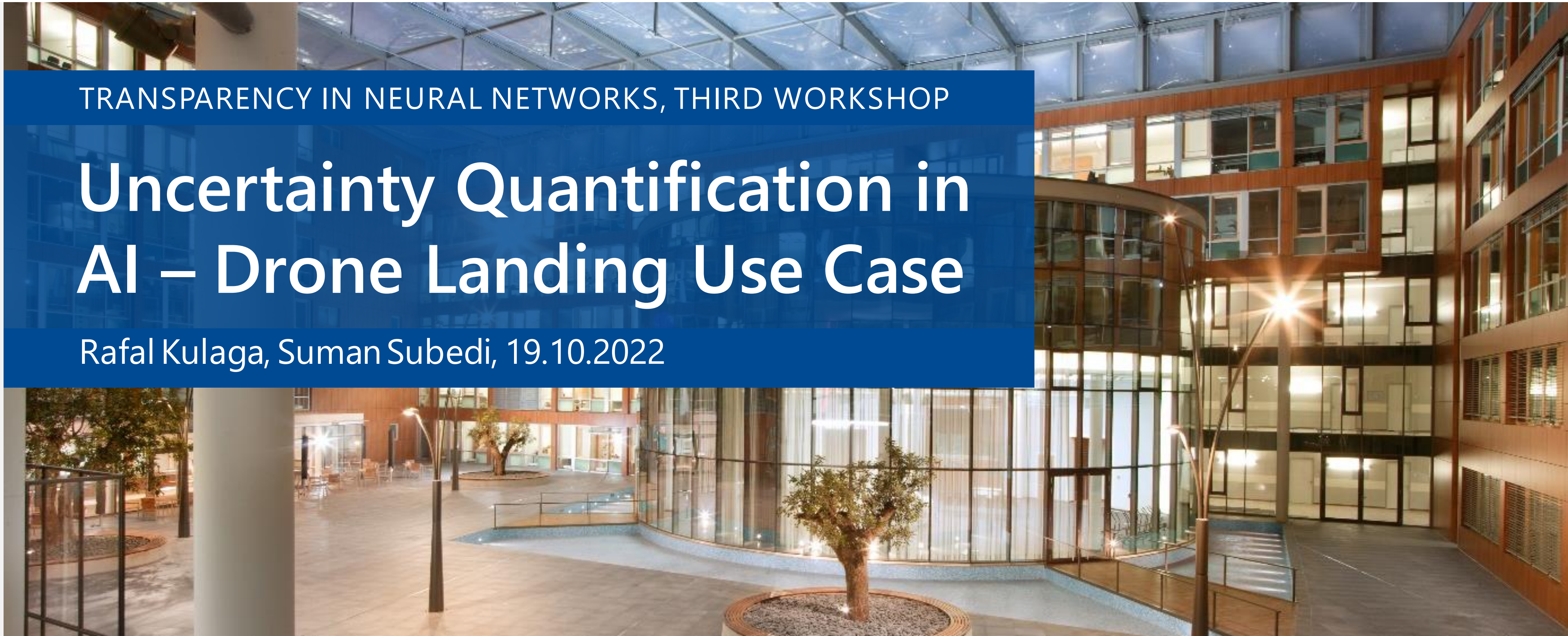
TRANSPARENCY IN NEURAL NETWORKS, THIRD WORKSHOP

Uncertainty Quantification in AI – Drone Landing Use Case

Rafal Kulaga, Suman Subedi, 19.10.2022

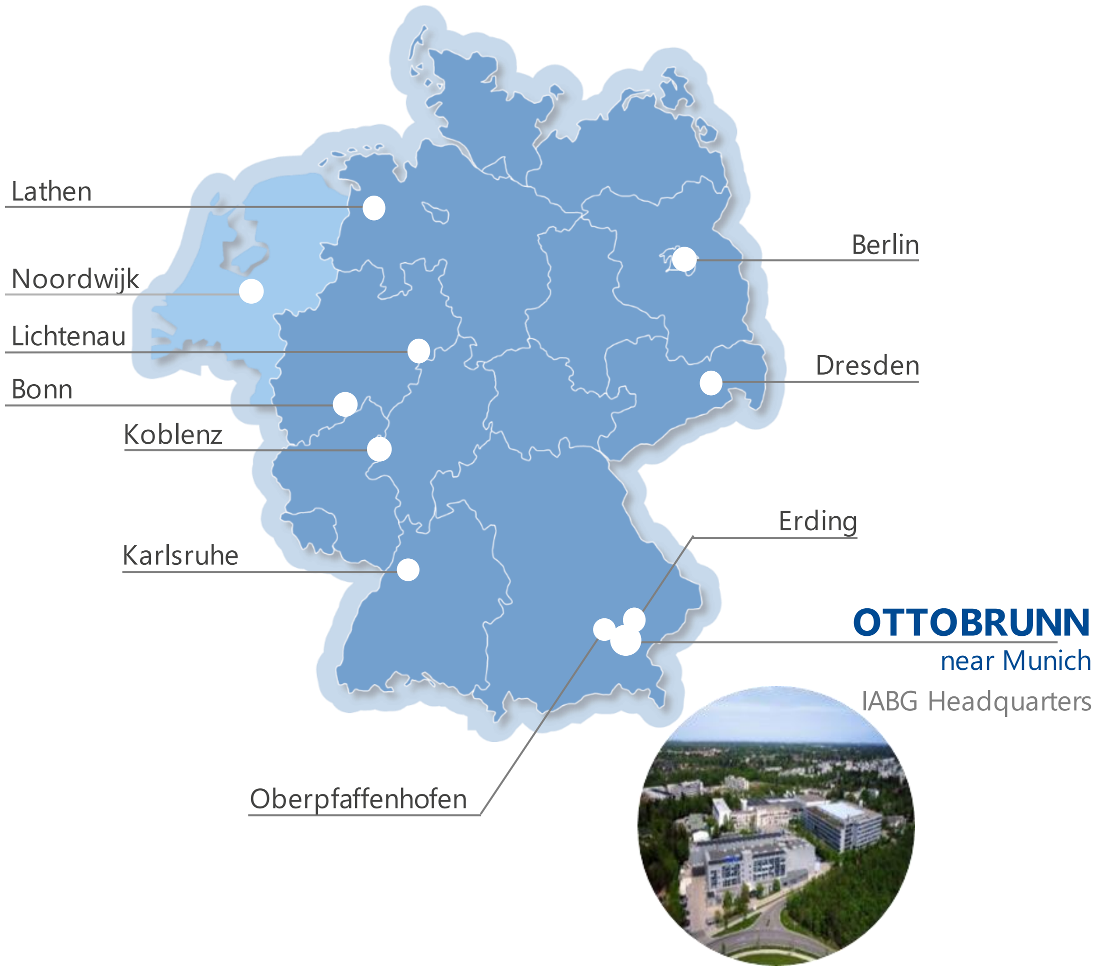


Agenda

01 Introduction

European Tech Company in the Middle of Europe.

