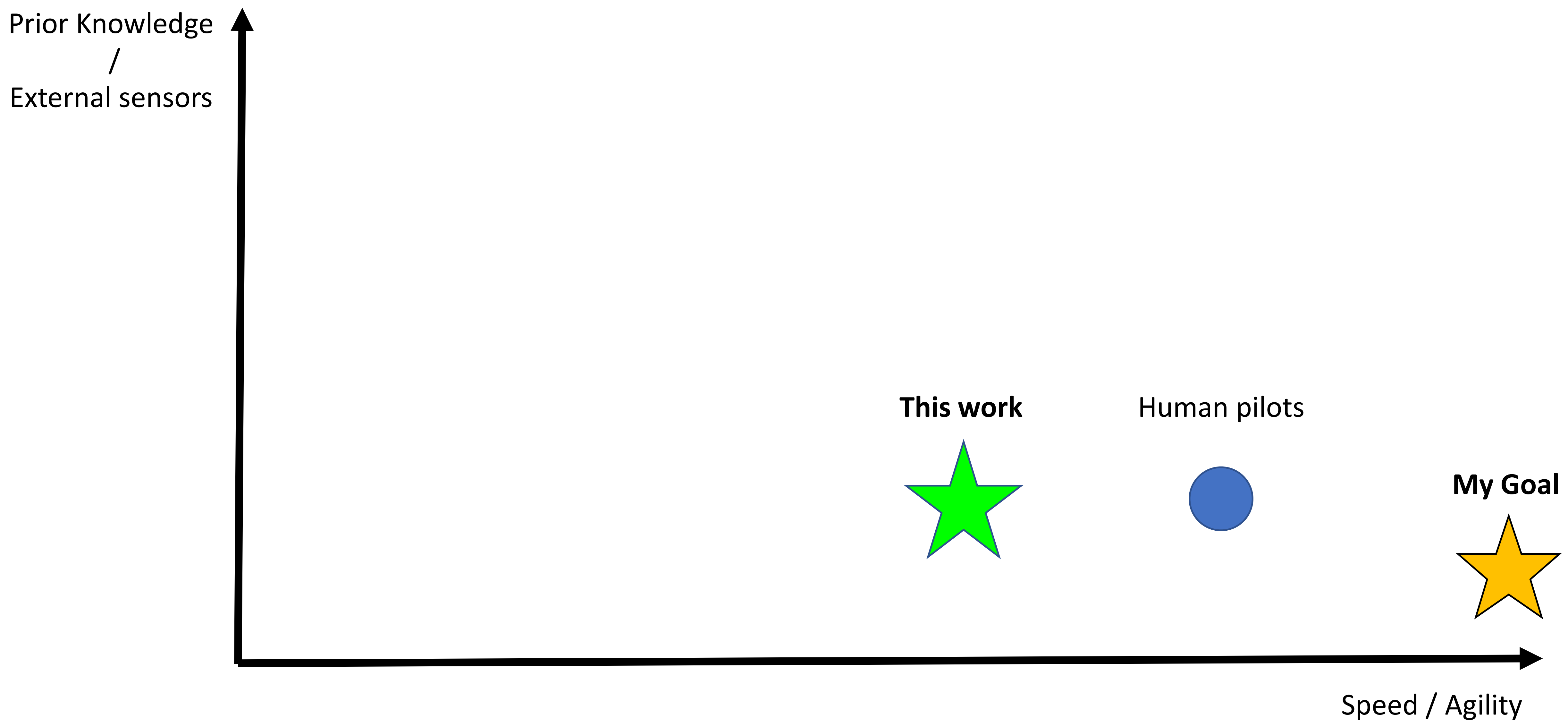
- Aerodynamic effects: **Rotor-to-rotor interactions**, **turbulences**
- Neural network to model **residual forces and torques** unexplained by first-principles models (BEM)
- **Improves physics realism** wrt classic drone simulators by up to **60%**



Bauersfeld et al. *NeuroBEM: Hybrid Aerodynamic Quadrotor Model*, **RSS'21**
Torrente et al., *Data-Driven MPC for Quadrotors*, **RAL'21**


The international journal of science / 31 August 2023
nature
DRONE RACER
AI pilot beats human champions in aerial contest
Offset agreement
Overhaul pricing of carbon credits to help fund climate projects
Dining companions
Corals devour algal partners when food supplies run low
Sentence synthesis
Brain implants show promise in rendering speech from thoughts
Vol. 620, No. 7976
nature.com

