Challenges in real-time application development – The I4*Copter* project

Invited talk

DFKI Bremen

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/Research/I4Copter

Chair in Distributed Systems and Operating Systems

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Motivation

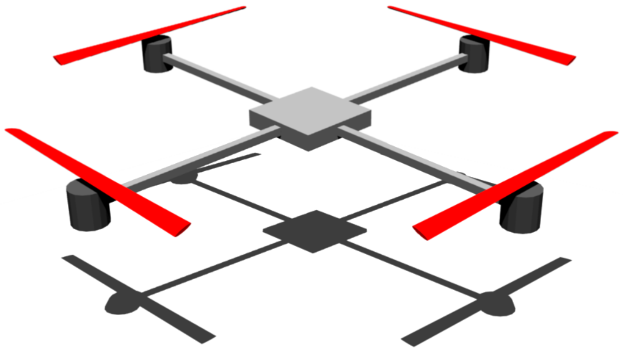
- **Showcase for embedded and real-time system software?**

- **System research and industry projects**
  - Creditable safety-critical application available
  - Research project evaluation

- **Real-time system engineering**
  - Drawing conclusions from development process

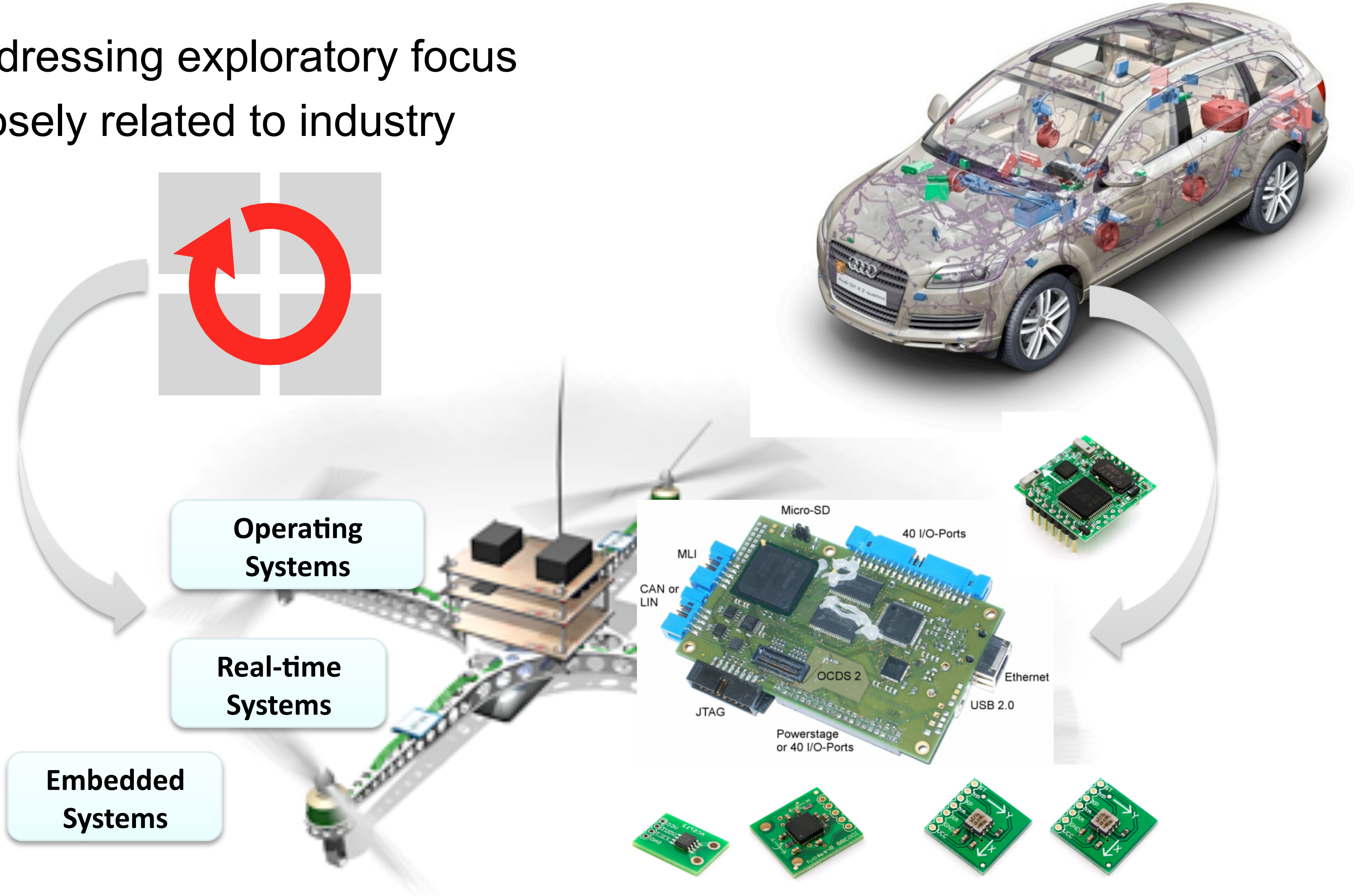
- **Teaching**
  - Comprehensive and demanding application
  - Cross-domain education

→ **A quadrotor helicopter! (Quadrocopter)**



Requirements (1)

- Addressing exploratory focus
- Closely related to industry



Requirements (2)

- **Microcontroller → Infineon TriCore**
  - Widely used in automotive domain
  - Sufficient performance reserves (150MHz, 2MB Flash, 256KB RAM)
  - Substantial periphery support
- **Off-the-shelf sensors**
  - Heterogeneous communication type (analog, digital, bus)
  - Software signal processing and filtering

→ **No adequate construction set available on the open market!***

*at that time

Timeline

Late 2007

- A bagful of hardware
- First clumsy copter
- Incapable of flying

Early 2008

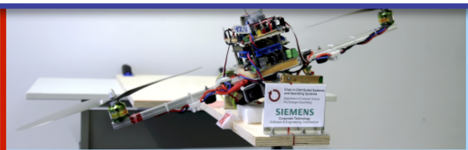
- Back to drawing-board
- 1-axis test rig
- Engine test rig

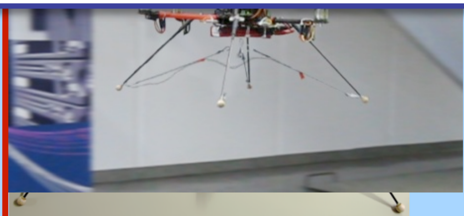
Mid 2008

- I4Copter Prototype V1.0
- First flight (Late 2008)
- I4Copter

Early 2009

- I4Copter Prototype V2.0
- Acceptable flight behaviour





Why did it take so long?