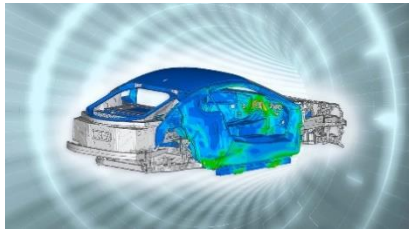
IABG at a glance.



Name	Industrieanlagen-Betriebsgesellschaft mbH (IABG)
Foundation	1961
Headquarters	Ottobrunn near Munich, Germany
Supervisory Board (Chair)	Engelbert Kupka MdL a.d.
Managing Board	Prof. Dr. Rudolf F. Schwarz Thomas Köhler
Number of Employees	Approx. 1,100
Turnover	Approx. € 215 million (2019)
Locations	11
Business Fields	• Automotive • InfoCom • Mobility & Energy • Environment & Geodata • Aeronautics • Space • Defence & Security

Status 2021

We Support Analyses, Conception, Implementation and Operation of High Technology along the Whole Life Cycle.



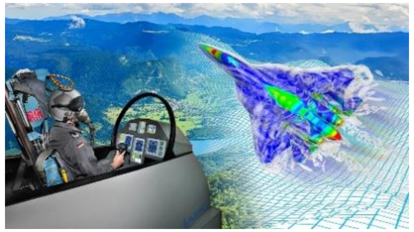
Automotive
Testing & simulation; development and construction of customer-specific test systems; method development & virtual qualification

Aeronautics
Qualification of parts, components and complex overall systems; life-time predictions; digital twins & virtual qualification

InfoCom
Advising public and industrial customers with secure networked information and communication systems

Space
Environmental & qualification tests of satellites and launchers at the space centre; consulting on space programmes; new-space applications

Mobility & Energy
Securing electric mobility for roads and rail-guided traffic: batteries, H2 fuel cells, drives, inductive charging; qualification of alternative energies



Defence & Security
Independent consulting, testing and simulation services for armed forces in all operational dimensions and capability domains

Environment & Geodata
Applications and solutions from geodata/geoinformation; environmental engineering; remediation of contaminated sites & land recycling

Innovation
Innovation centre as incubator for the future service portfolio with a focus on digitisation, data science & AI as well as networked, electrical, autonomous systems

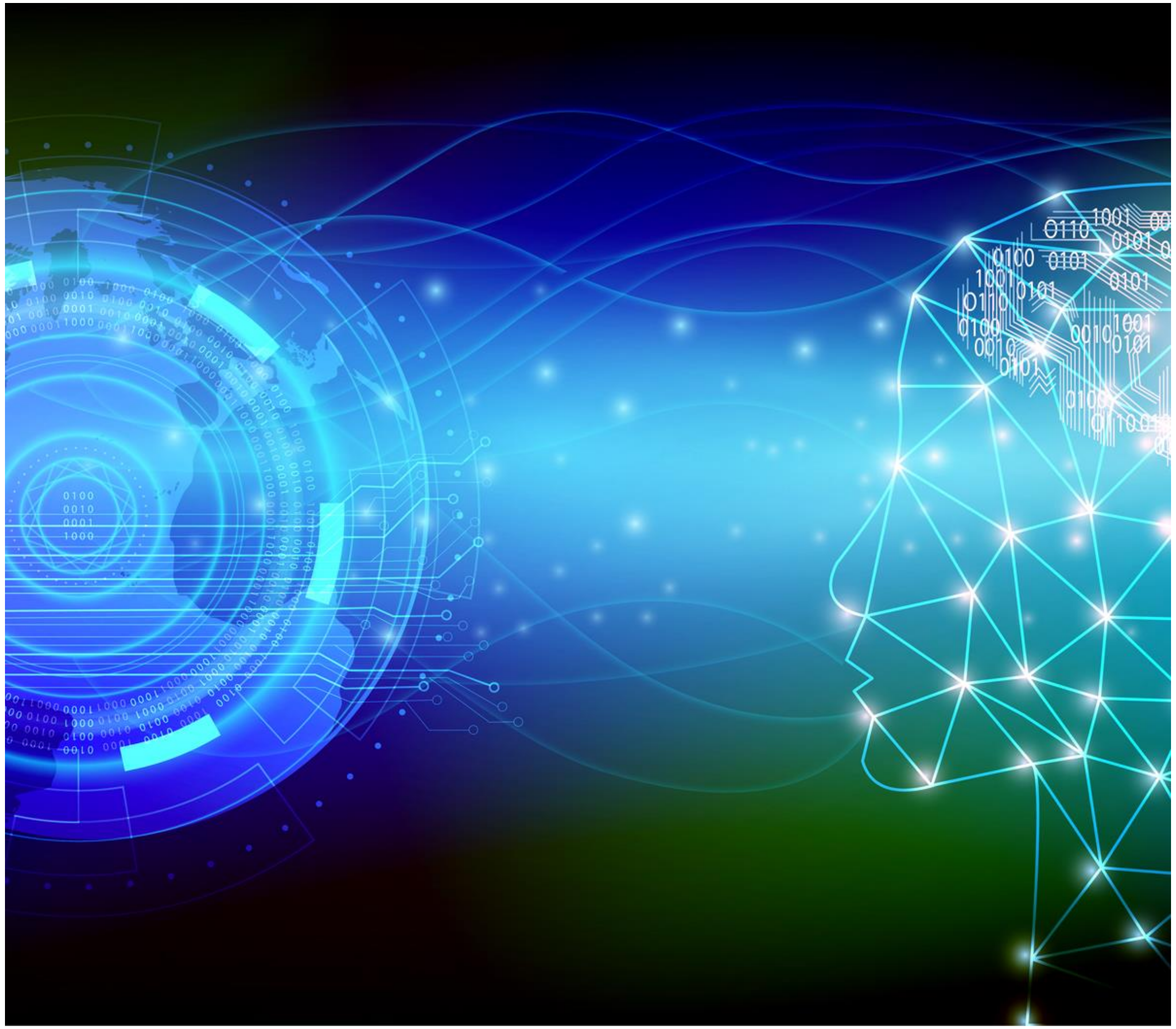
IABG Innovation

Shaping the future.

The Innovation Centre anticipates trends and serves as an incubator and accelerator for the development of new (digital) business models for the entire IABG group.

