Selected Literature and Future Research Direction for Cyber Physical Networks (CPNs)

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Agenda

(Personal) Motivation

Simulation of CPNs

Design & Evaluation of CPNs

Conclusion & Future Research Directions

Motivation

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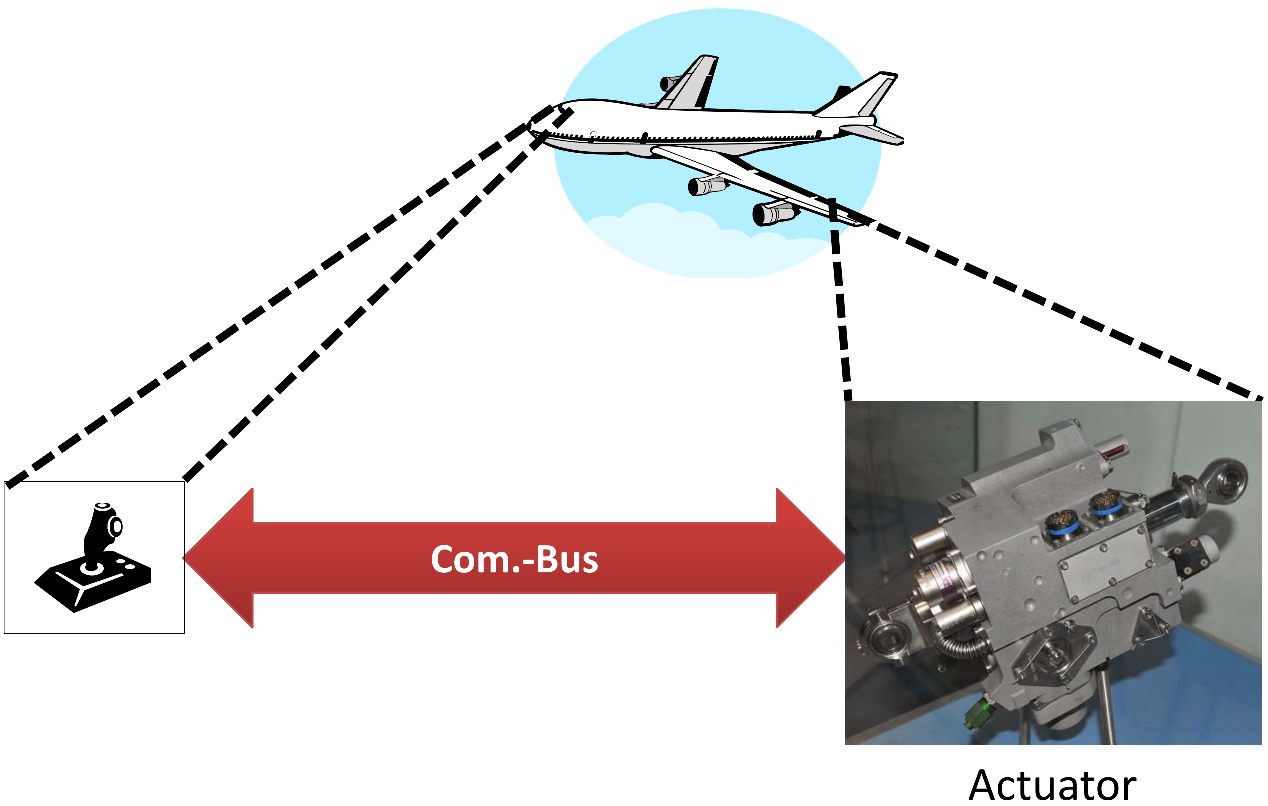
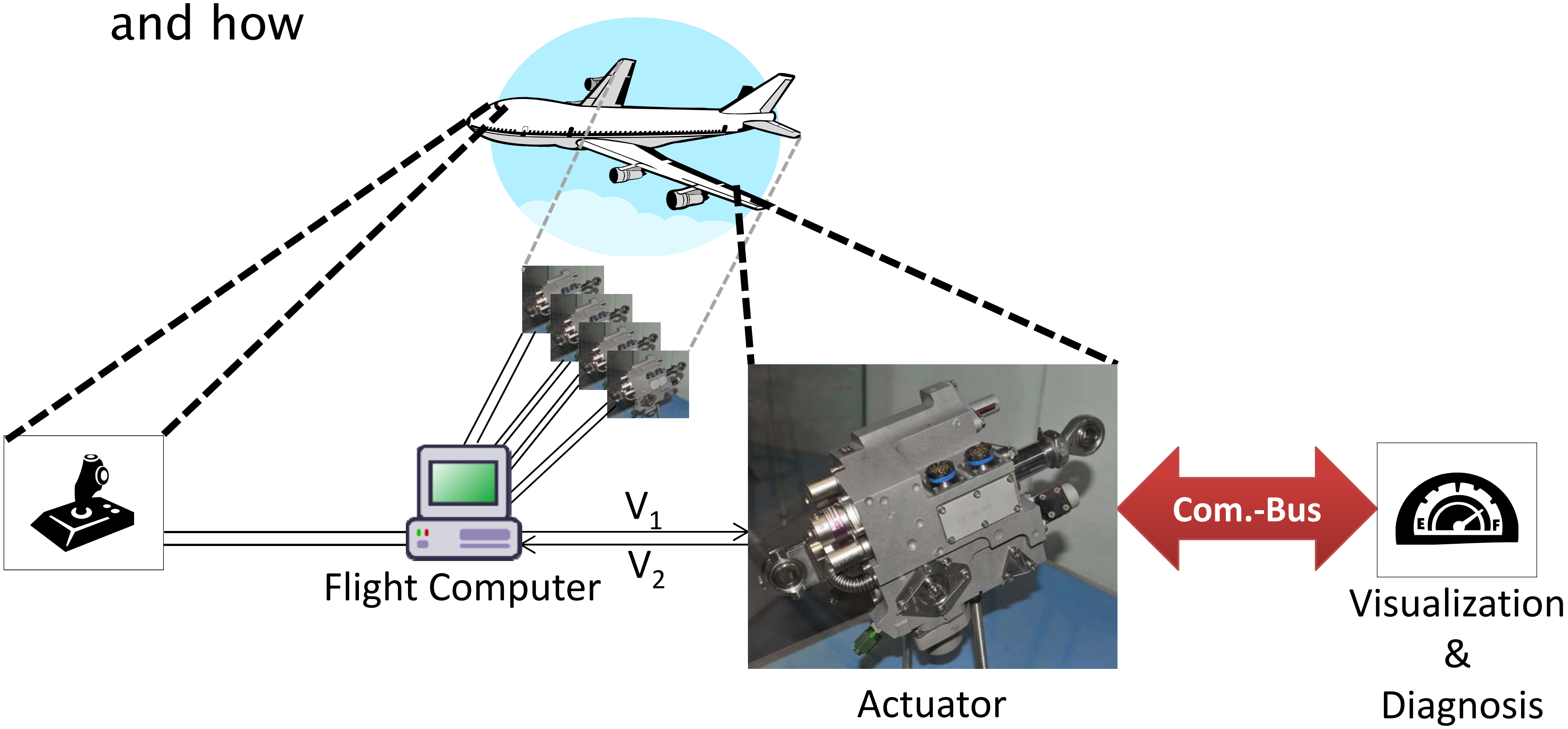
- A misunderstanding about “Fly-by-Wire”