Outline

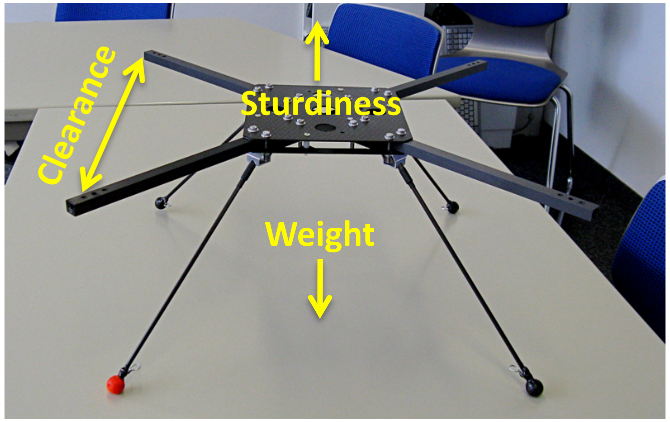
- **Building the quadrocopter**
  - Prototype development
- **Real-time application analysis and design**
  - Physical model
  - Real-time system
- **System implementation**
  - Component design
  - Loose coupling
- **Lessons learned and conclusion**

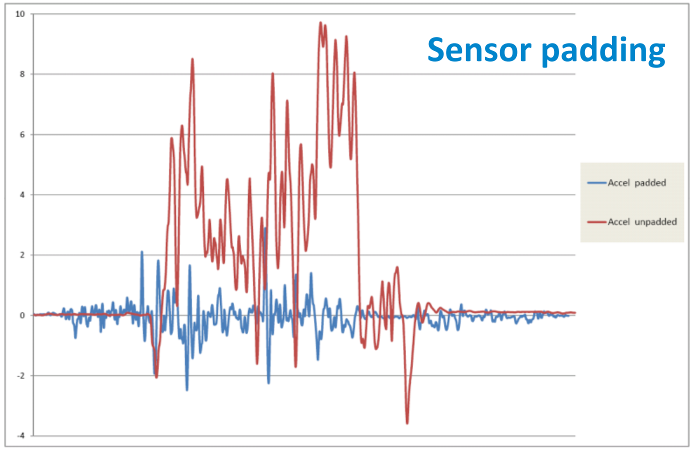
Building the quadrocopter

System complexity

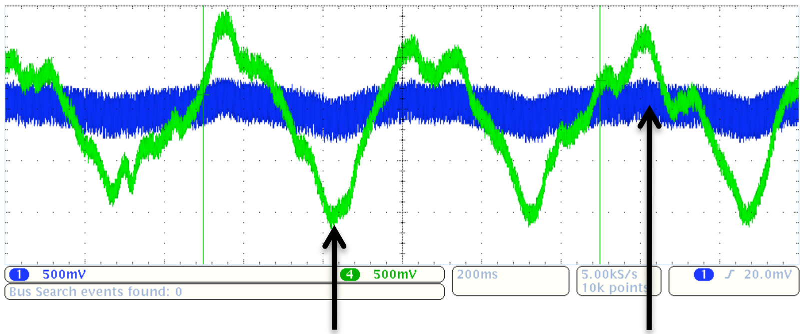
- A quadrocopter is highly complex system (in every sense)
  - Beyond the domain of computer science and automation control
- Simply the construction took months:

Manufacturing





Electrical engineering



Using differential amplifier　Plain signal

The I4*Copter* prototype v2

- **3rd Iteration: Prototype „Apollo“**
- **Specifications:**
  - **Thrust performance:** max. 530W → 2800g (12“ airscrews)
  - **Span:** 56cm / **Weight:** 1480g