Our focal points are

- **Methods and Technologies**
  - Data Sciences (Big Data, Data Mining, Natural Language Processing, Predictive Analytics)
  - Cognitive Systems (Machine Learning, EdgeAI[1])
  - Dependability
- **Applications / InnoLab**
  - Autonomous systems (MBSE[2], VR/AR[3], Human Factors)
  - Smart Society (Smart City, future transportation/mobility, ageing society, renewable energies)
  - New Space (micro launcher, earth observation, SatCom, SatNav)
- **Current Innovation Projects and Programmes**
  - SPARTA - Society, Politics and Risk with Twitter Analysis
  - RAISE - Resilient deep learning in space
  - safeAI - Safeguarding of AI algorithms



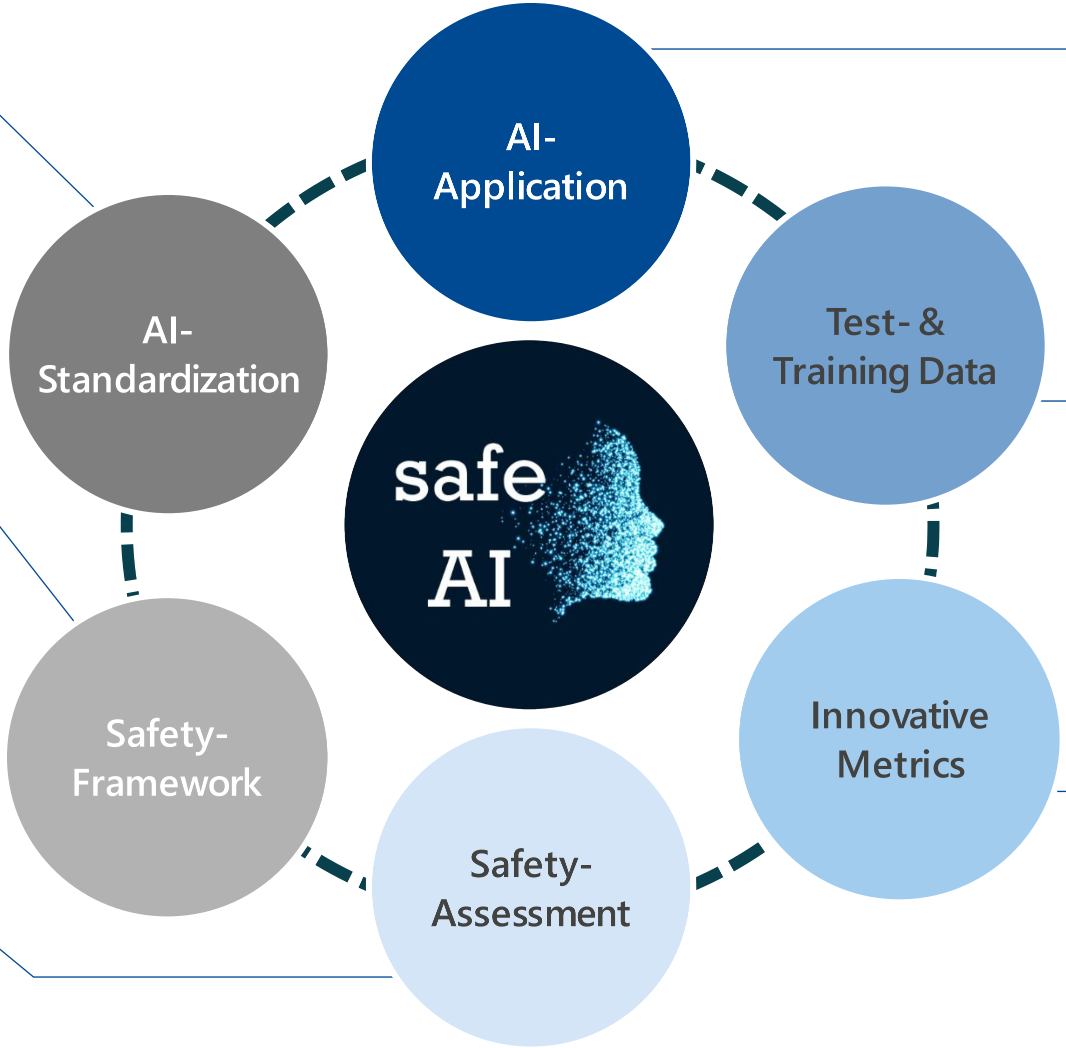
1 Intelligence directly at the sensor, 2 Model-based Systems Engineering, 3 Virtual/Augmented Reality

safeAI – Overview

AI-Standardization
IABG-AI-Specialists actively involved in standardization bodies on reliability, quality, and conformity assessment of AI (e.g. DIN/DKE, ISO/IEC, EUROCAE)

Safety-Framework
safeAI is embedded in the IABG Safety-Framework and is part of the V&V concept of automated functions

Safety-Assessment
Qualitative and quantitative safety assessment of the AI



AI-Application
Analysis of the application and its context as basis for a specific safety assessment

Test- & Training Data
Generation of specific, extensive test data for the required design domain as well as missing training data for the optimization of the AI Systems

Innovative Metrics
Utilization of innovative metrics to evaluate the AI performance.

Motivation Behind Uncertainty Quantification in AI

Huge demand for AI systems

AI plays an increasingly important role in many application fields, e.g. automotive, aviation, finance, healthcare, scientific computing.

1

Growing concern over safety of AI systems

Transition from lab to real-life applications of AI systems raises safety concerns.

2

Growing research in uncertainty quantification in AI

Multiple papers on uncertainty quantification in AI are published every year [1].

3

Uncertainty quantification as a building block of safe AI

Apart from other use cases, uncertainty quantification can be used to increase reliability and safety of systems with AI components.

4

[1] Gawlikowski et al., A Survey of Uncertainty in Deep Neural Networks, 2021

02 Probabilistic Object Detection

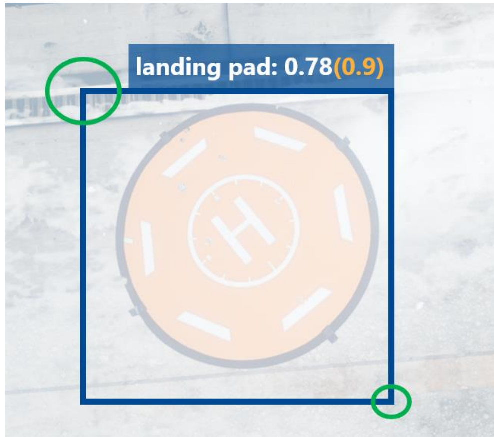
Probabilistic Object Detection

General Concept

(Standard) Object Detection (OD)

The task of detecting objects in images

- Model is supposed to localize and classify objects of interest in an image
- Most popular object detection models can perform (standard) object detection



Probabilistic Object Detection (POD)