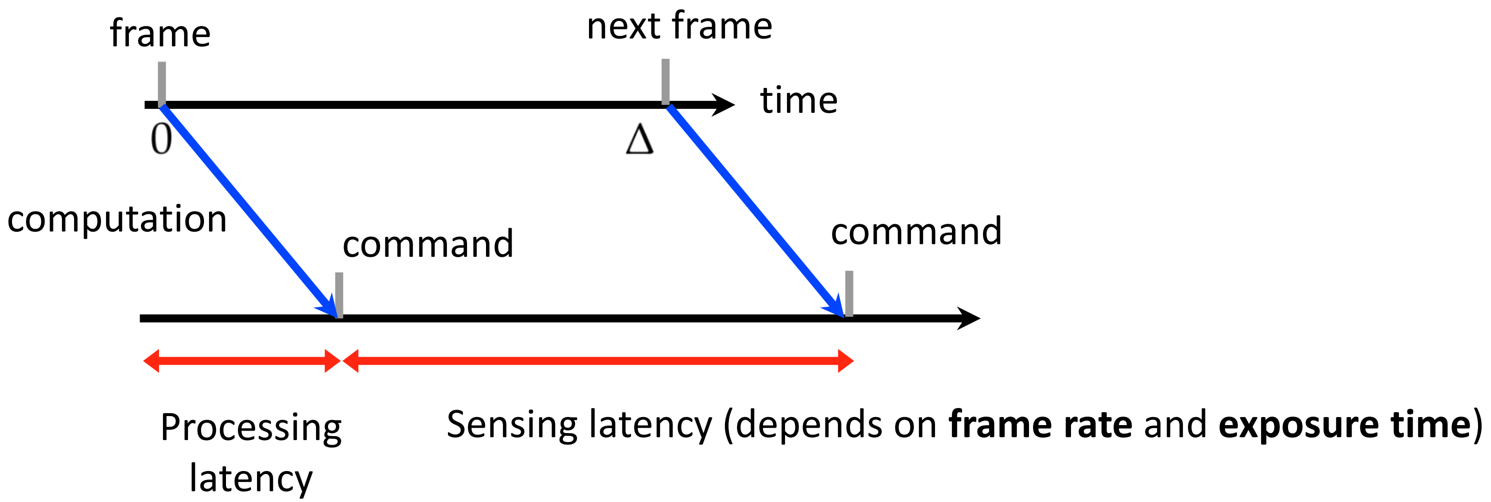
Agile Flight: where are we?



Future of Drones?

BBC: “How sparrowhawks catch garden birds”
https://youtu.be/Ra6I6svXQPg

The agility of a robot is limited by the **latency** of the **sensors** and **algorithms**

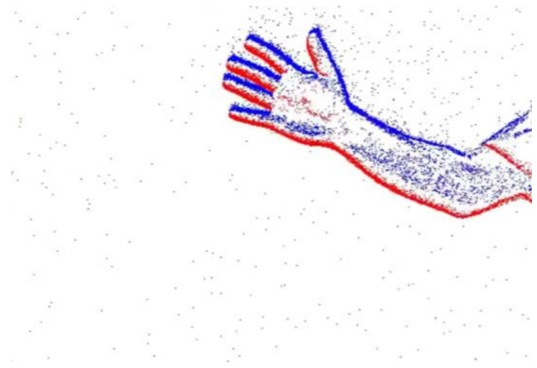


Can we create a low-latency perception pipeline?