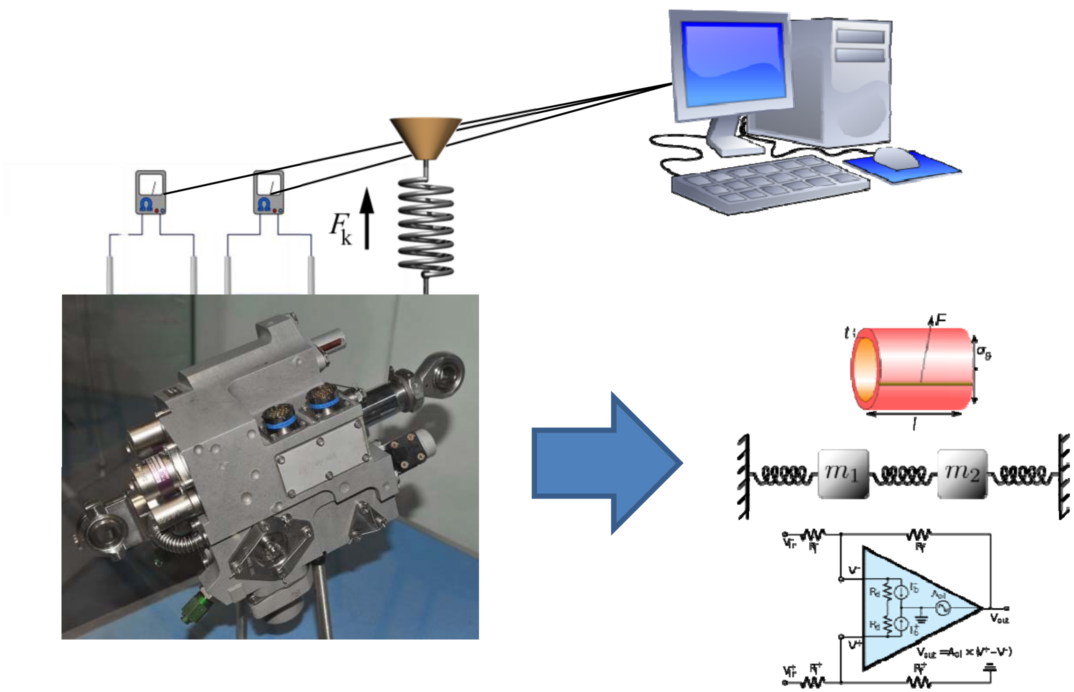
Motivation

- "Fly-by-Wire":
  - Analogue control loop
  - Flight Computer decides which actuators should be adjusted and how