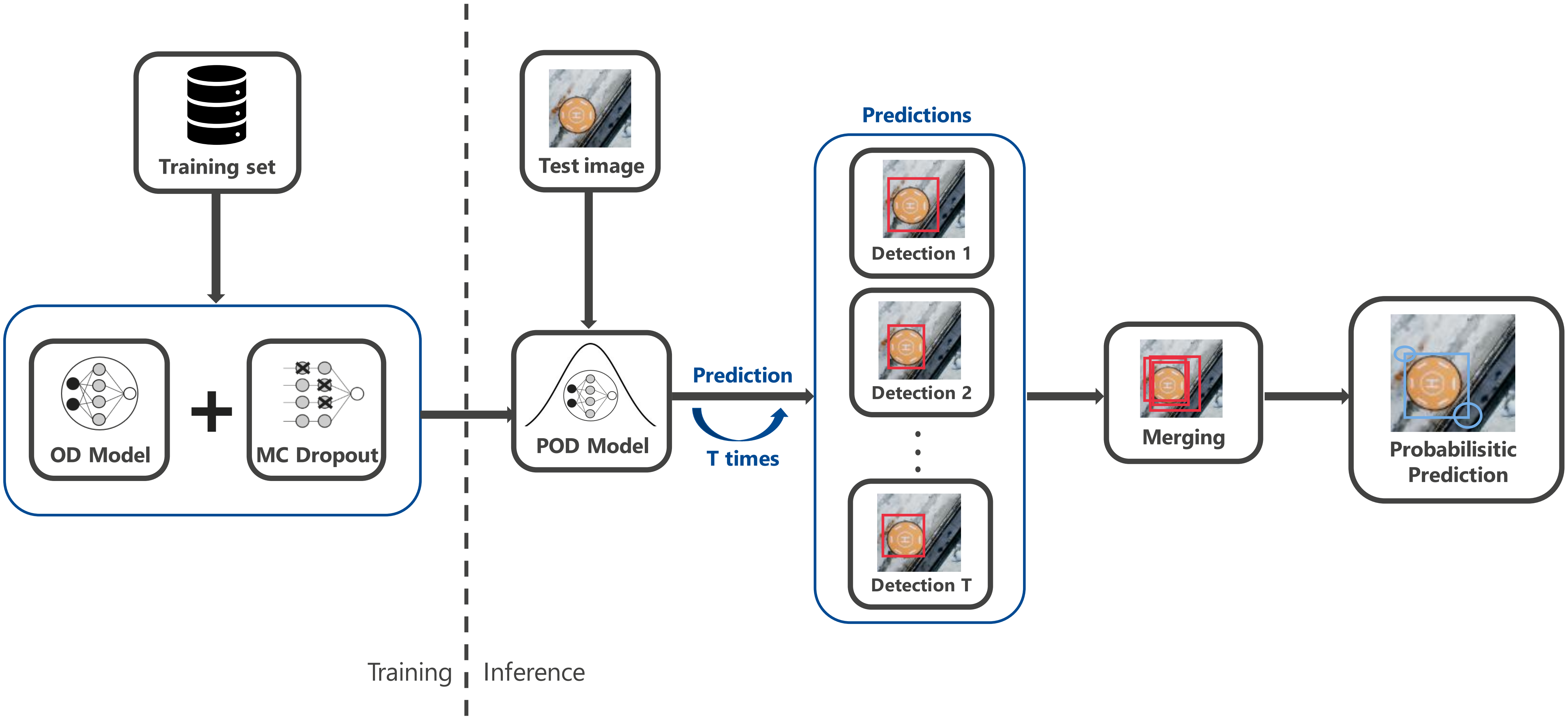
The task of detecting objects in images while accurately quantifying the **spatial (bounding box location)** and **semantic (label)** uncertainties of the detections. [1]

- There are various uncertainty quantification methods that can be integrated with standard object detection models.

[1] Hall et al., Probabilistic Object Detection: Definition and Evaluation, The IEEE Winter Conference on Applications of Computer Vision, 2020

Probabilistic Object Detection

Inference Pipeline with MC Dropout



Probabilistic Object Detection

Motivating Example

Detection of a Landing Pad in Various Conditions

Fully visible landing pad:
- Low uncertainty

Not fully visible landing pad:
- High uncertainty

Landing pad with sun reflection:
- Unexpected case
- High uncertainty

Conclusion

Uncertainty can deliver very valuable information but **how to take advantage of it in practical use cases?**

03 Use Case 1 – Uncertainty Monitoring

Uncertainty Monitoring

Scenario, Problem and Task Definition

Scenario – Autonomous Drone Landing

- Autonomous landing is a manoeuvre during which a drone lands on a designated landing pad.
- The drone is equipped with a downward-facing camera.
- The landing pad is detected using deep learning object detection model.

- Scenario has been realized in a virtual environment AirSim [1]

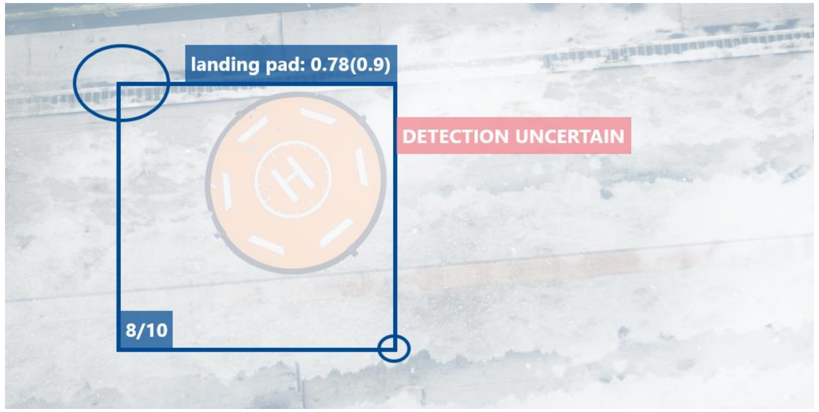
Created using AirSim [1]

Problem and Task Definition

For complex, real-life use cases it is difficult to cover in a training set all potential scenarios that model can encounter in operation. Nevertheless, it is necessary to safely handle also new/unknown cases.

The task has been defined as follows:

- Monitor model's confidence/uncertainty
- Deem each prediction certain or uncertain
- Act on the results of UQ



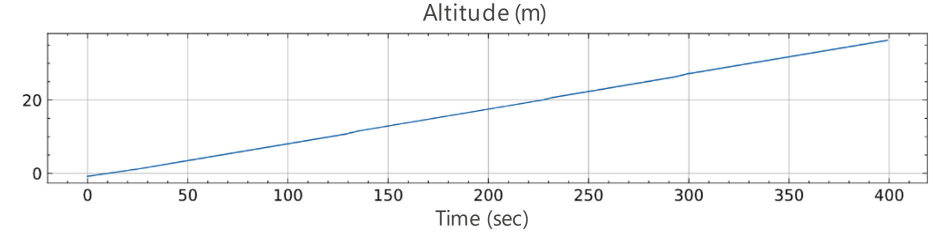
[1] https://github.com/microsoft/AirSim

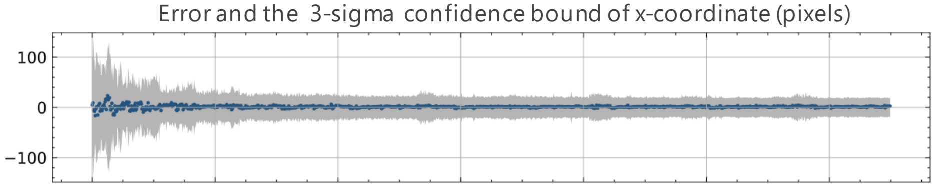
Uncertainty Monitoring

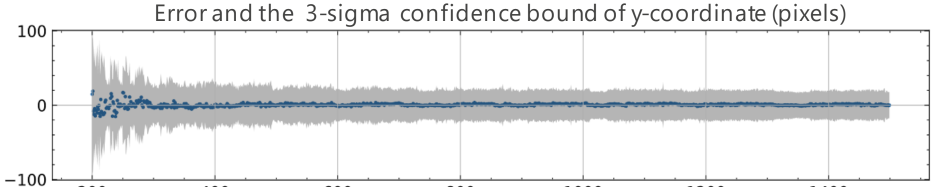
Illustrative Analysis of Estimated Uncertainties