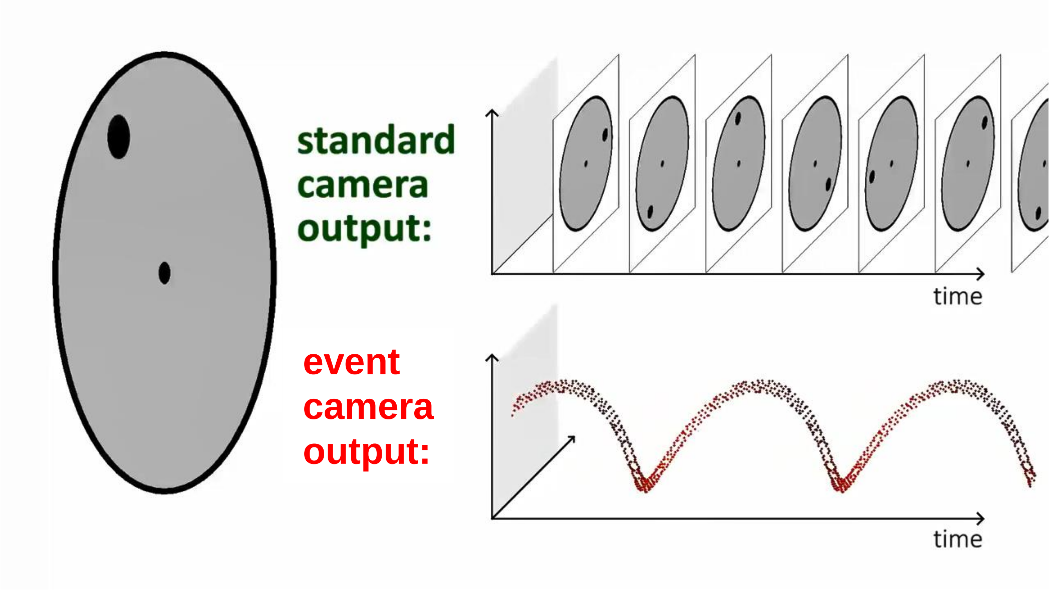
Yes, using event cameras

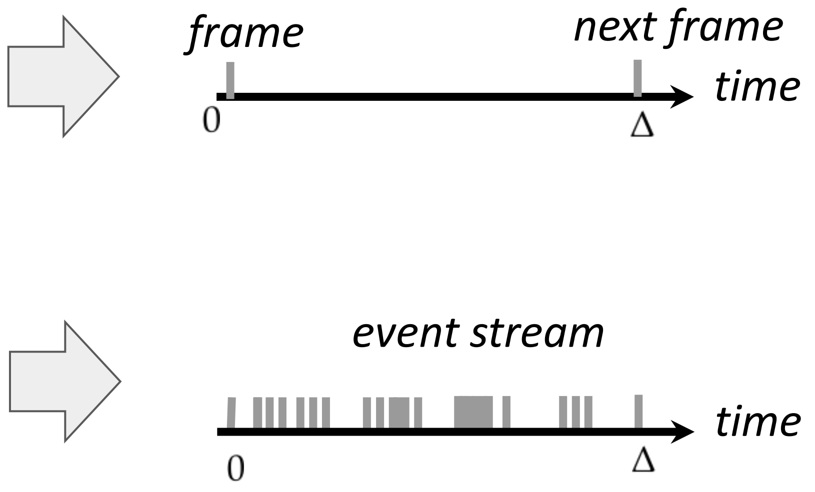
What is an Event Camera?

- It is camera that measures only **motion in the scene**
- **Key advantages:**
  1. Low-latency (~ 1 μs)
  2. Low bandwidth
  3. Negligible motion blur
  4. Very high dynamic range



Traditional vision algorithms cannot be directly applied!