Facts

InvenSen

Gyr

2x

Sharp

Pr

Sa

4x

Mikr

Engi

WiPort

AN

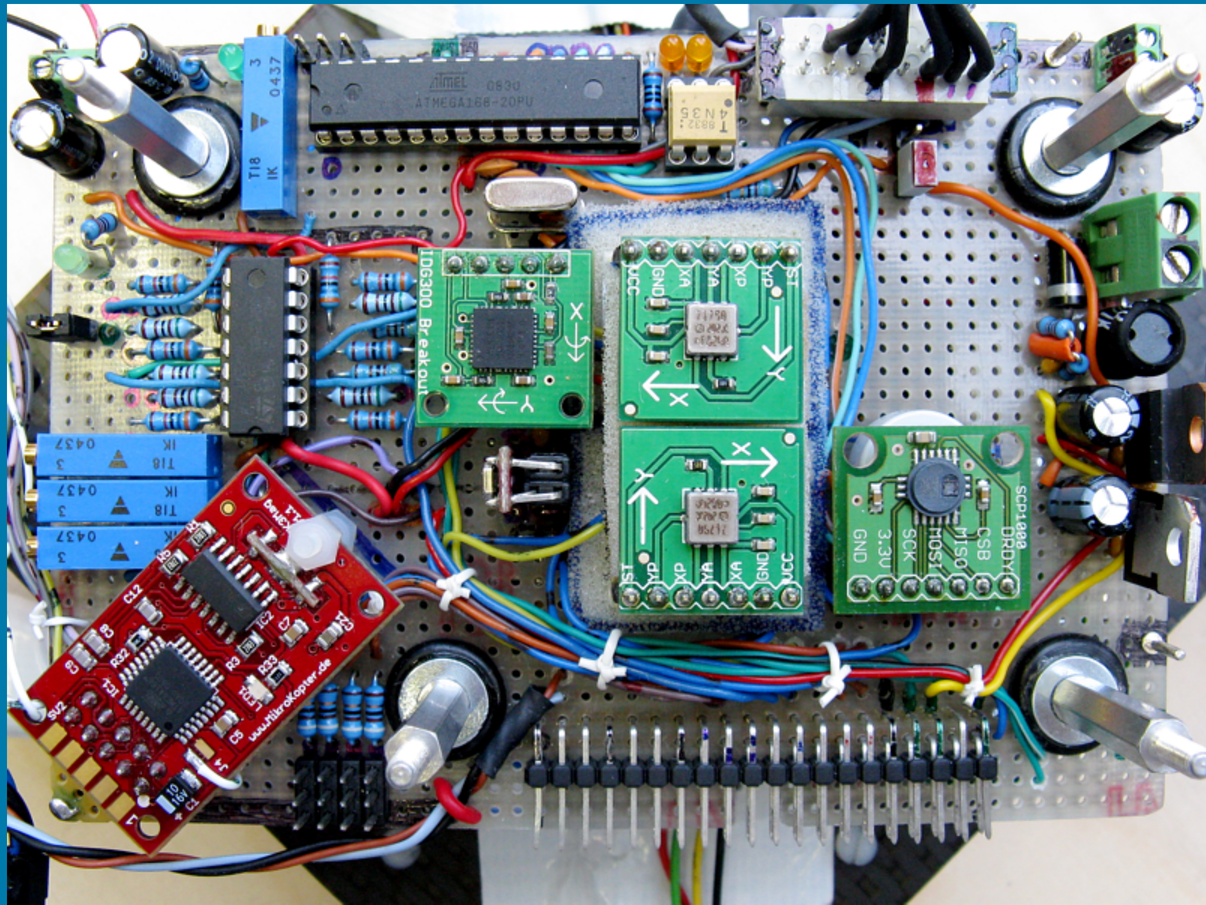
1000

ure

MK3Mag

pass

Prototype periphery board – Mark II



Real-time application analysis and design

Application Requirements (Excerpt)

- **Goal:** semi-autonomous flight
  - Safe **hovering** (maintain position, heading and height)
  - **Steering** by remote and/or WLAN
  - Support by automatic **take off** & **touch down**
  - Heading for waypoints – **Autopilot**

- **Allocation**
  - *Behaviour engine* – firm real-time
  - *Attitude control* – hard real-time

System classification

- **Relationship** between **Event** and **Result**
  - **Temporal** – Time allowed to pass → Deadline
  - **Physical** – Way of determine the result
- **Physical object**
  - Relevant parameters and their connection?
- **Real-time system**
  - Events to be handled? Deadlines?
  - Relationship: Deadline ↔ Physical object
- **Physical model**
  - Parameters to be mapped?
  - How to map parameters?

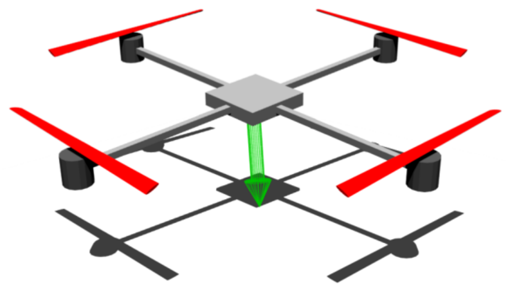
→ **Is it possible to reduce the model to simple state observance?**

Quadrocopter analysis

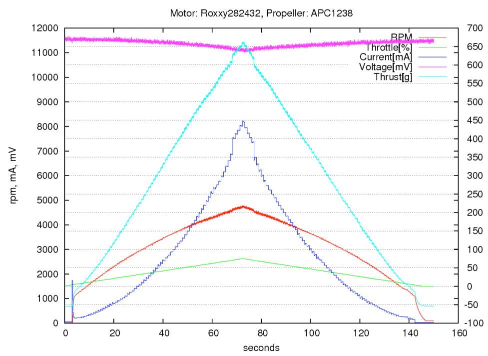
- State is **not** fully observable but calculable → **control engineering**
- **Observation**
  - **Angular rate** ω and **angle** φ of X,Y and Z-axis
- **Manipulation**
  - **Voltage** U of the engines
- **Response (Calculable)**
  - **Angular rate** ω_{Mot} of the engines and **thrust** T generated, depending on the engine / airscrew (friction, inertia, efficiency)
  - **Change of position**, depending on the objects momenta (mass, inertia)
- System model describes the correlation between **observable**, **calculable** and **manipulable** parameters

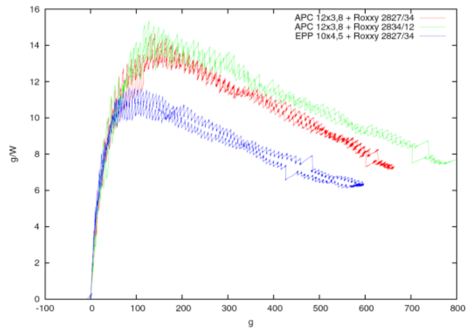
Physical parameters

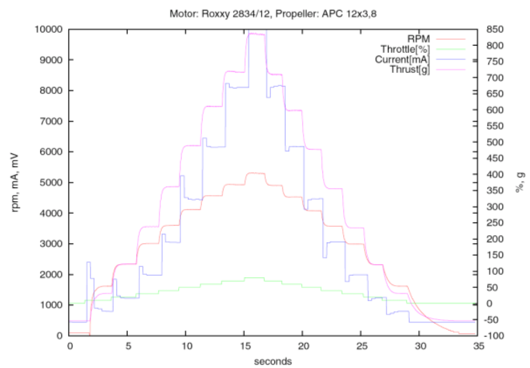
- **Determining by measurement**
  - e.g. thrust, power consumption, voltage, weight
- **Derivation of parameters**
  - e.g. inertia, efficiency



- **Examples:**
  - Moment of inertia: 37.74 m²g
  - Engine response time: ~160ms (66% nominal)