Spatial (bounding box) uncertainty

- Spatial uncertainty correlates with localization error

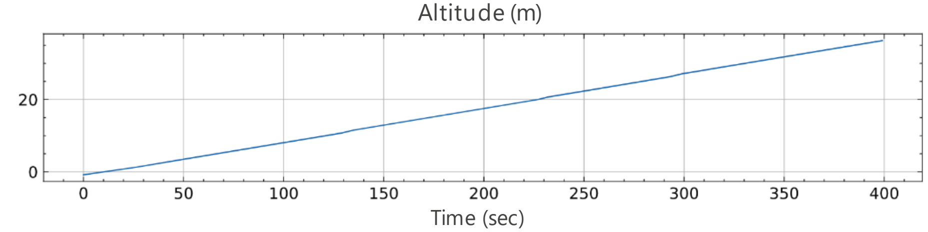


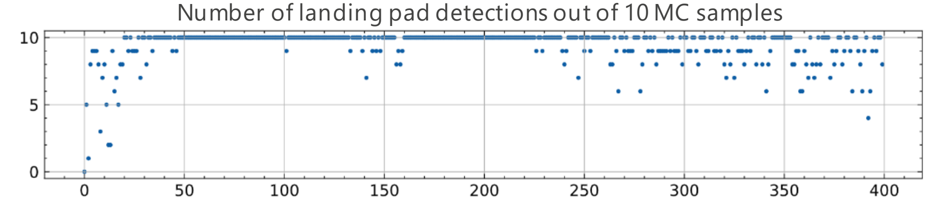


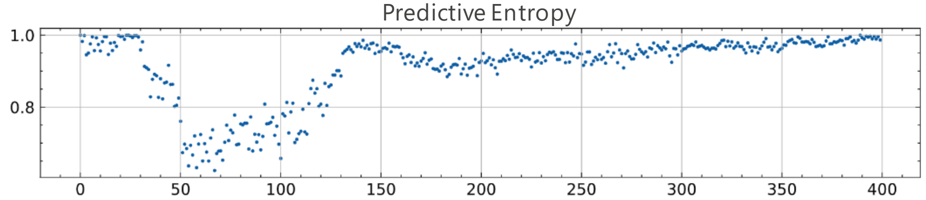


Semantic (label) uncertainty

- Semantic uncertainty depends on the drone altitude







Uncertainty Monitoring
Standard Object Detection - Unsafe Detection

American Crow V1 (https://skfb.ly/S88s) by warrenblyth (http://www.warrenblyth.com/index.html) is licensed under Creative Commons 4.0 Attribution
Parrot-Anafi drone (https://skfb.ly/6RuSB) by Gerhard Kempf Grafikdesign is licensed under Creative Commons 4.0 Attribution
Traffic Cone: https://www.cgtrader.com/free-3d-models/industrial/other/traffic-cone-1b4a9fa5-ba98-4841-b81a-774ba2076637
Traffic Cone Texture: https://www.cgtrader.com/free-3d-models/architectural/street/traffic-cone-low-poly-d2d5c607-afbf-4fc3-96dd-651ab6d92e18

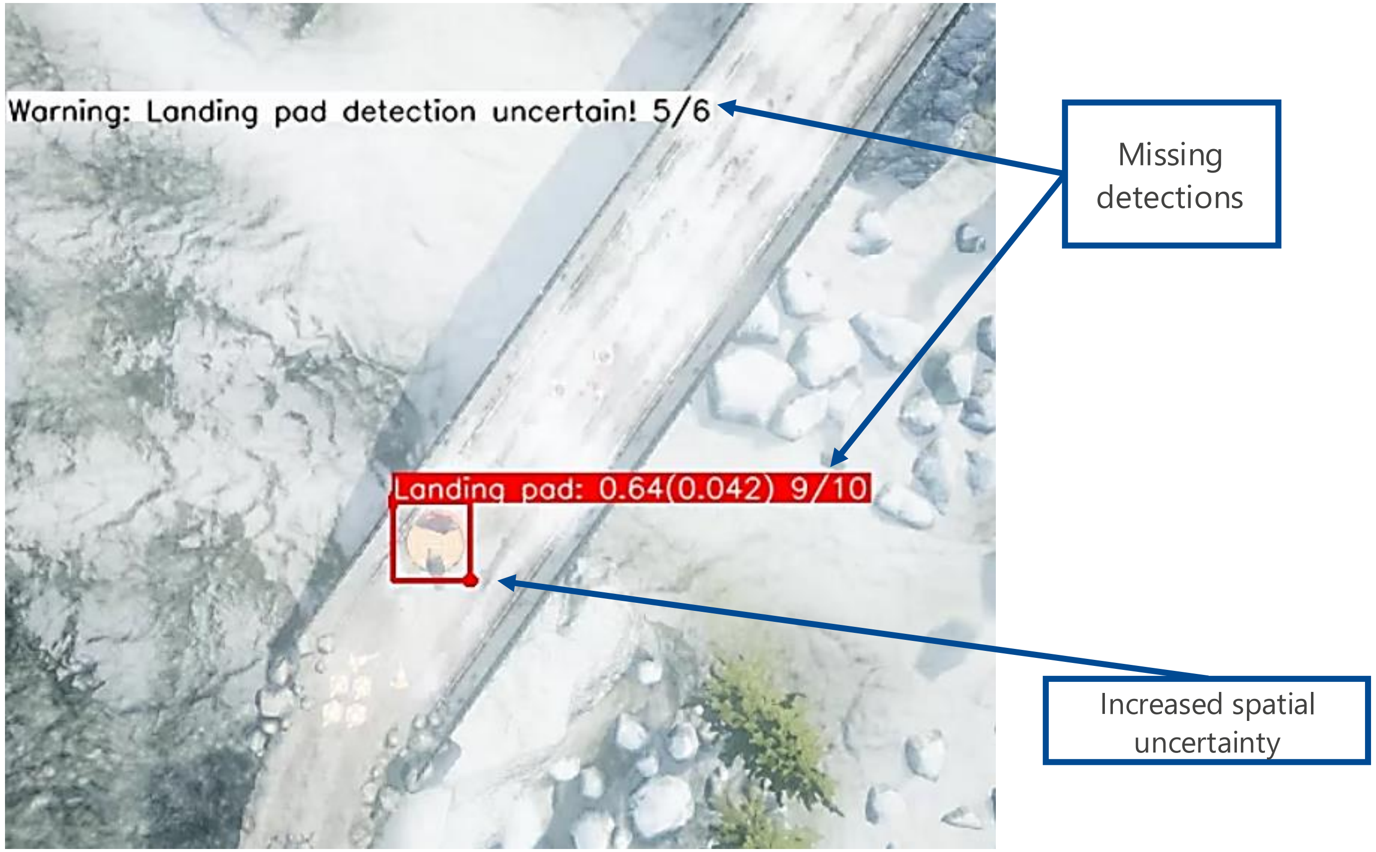
Overconfident prediction (model was intentionally trained only on images of empty landing pads)