Motivation

- Actuator maintenance and testing:
  - "The actuator must reach its final position in 3 ± 0.05 s"
  - Model behavior (differential equations / MATLAB **Simulink**)
  - Measure to validate model



Motivation

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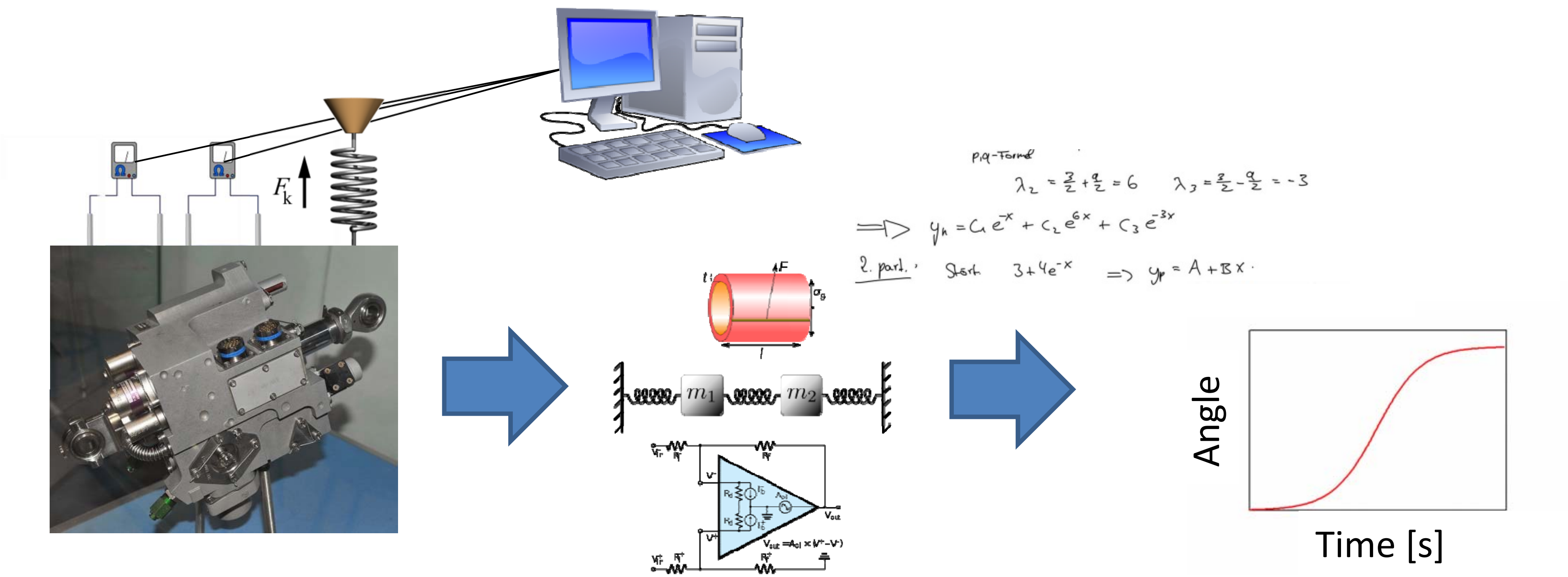