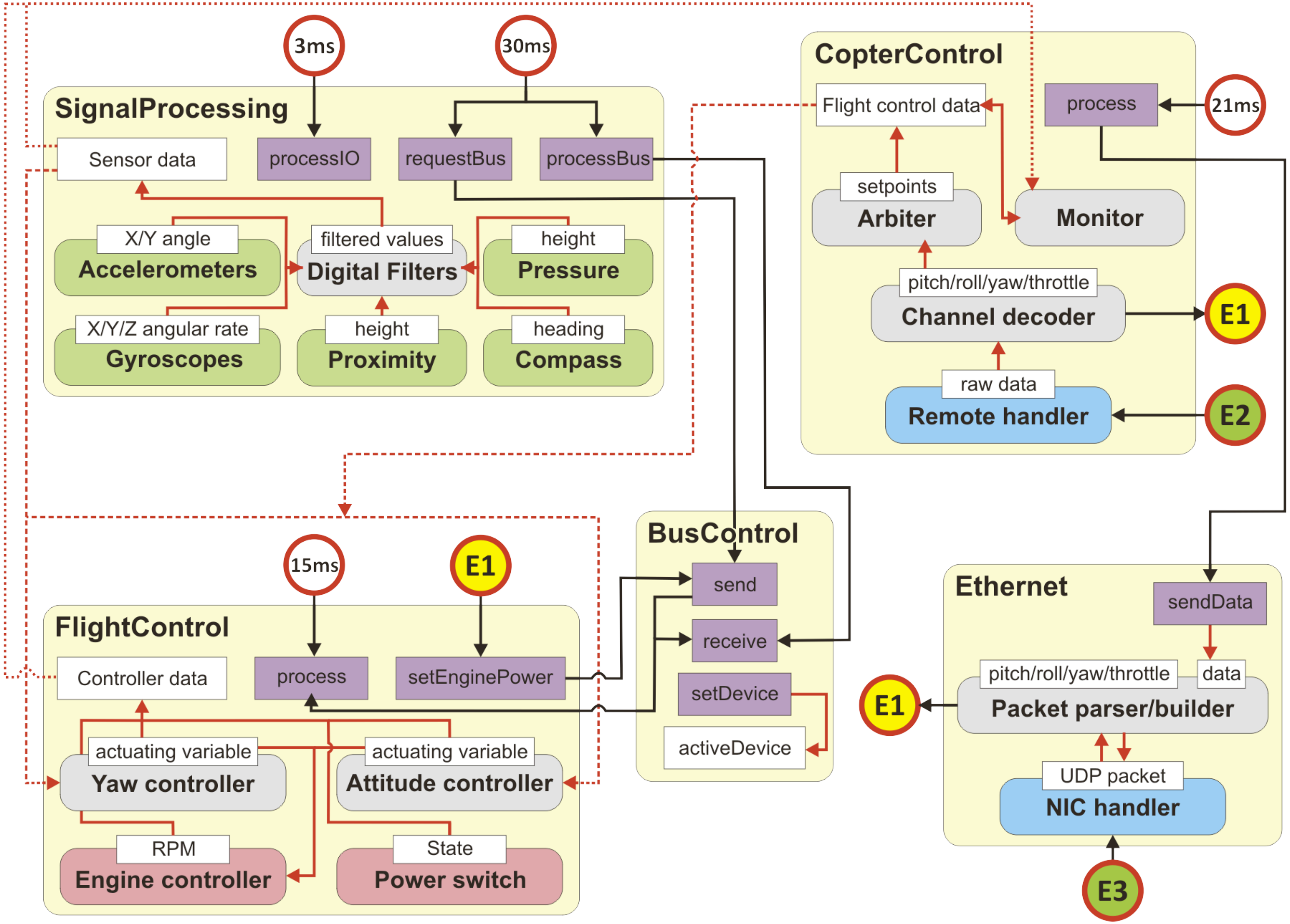
Real-time system - Events

- **Signal processing → periodical** – 3ms / 30ms
  - 2x oversampling (sampling theorem)
- **Flight control → periodical** – 15ms
  - 10x compared to engine response time (school of thought)
- **Monitoring → periodical** – 25ms
  - 10x compared to object inertia (school of thought)
- **Command → aperiodical** – 20..250ms
  - 2x oversampling, depending on human response time and object inertia

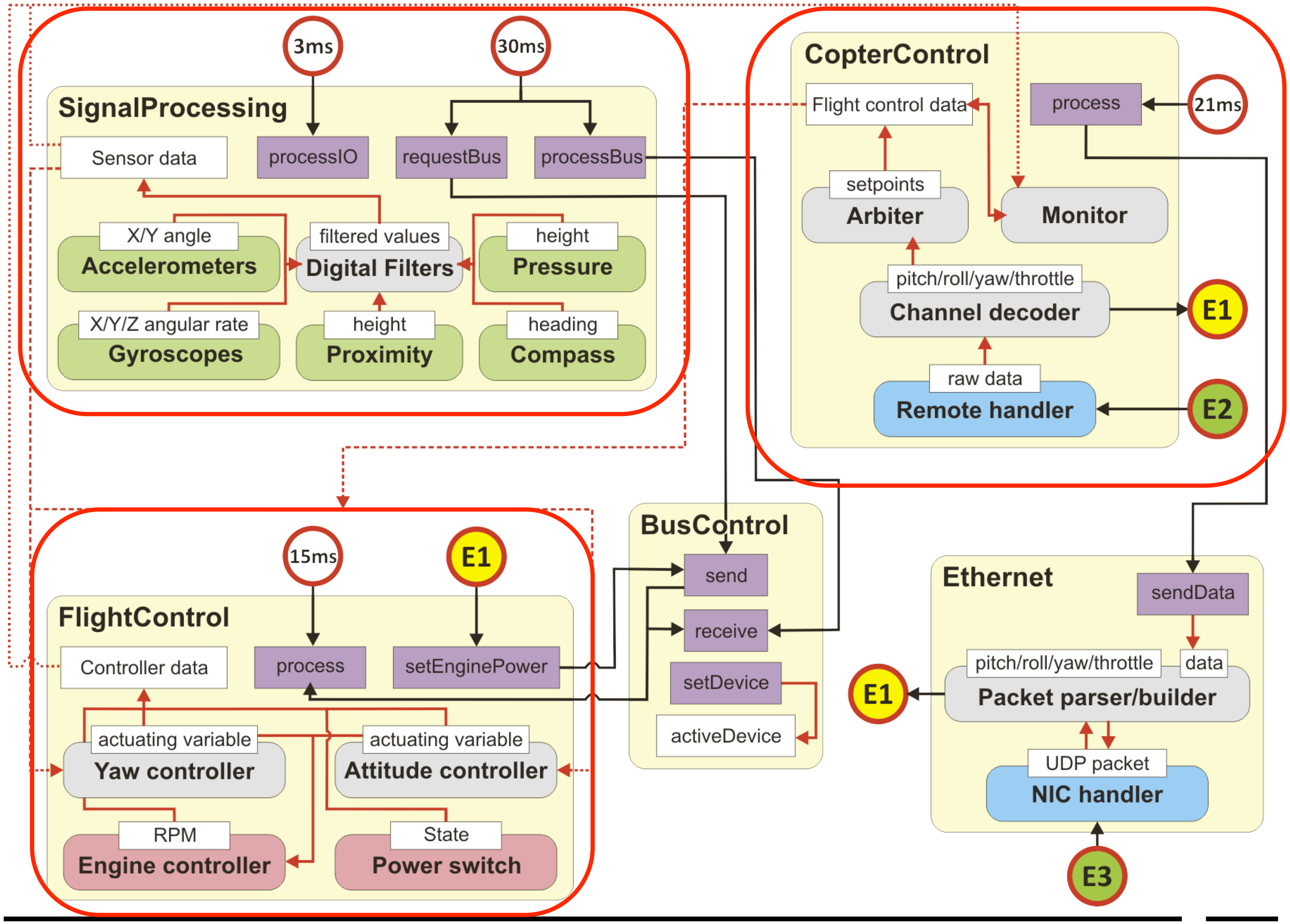
→ **50% of events depend on physical properties**