Details

- There are no measures that would allow to detect that the prediction is overconfident and might be wrong.
- Detection score/probability (output of the softmax function) is often overconfident.
- Even if a softmax output (detection score) is high, a model can be uncertain. [1]

[1] Gal, Uncertainty in Deep Learning, 2016, University of Cambridge

Uncertainty Monitoring
Probabilistic OD – Risk Mitigation



American Crow V1 (https://skfb.ly/S88s) by warrenblyth (http://www.warrenblyth.com/index.html) is licensed under Creative Commons 4.0 Attribution
Parrot-Anafi drone (https://skfb.ly/6RuSB) by Gerhard Kempf Grafikdesign is licensed under Creative Commons 4.0 Attribution
Traffic Cone: https://www.cgtrader.com/free-3d-models/industrial/other/traffic-cone-1b4a9fa5-ba98-4841-b81a-774ba2076637
Traffic Cone Texture: https://www.cgtrader.com/free-3d-models/architectural/street/traffic-cone-low-poly-d2d5c607-afbf-4fc3-96dd-651ab6d92e18

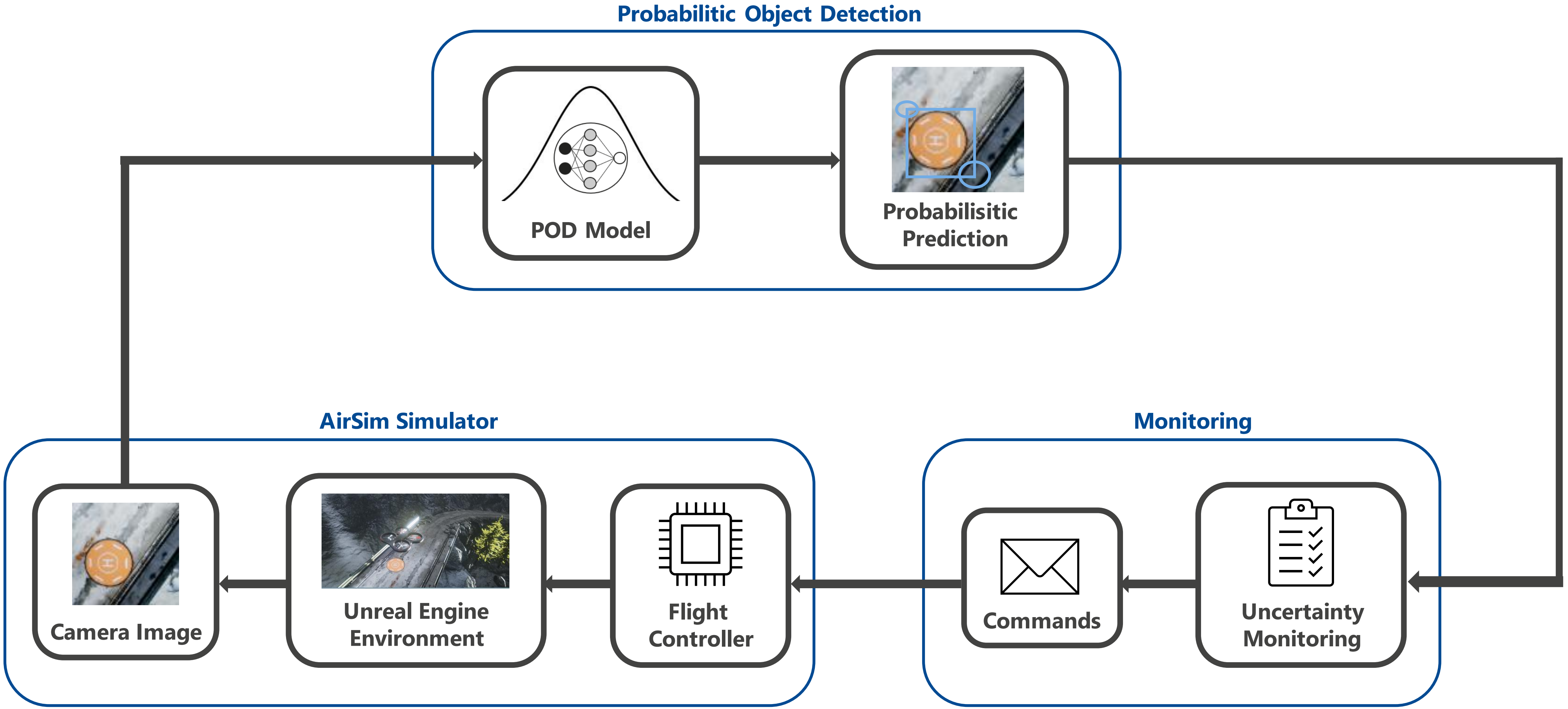
Access to additional information (uncertainties, number of detections) can be used to detect and handle unexpected scenarios.

Details

- Estimation of uncertainty takes place during runtime
- Computationally efficient uncertainty quantification is needed
- Assessment of reliability of each prediction and use of uncertainty as input to command generation (safe decision making) as shown in this simplified sequence:

```
if confidence_is_low(camera_img):
    stop_landing_manoeuvre()
    signal_safety_issue()
    switch_to_manual_control()
```

Uncertainty Monitoring
Integration into a Drone Landing Loop



Uncertainty Monitoring
Takeaways and Challenges

- **Takeaways**
  - Uncertainty can be used to detect unexpected (potentially dangerous) situations and handle them better
- **Challenges**
  - Tuning of the probabilistic models to the task at hand
    - UQ methods like MC dropout increase number of model's hyperparameters
  - Real time requirements
    - Sampling based UQ methods (e.g. MC dropout, ensembles) require strong optimization to allow fast inference on small devices
  - Acting on uncertainty and selecting safety/certainty thresholds
    - Selection of uncertainty thresholds (to distinguish certain detections from uncertain detections) depends on multiple aspects (e.g. AI task, applied UQ method, used uncertainty measure)

04 Use Case 2 – Drone Sensor Fusion

Drone Sensor Fusion
Scenario, Problem and Task Definition

Scenario – State Estimation

- Kinematic state estimation of a flight vehicle is critical for control of the vehicle.
- **Kinematic states:** 3D position, 3D linear velocities, and 3D orientation.
- Extended Kalman filter is used as the standard method for state estimation.