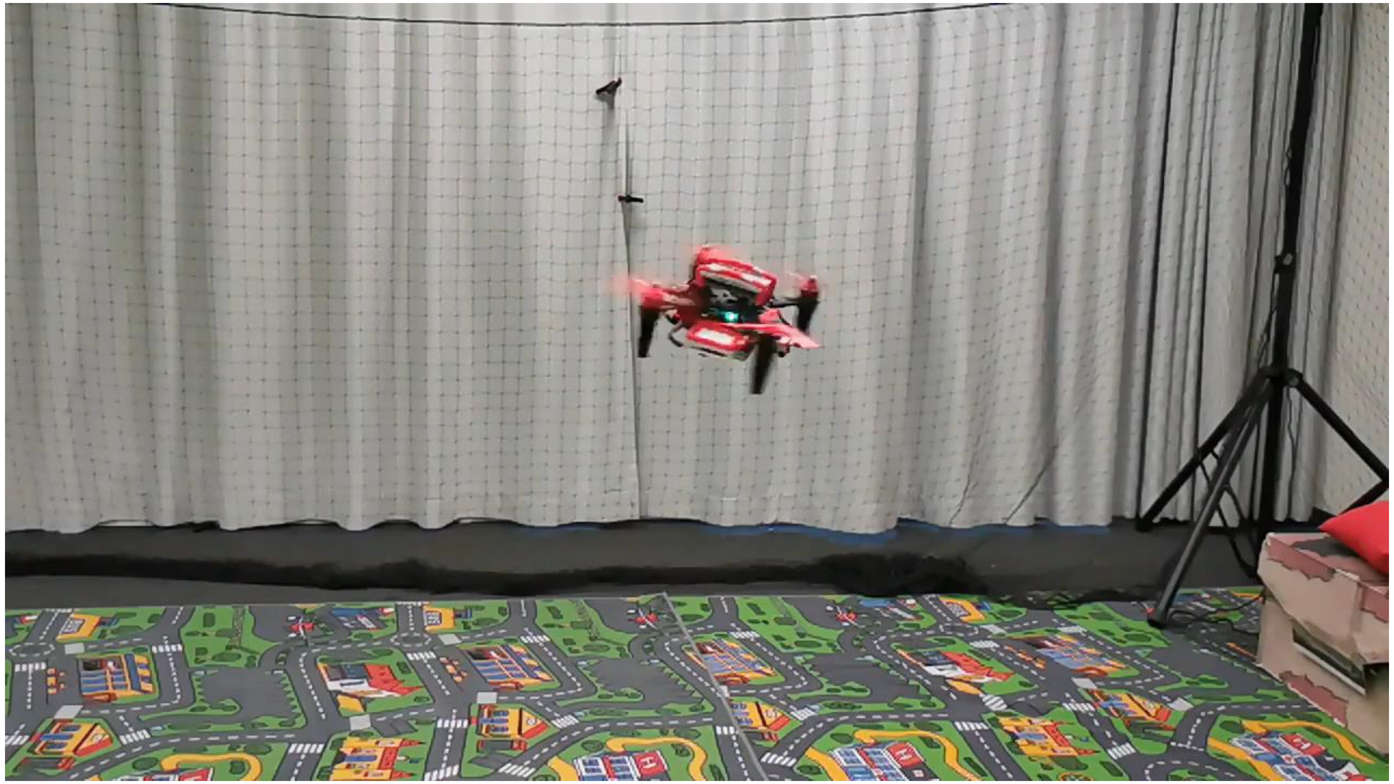


[1] Lichtsteiner, Posch, Delbruck, *A 128x128 120 dB 15μs Latency Asynchronous Temporal Contrast Vision Sensor*, IEEE Journal of Solid-State Circuits, 2008
[2] Gallego et al., *Event-based Vision: A Survey*, **T-PAMI, 2020**

Event cameras unlock scenarios inaccessible to standard cameras

Keeping drones Flying when a **Rotor Fails**

- Quadrotors subject to full rotor failure **require accurate position estimates** to avoid crashing
- Event cameras are **not affected by motion blur**



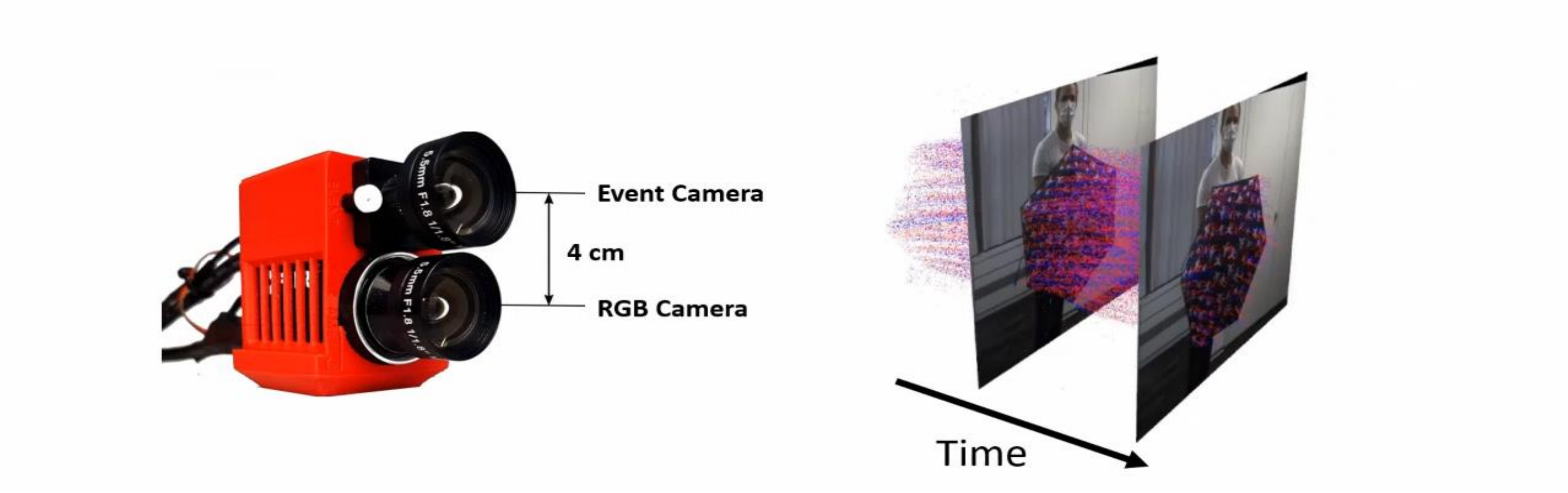
Sun, Cioffi, de Visser, Scaramuzza, *Autonomous Quadrotor Flight despite Rotor Failure with Onboard Vision Sensors: Frames vs. Events*, **RAL'21 Best Paper Award & NASA TechBrief Award** (out of 700 participants)