System implementation

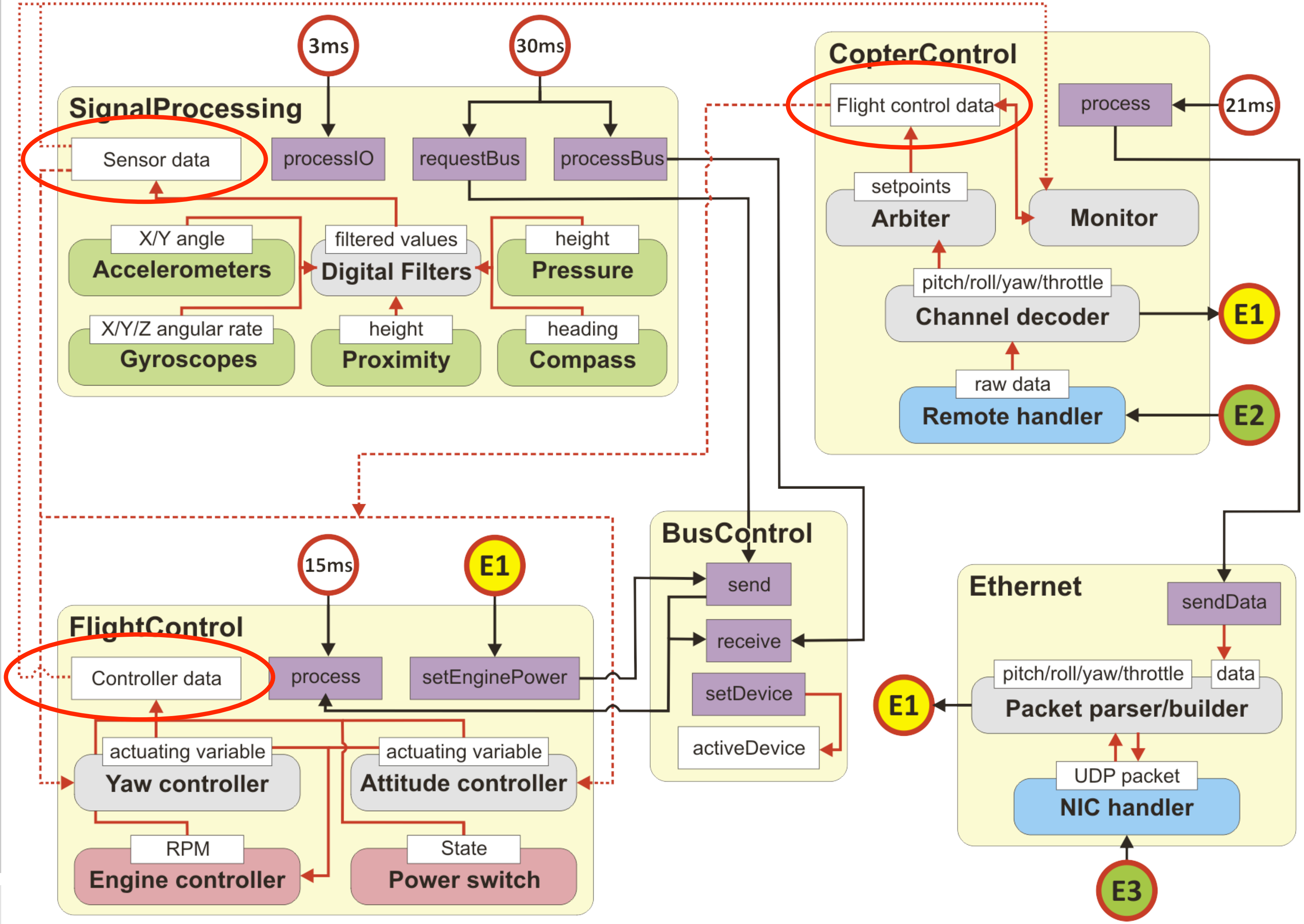
System overview



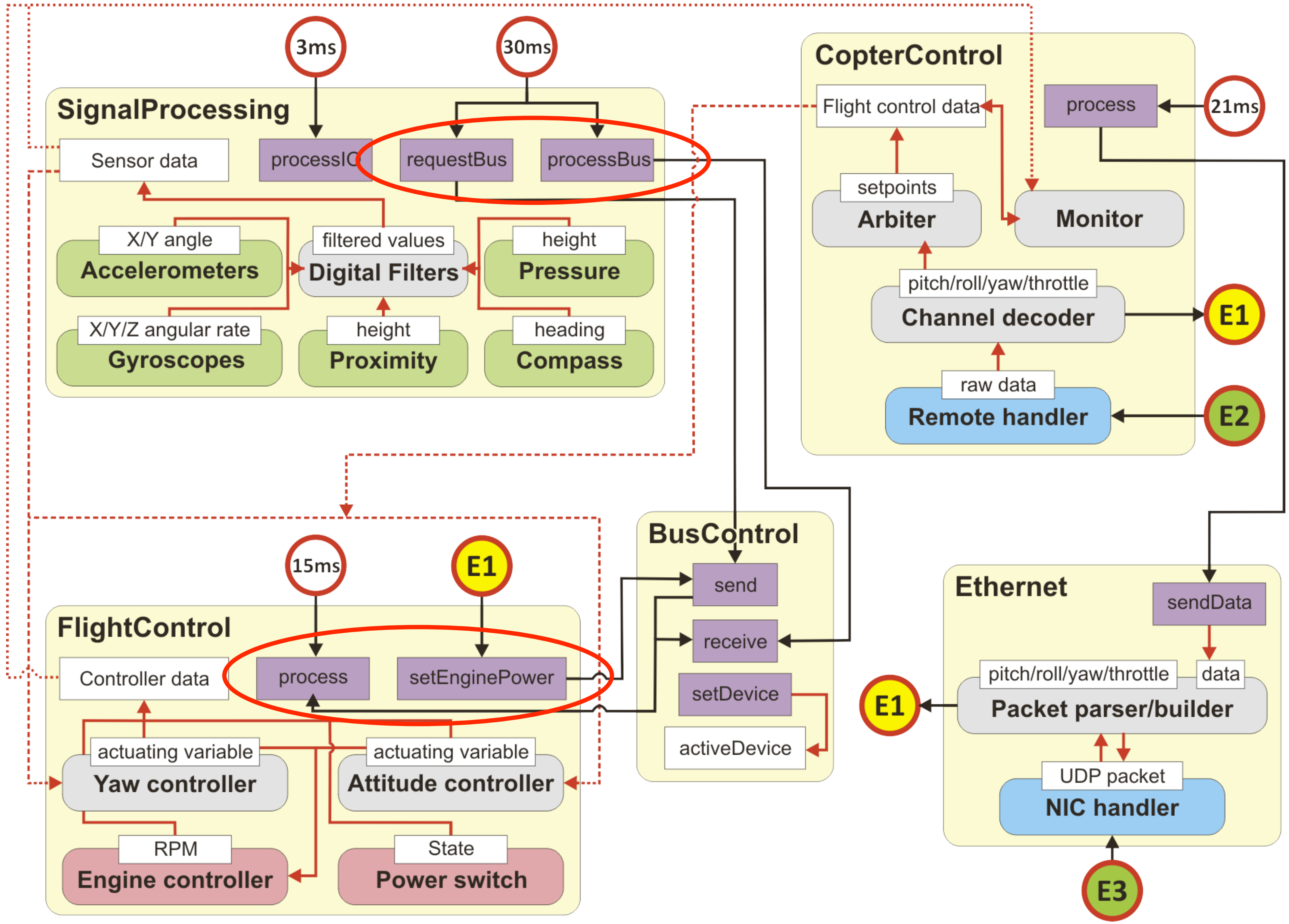