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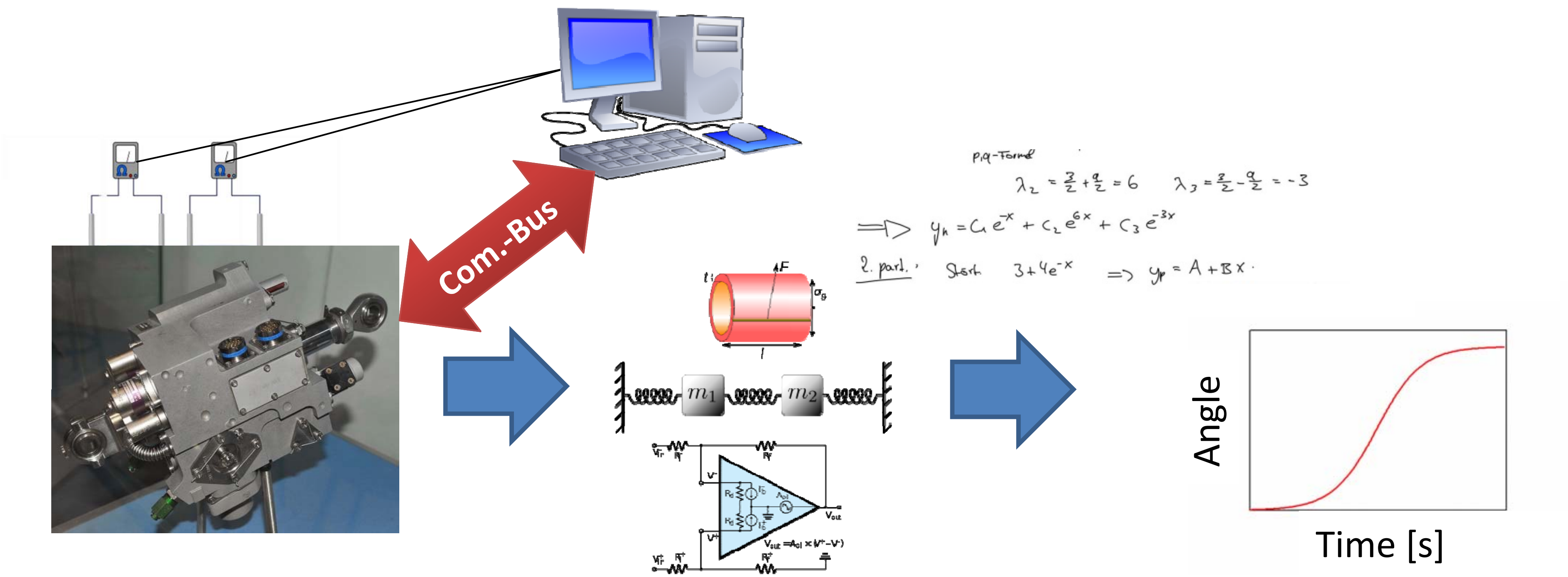