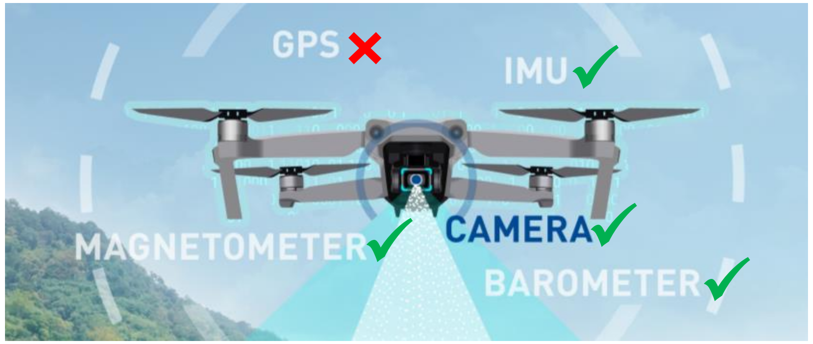
Created using AirSim [1]

Problem and Task Definition

- Failure of one of the sensors can lead to a dangerous drop in state estimation quality.

The task has been defined as follows:

- Use probabilistic object detection as a redundant localization information source
- Add object detection uncertainties to the fusion algorithm (extended Kalman filter)

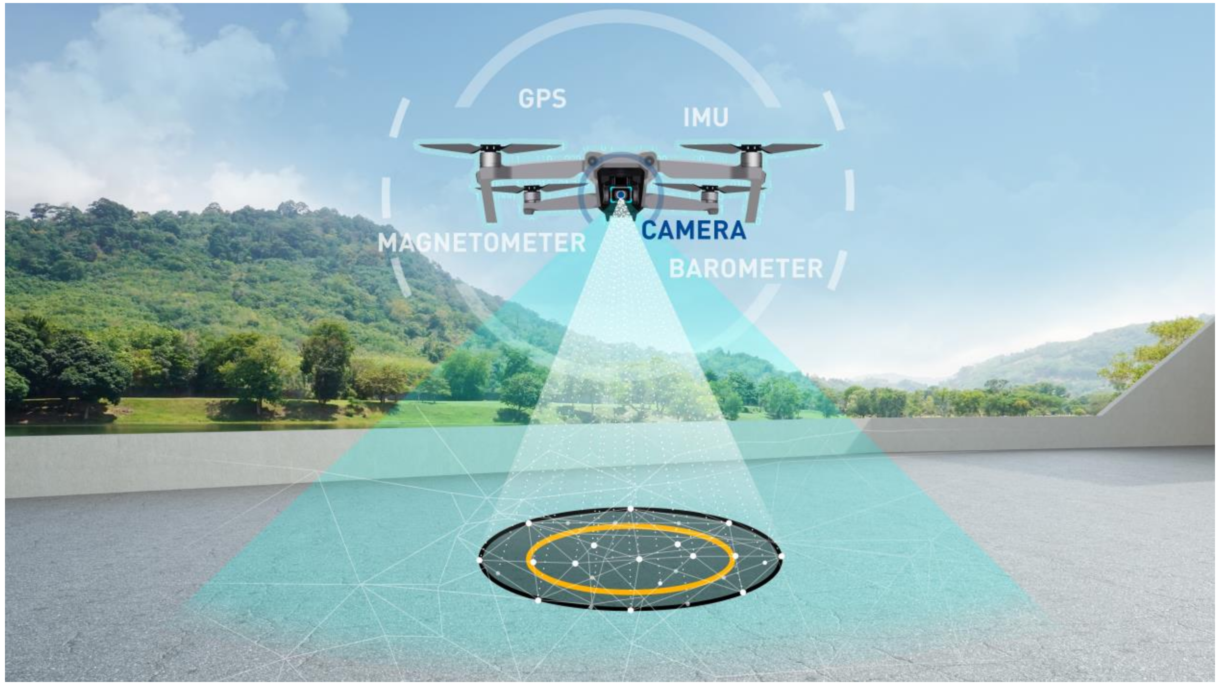


[1] https://github.com/microsoft/AirSim

Drone Sensor Fusion

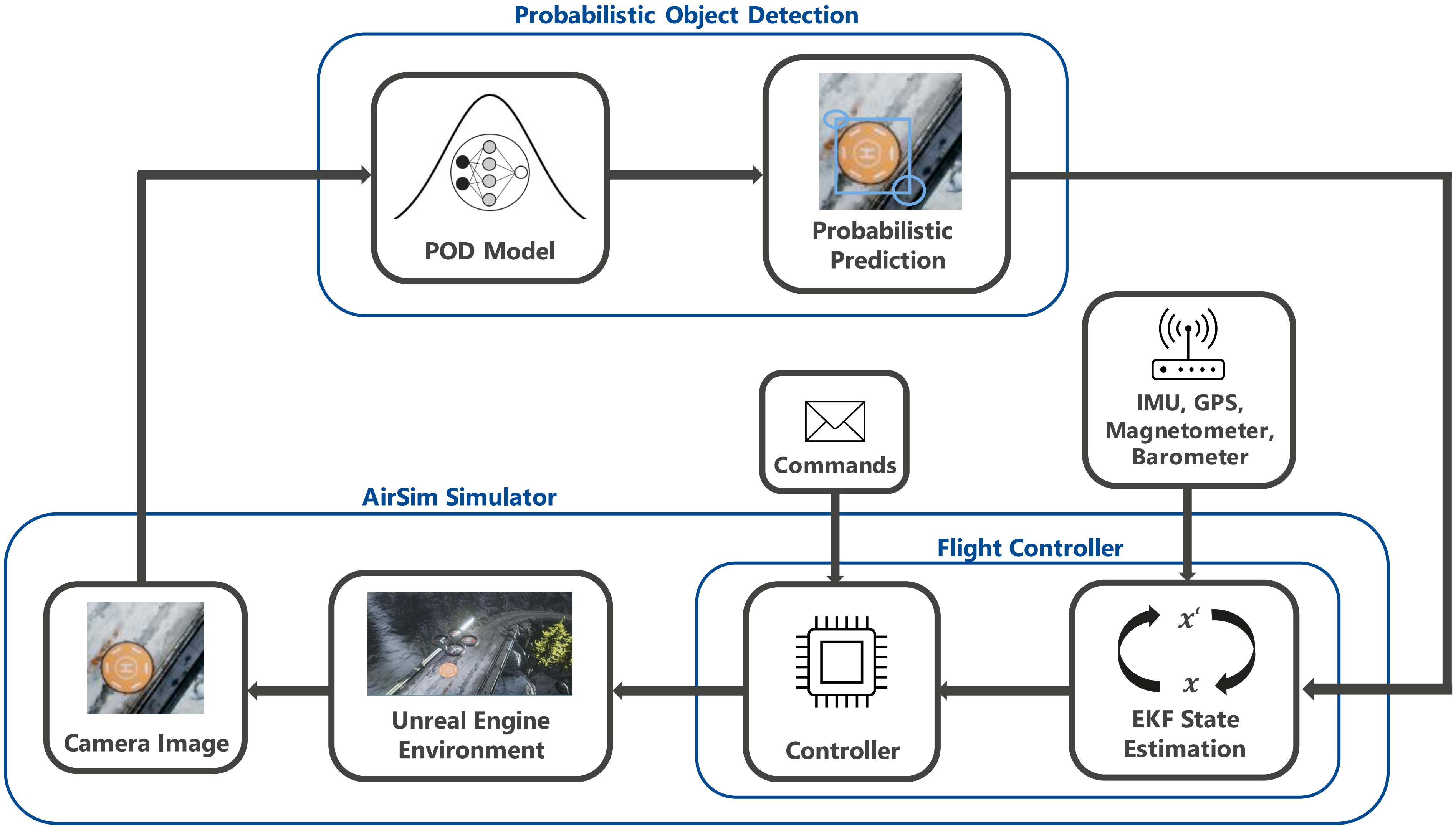
Sensors and Object Detection Uncertainties