System overview – Coherence



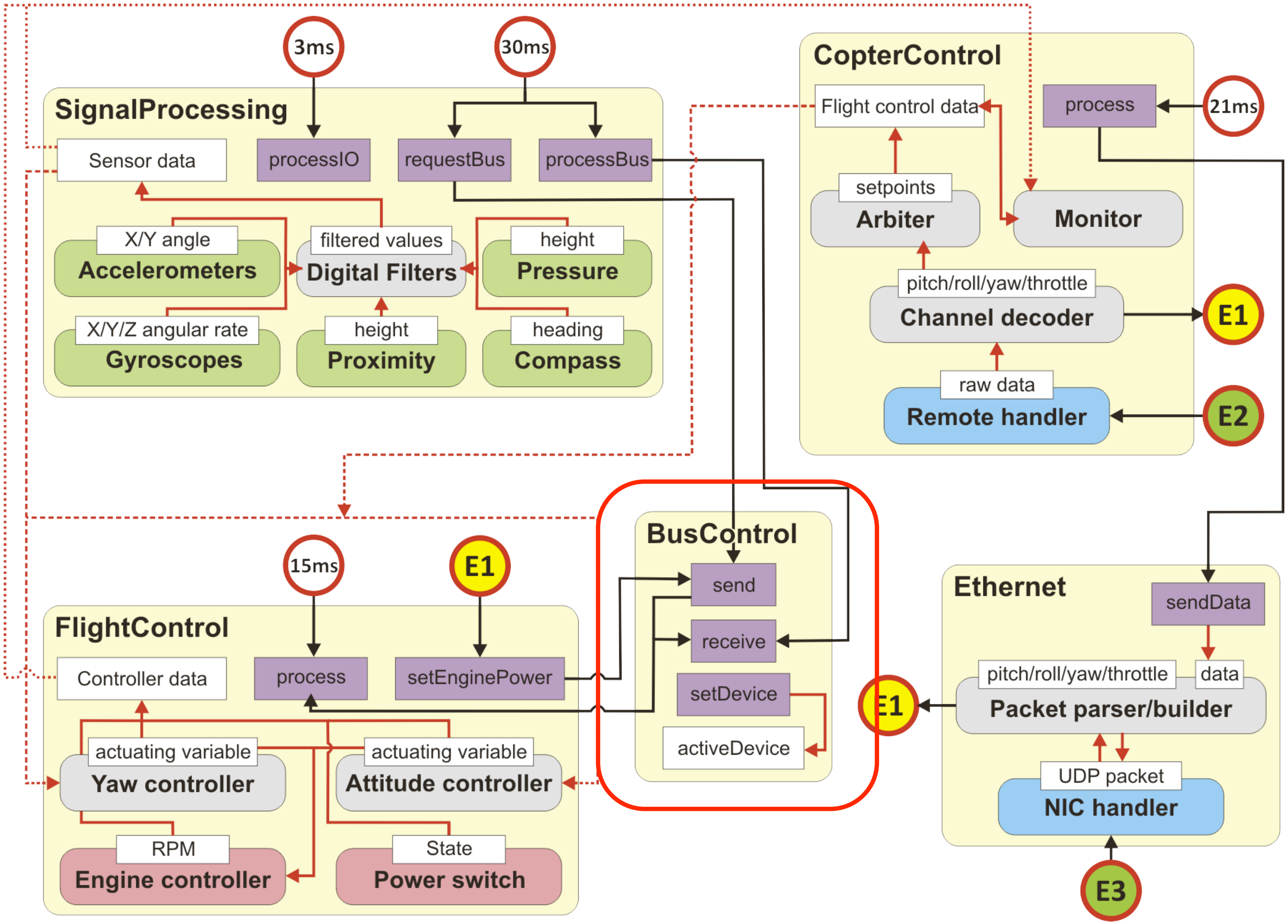
System overview – Coupling (1)