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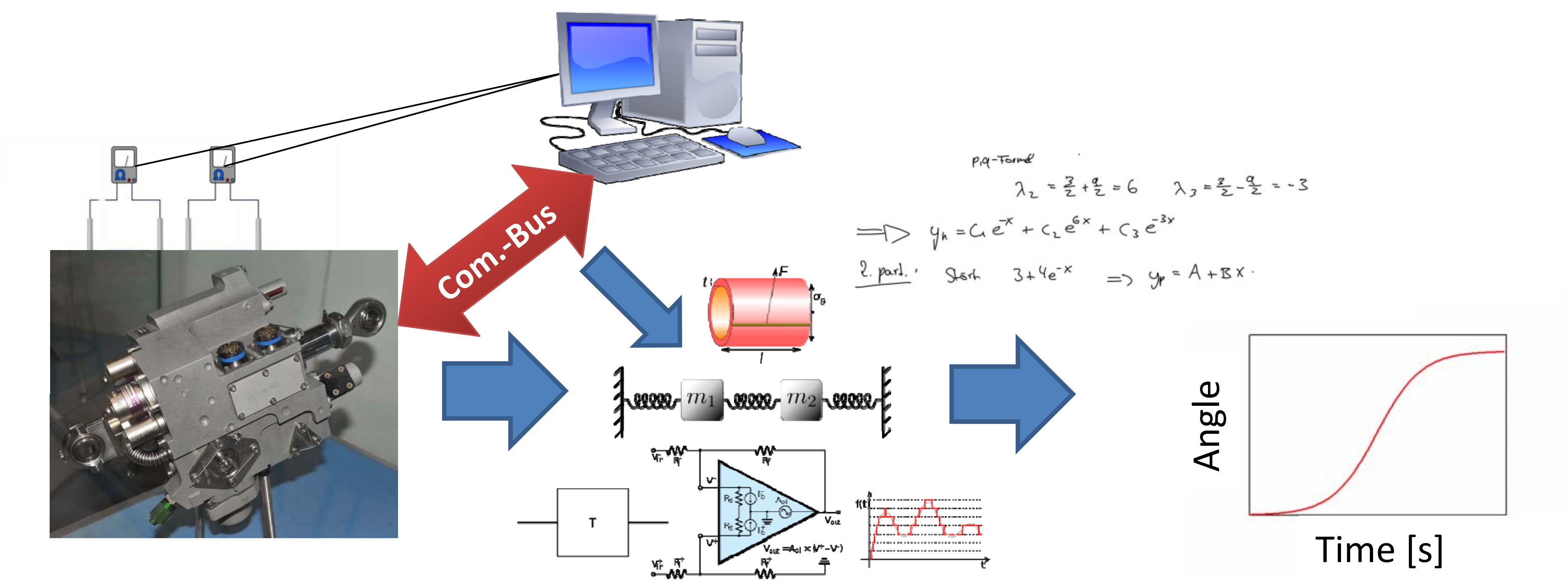
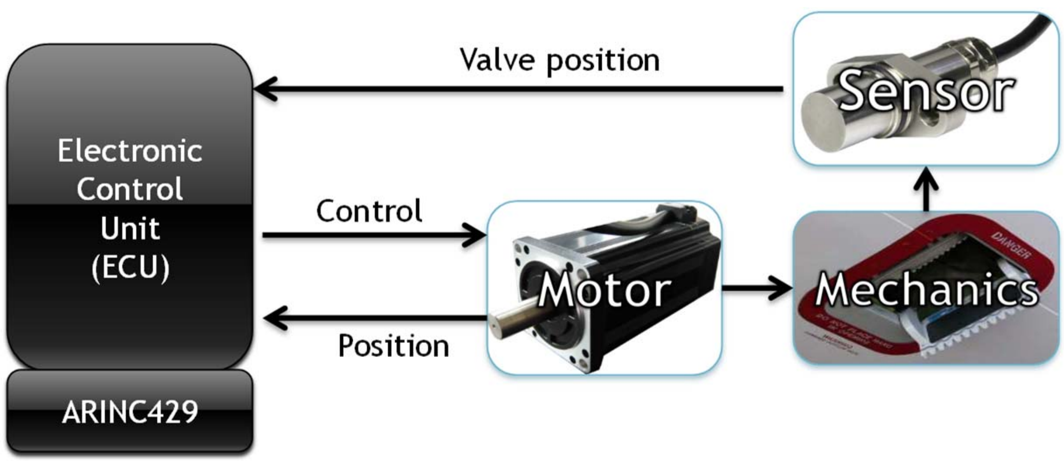
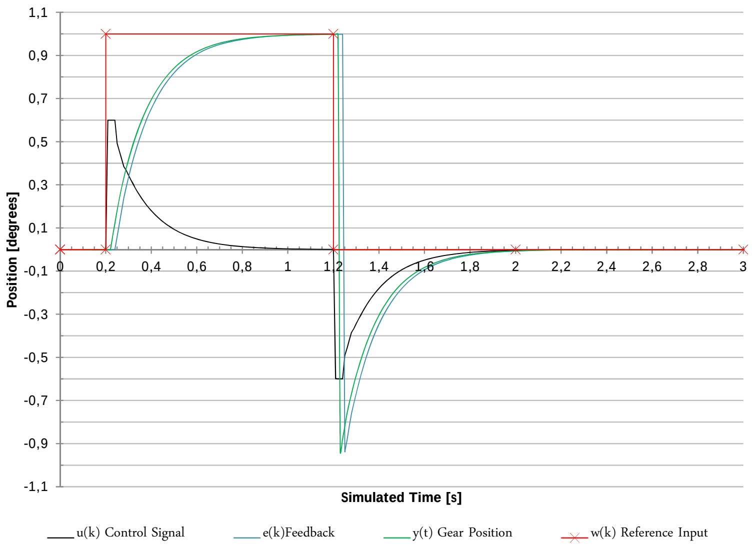