Dodging Dynamic Objects

- Perception latency: **3.5 ms**
- Works with relative speeds of up to **10 m/s**

Falanga, Kleber, Scaramuzza, *Dynamic Obstacle Avoidance for Quadrotors with Event Cameras*, **Science Robotics,** 2020

Outlook:
Combining Events and Frames for Ultimate Performance

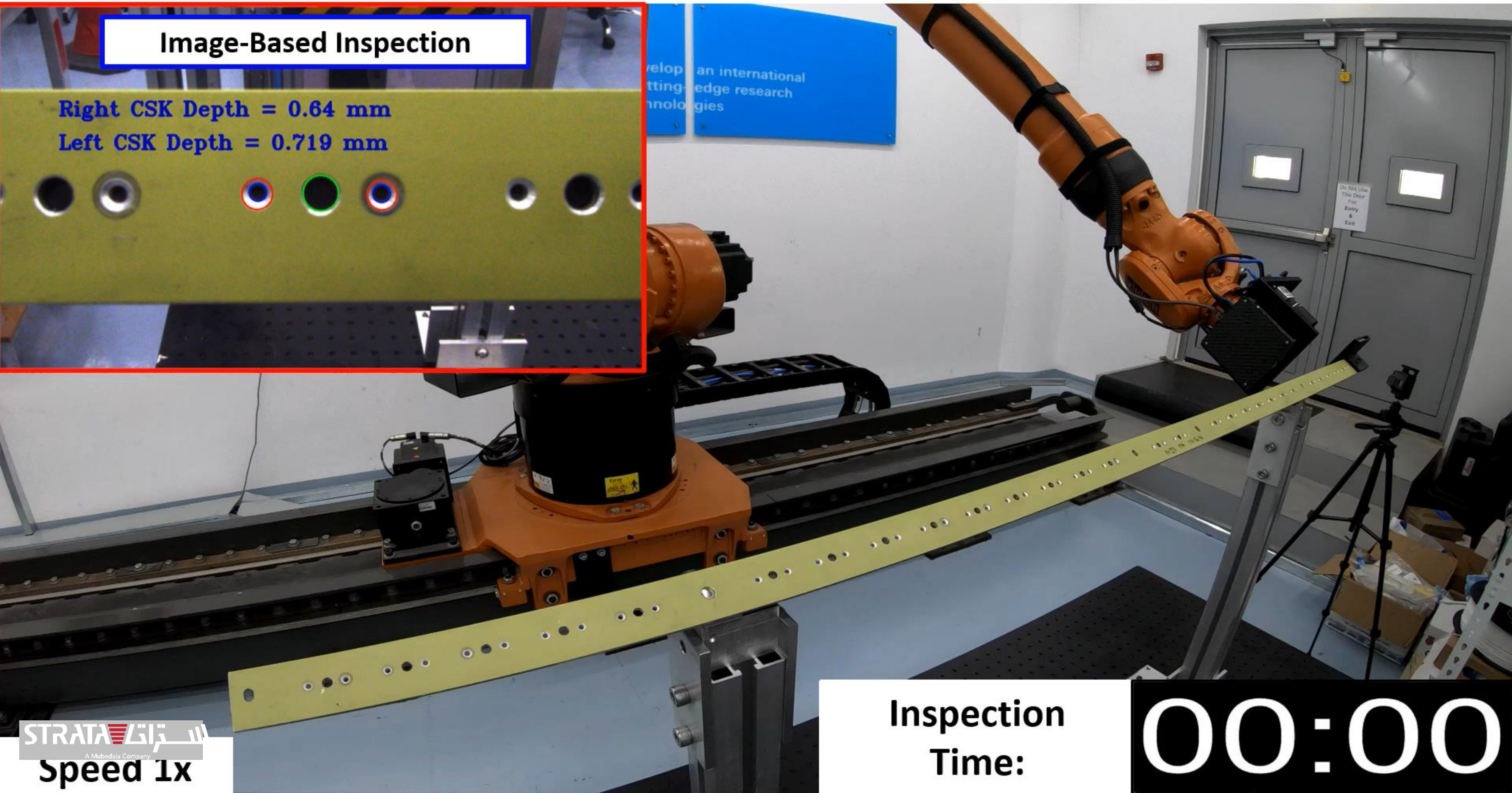


Tulyakov, Gehrig, et al., TimeLens: *Event-based Video Frame Interpolation*, CVPR'21. PDF. Video. Code. Featured on Two-Minute-Papers: Video.

Tulyakov, Gehrig, et al., TimeLens: *Event-based Video Frame Interpolation*, CVPR'21. PDF. Video. Code. Featured on Two-Minute-Papers: Video.

Courtesy of Prophesee

Conventional *Image-Based* Inspection Methods



LINA Project: Funded by Canton of Zurich

www.lina-switzerland.ch

- **Largest European infrastructure** for the **development, safe testing, and certification** of autonomous systems, equipped with **digital twin** simulations and **5G compute zone**

- Location: Dubendorf airport, Canton of Zurich