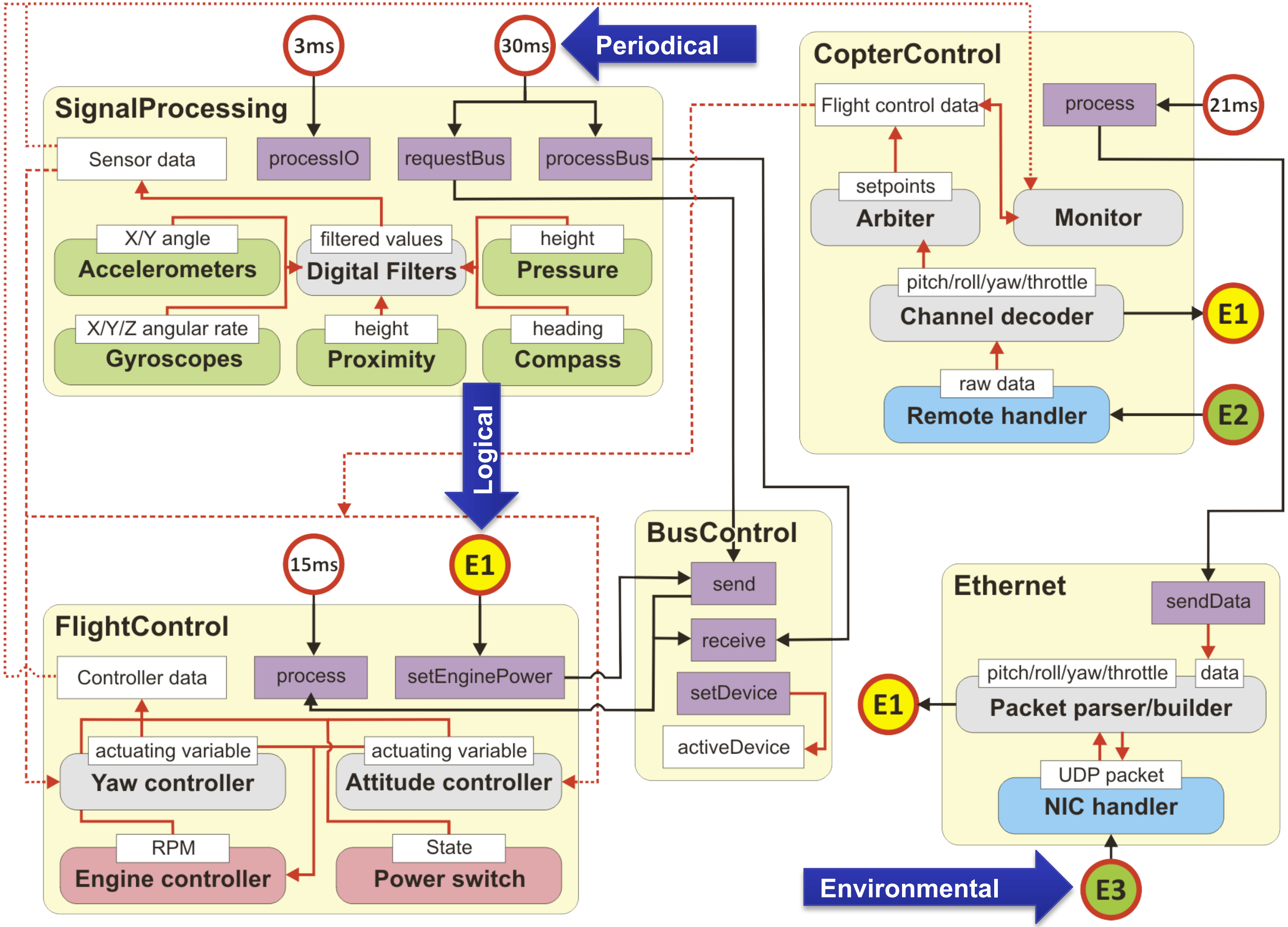
System overview – Coupling (2)