Simulation of CPNs

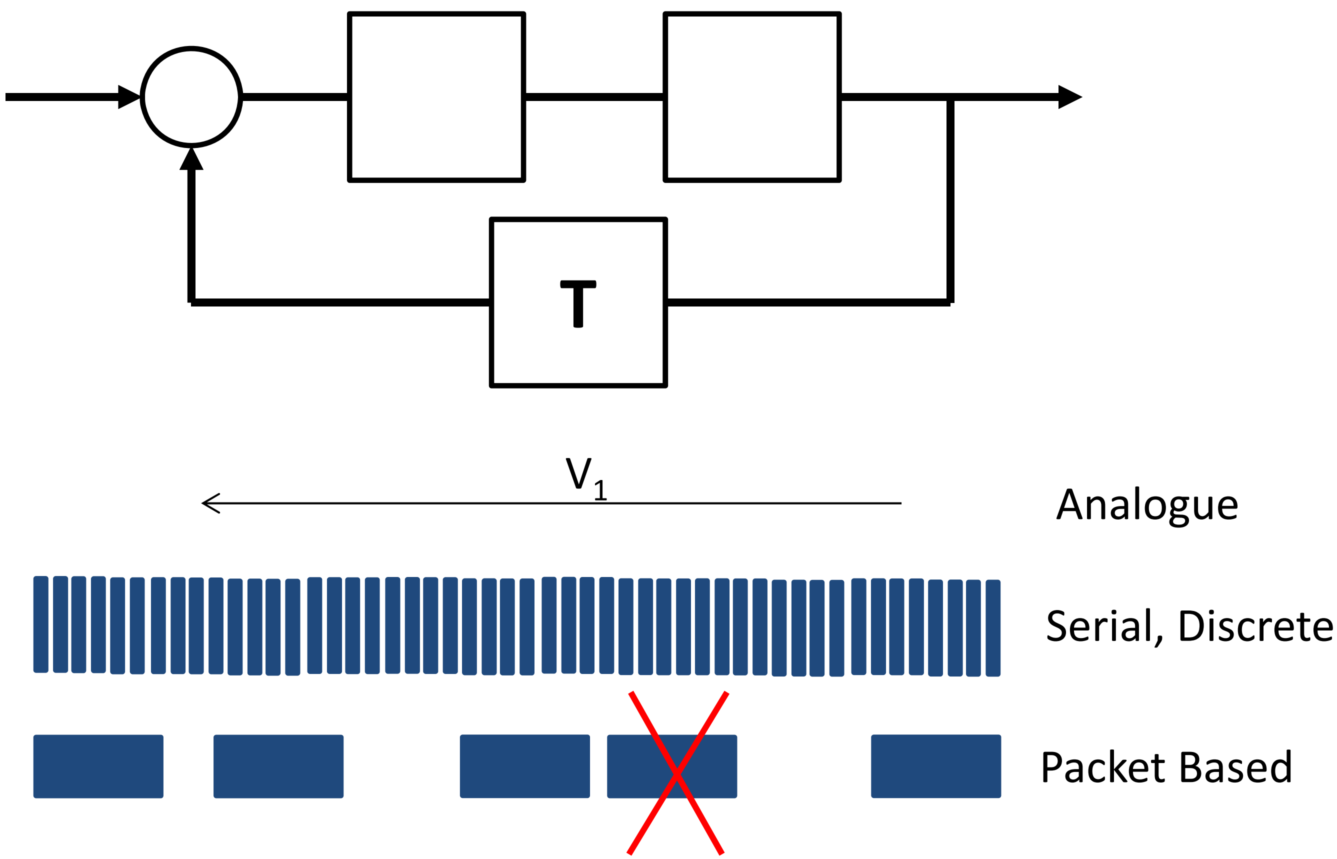
- H. C. Ihle, “**Entwicklung einer AFDX[1)] Simulation für Simulink**”, Bachelor Thesis, Institut für Flugzeug Systemtechnik (FST), TUHH, 2015
  - Development and evaluation of Simulink blocks to model the “behavior“ of AFDX
- P. Eisenmann, “**Modeling and Testing Mechatronic Components using SDL[2)] and TTCN-3[3)]**”, ComNets, TUHH, 2015
  - Extend SDL to simulate and test physical systems in discrete time





1) AFDX: Avionics Full-Duplex Switched Ethernet 2) SDL: Specification and Description Language
3) TTCN-3: Testing and Test Control Notation (Version 3)

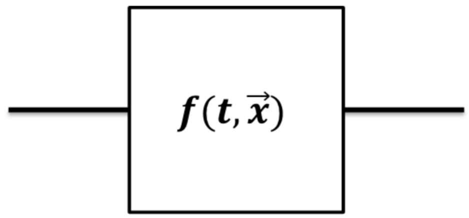
Simulation of CPNs



Simulation of CPNs

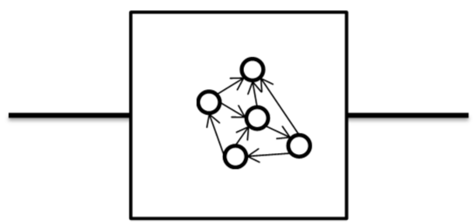
Have other communication systems than AFDX been modelled with Simulink or similar tools („continuous time simulation“)?

- Yes, mostly for Smart-Grid evaluation [1, 2, 3] using Simulink S-Function



- W. Li et al. “Simulation of the smart grid communications: Challenges, techniques, and future trends”, 2014

“the communication models are often too simplistic to simulate complex communication networks precisely”



[1] R. Majumder et al. “Closed loop simulation of communication and power network in a zone based system”, 2013
[2] D. Henriksson et al. “TRUETIME: SIMULATION OF CONTROL LOOPS UNDER SHARED COMPUTER RESOURCES”, 2002
[3] B. Lincoln et al. “JITTERBUG: a tool for analysis of real-time control performance”

Simulation of CPNs

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Hybrid simulation

- IEEE 1560 “Modeling and Simulation (M&S) High Level Architecture (HLA)” [1, 2, 3]
  - Define a very abstract meta simulation model and **interfaces**
  - Simulators applying it can be easily connected

Check Figure 1 here:
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20010016107.pdf

NASA “An Evaluation of the High Level Architecture (HLA) as a Framework for NASA Modeling and Simulation”, 2000

- Pros & cons:
  - Positive: very realistic model in physical and communication domain
  - Negative: users must understand two simulation models and frameworks