- The drone localizes itself using **extended Kalman filter** based on the information from sensors:
  - IMU
  - GPS
  - Magnetometer
  - Barometer
- In addition, it strengthens its localization using **object detection** of a landing pad that is placed on a known location.
- A measurement sensor model of camera is used to fuse landing pad detection (perform measurement update) taking the **spatial uncertainty** as the time-varying measurement noise characteristics.
- **Semantic uncertainty** is used to filter out detections with high uncertainty to preserve the correctness of the mathematical sensor model.



Drone Sensor Fusion

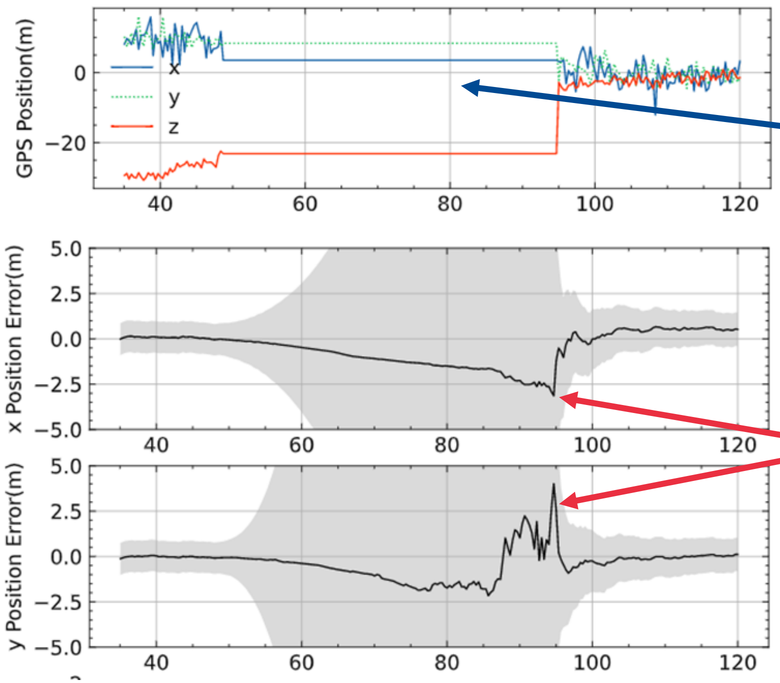
Integration into a Drone State Estimation Loop



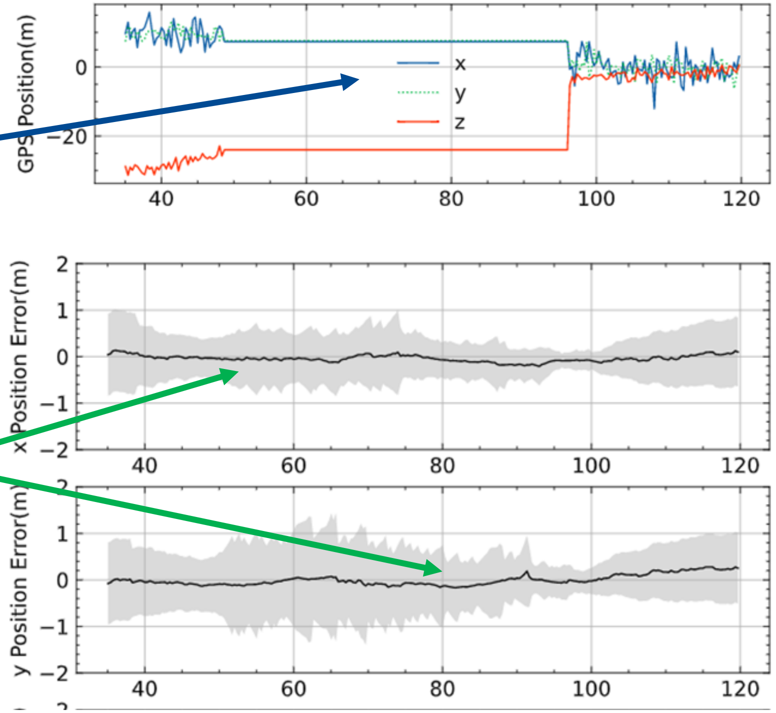
Drone Sensor Fusion

Advantage of Fusing Landing Pad Detection

Without fusion of landing pad detection



With fusion of landing pad detection



GPS failure (signal unavailable)

Lack of GPS signal leads to significant error in position estimation

Quality of position estimation is maintained even with failure of GPS.

Conclusion

Sensor fusion of probabilistic object detection results can help maintain the state estimation quality even under failure of substantial components (such as GPS).

Drone Sensor Fusion
Takeaways and Challenges

- **Takeaways**
  - Fusion of object detection for state estimation can be valuable for landing scenario in absence of GPS signals.
  - Detecting foreign objects as a landing pad makes the fusion of object detection incorrect.
    - Semantic (label) uncertainty is crucial to filter out false detections.
  - It is necessary to calibrate the spatial (bounding box) uncertainty for the given dataset.
- **Challenges**
  - The integration is complicated as the low-level EKF algorithm in a flight controller needs to be modified.
  - Calibration of the uncertainty is hard as the uncertainty depends on the flight trajectory.

05 Summary

Summary

- Uncertainty quantification can play an important role in increasing safety of AI based system such as vision systems.
- Goal of probabilistic object detection is to detect objects in images while accurately quantifying the spatial and semantic (label) uncertainties of the detections.
- We presented how uncertainty can be used in two practical use cases:
  - Uncertainty monitoring for safer decision making
  - Fusion of uncertainty for reliable state estimation

Your contact

IABG mbH

Einsteinstraße 20
85521 Ottobrunn

Tel. +49 89 6088-0
Fax +49 89 6088-2220

info@iabg.de
www.iabg.de

Rafal Kulaga
Data Scientist

Predictive Modeling and Decision Support

Tel. +49 89 6088 4733
kulaga@iabg.de

Suman Subedi
AI Safety Engineer

Predictive Modeling and Decision Support

Tel. +49 89 6088 2462
subedi@iabg.de