- **Automatic booking and scheduling approval process** and the outdoor test area

Team:

zhaw School of Engineering ZAV Zentrum für Aviatik

University of Zurich UZH

hdk Zürcher Hochschule der Künste Zurich University of the Arts

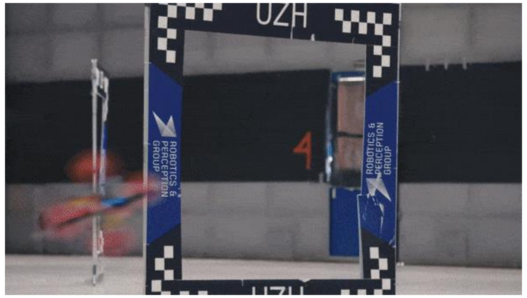
skyguide

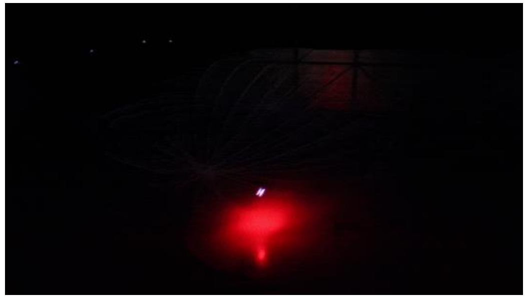
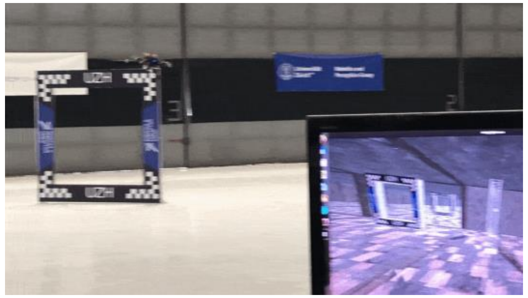
MATTERNET

SOMNIACS

Agilicious – Open Hardware & Software for Agile Flight

- Easy transfer between prototyping in simulation and real-world deployment
- SoTA controller implementations:
  - Nonlinear MPC, DFBC
- Hardware-in-the-loop simulation
- Fast & accurate integrated simulation for testing & RL
- Proved on hundreds of flight hours indoors and ourdoors
- **Successfully used in >20 publications**, e.g. SciRob, RA-L, T-RO, ICRA



https://agilicious.dev/

Foehn et al., *Agilicious: Open-Source and Open-Hardware Agile Quadrotor for Vision-Based Flight*, **Science Robotics**, 2022.

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Thanks!


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