[1] M. Ficco et al. “An HLA-based framework for simulation of large-scale critical systems”, 2015
[2] C. Sung et al. “Framework for Simulation of Hybrid Systems: Interoperation of Discrete Event and Continuous Simulators Using HLA/RTI”, 2014
[3] H. Georg, C. Wietfeld et al. “Analyzing Cyber-Physical Energy Systems: The INSPIRE Cosimulation of Power and ICT Systems Using HLA”

Motivation

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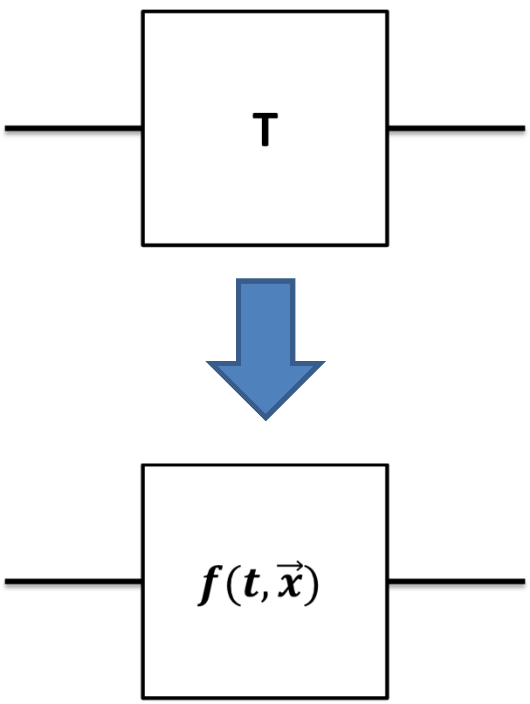
- BMBF “Industrie 4.0” call “**Zuverlässige drahtlose Kommunikation in der Industrie**”: delay < 1ms; jitter < 250 µs
  - Why would anyone need that?

- G. Fettweis, “**A 5G Physical Layer Framework Based on GFDM**”, Invited Speech, SCC2015
  - Electronic Stability Control (ESC) **for vehicles** requires delays in the range of milliseconds
  - Concluded from system model of **control loop**, its closed form solution and location of poles
- G. Fettweis et al. “**The Tactile Internet**”, ITU-T Technology Watch Report, 2014
  - Clearly states eye/ear/muscle coordination requires delays in range of 1 millisecond
  - Reason why required in industrial production remains unclear

Design & Evaluation of CPNs

Control loops experience delays; what if they are not fixed?

- T. Bund et al. “Guaranteed Bounds for the Control Performance Evaluation in Distributed System Architectures”, Ulm University, 2010
  - Mathematical analysis of the influence of jitter on control loop performance



Check Figure 8 here: http://www.uni-ulm.de/fileadmin/website_uni_ulm/iui.inst.050/publications/BundMKS2010.pdf

Design & Evaluation of CPNs

- Adaptive Cruise Control (ACC) vs. Cooperative ACC

https://www.youtube.com/watch?v=STtFcgG91fk

Design & Evaluation of CPNs

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- X. Liu & A. Goldsmith, "Effects of communication delay on string stability in vehicle platoons", Stanford/Berkley, 2001
  - "Communication delay [...] is highly dependent on the network architecture adopted and the underlying wireless channel. It also depends **on how the control law is executed**."
  - All results derived analytically using control theory
  - Must know velocity and acceleration of leader for stable system
  - How to design control loops to be tolerant against delay and jitter?
    - Problem: Instantaneous information about predecessor but only periodic updates about leader
    - Decide when (which received packet) to trigger the adjustment ➔ adjust when all vehicles received the information for sure (**no packet loss assumed**)
  - Second dimension (changing lanes) considered in [1] ➔ much more complex

Check Figure 1 here:
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.78.8844&rep=rep1&type=pdf

[1] R. Rajamani et al. "Demonstration of Integrated Longitudinal and Lateral Control for the Operation of Automated Vehicles in Platoons", 2000

Design & Evaluation of CPNs

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- H. Zhou et al. “**Vehicle Platoon Control in High-Latency Wireless Communications Environment**”, Univ. of Michigan, 2012
  - Detect packet losses by timeouts
  - Interpolate missing value using autoregressive moving average with exogenous terms (ARMAX)

Check Figure 3 here: http://www-personal.umich.edu/~rsaigal/papers/hao1.pdf

Design & Evaluation of CPNs

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- J. A. Fax et al. “**Information flow and cooperative control of vehicle formations**”, California Institute of Technology, 2003
  - Applicable to many different kinds of swarms
  - “virtual leader”: remove single point of failure
  - Key question: what influence does the data exchange model have on the system?
  - Graph theoretic approach allowing to analytically determine if system is stable (also for multi-hop communication)
  - **„it is possible for the vehicles to be formally stable, but to exhibit very poor performance”**
  - Form a hexagon, only exchange information with your neighbors vs. agree on a center and keep a defined distance and angle from it