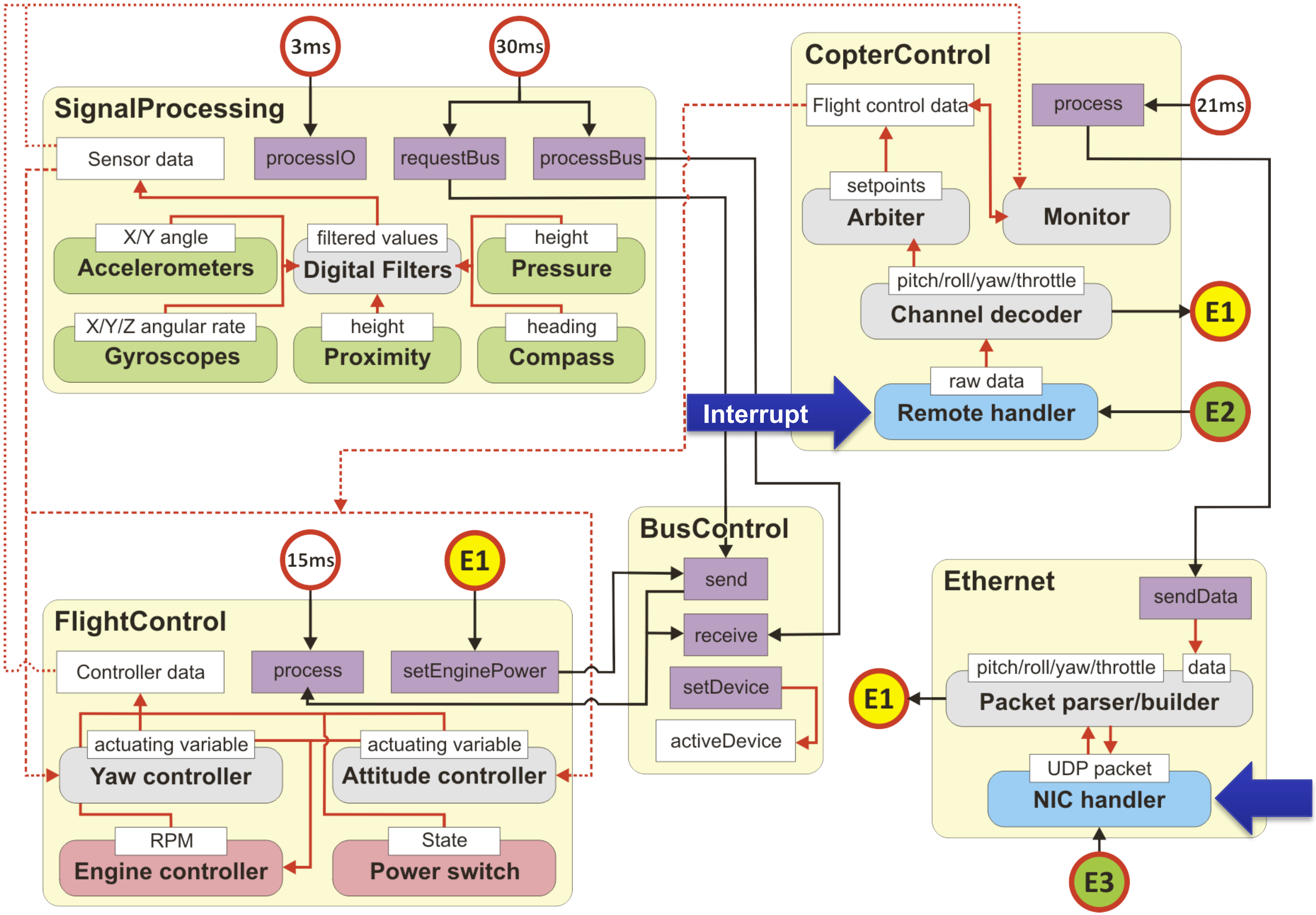
System overview – Shared resources



System overview – Events

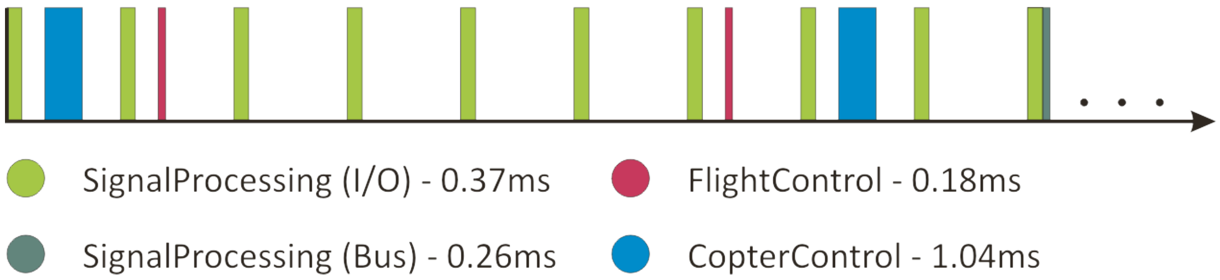


System overview – Priority inversion



Facts

- **Static schedule**
  - Interrupts: min. interarrival time known
  - Based on application and WCET analysis



- **Using PxROS-HR**
  - Priority based RTOS
  - Implemented using programmable timer

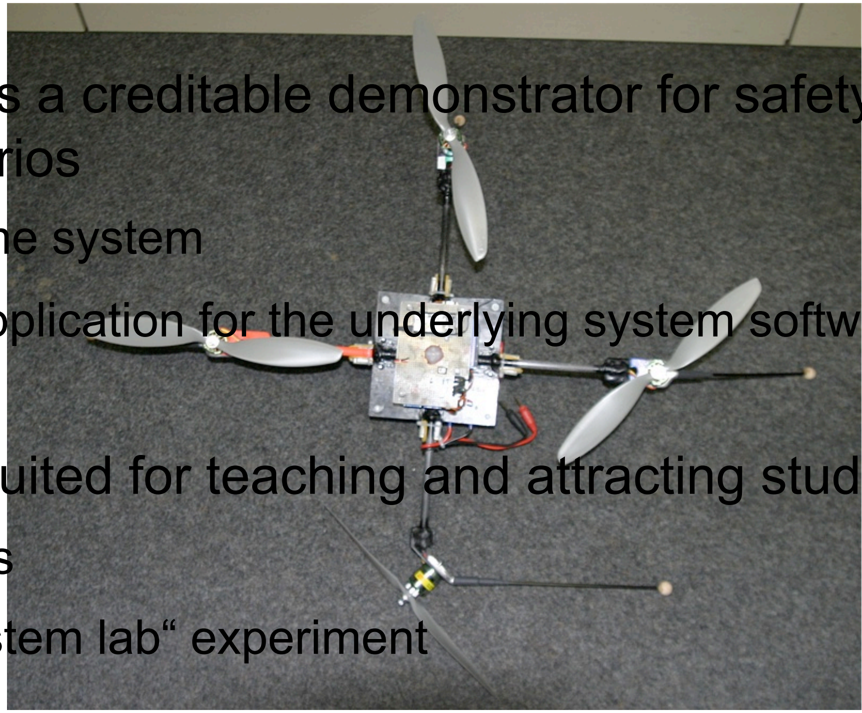
Lessons learned and conclusion

Lessons learned

- **A quadrocopter is an unforgiving system**
  - Apparent procedures are physically complex
  - Unobservable parameters have severe impact on the system
  - Control engineering necessary
- **Implementing a real-time application requires precise analysis**
  - Modularisation depending on application design
  - Aim loose coupling (data flow vs. control flow)
- **Building a real-time system requires familiarity with physical object**
  - Physical parameters have impact on **events** and **deadlines**
  - One has to see beyond ones own domain

Conclusion

- Designing and building a quadrocopter from scratch is challenging
  - Beyond the domain of computer science
  - Electrical engineering, manufacturing, control engineering
  - Real interdisciplinary project



- The I4*Copter* is a creditable demonstrator for safety-critical mission scenarios
  - A hard real-time system
  - Demanding application for the underlying system software
- It is perfectly suited for teaching and attracting students
  - Various theses
  - „Real-time system lab“ experiment

Thank you for your attention!

Questions?

Attitude control loop