Check Figure 1 here:
http://authors.library.caltech.edu/28022/1/fm03-tac.pdf

Conclusion & Future Research Directions

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- Every Cyber Physical System is a new challenge
  - There is currently no general optimization approach but performance might be improved by
    - Synchronizing the time of adjustment among nodes
    - Changing control loop parameters
    - Detecting losses and extrapolating missing data

- Hybrid / co-simulation is well researched compared to continuous time simulation (Simulink etc.)

Future work

- Extend and validate the toolchain (Simulink S-Functions)
- Develop analytic solution for control loop performance taking (stochastic) network properties into account

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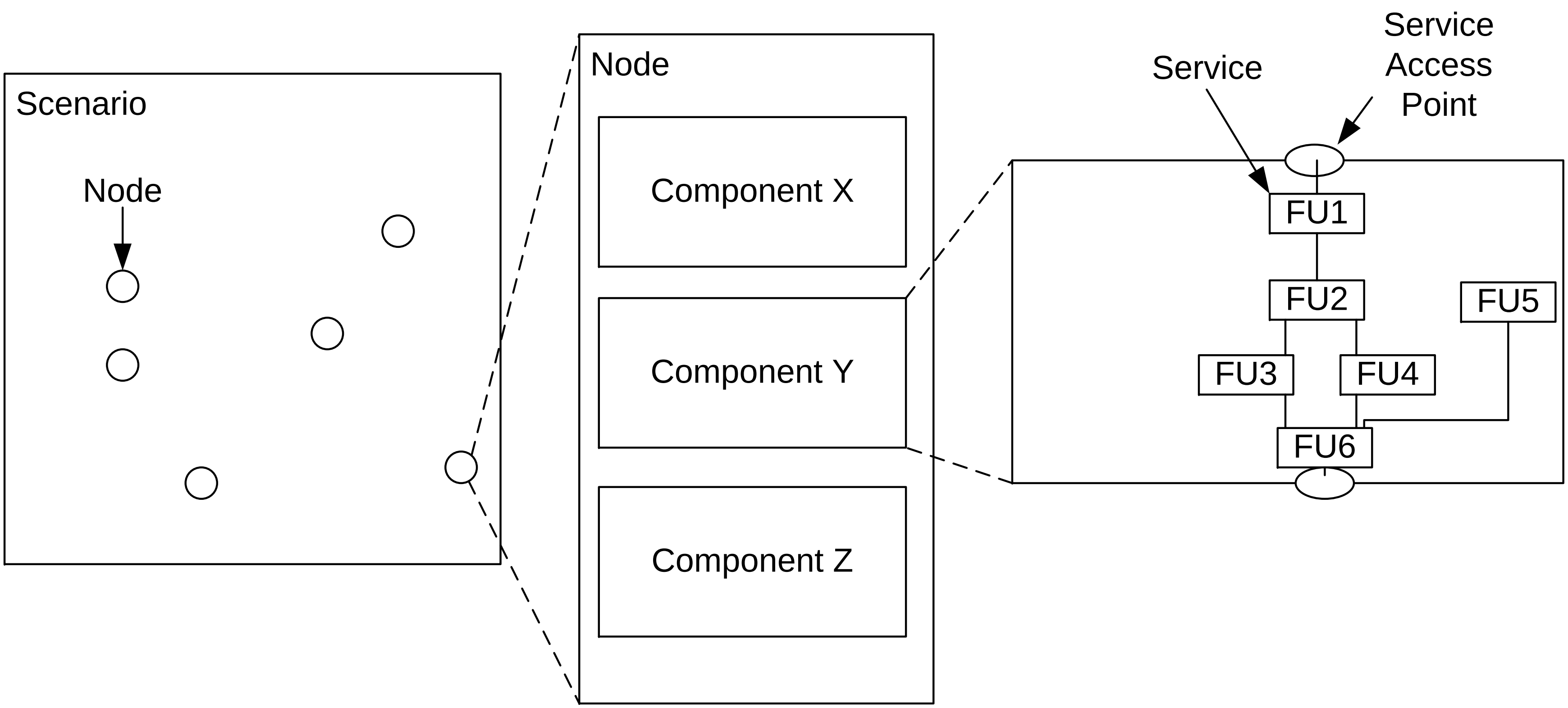
- Design network layer according to control problem and environment [1]



[1] M. Schinnenburg et al. "Application of Functional Unit Networks to Next Generation Radio Networks", RWTH Aachen, 2006

Thank you for your attention

www.tuhh.de