Intelligent Dependable Autonomous Systems

DFKI Research Fellow Talk

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smartFactory KL®

DFKI | IFS Innovative Fabriksysteme

WS KL Werkzeugmaschinen und Steuerungen TU KAISERSLAUTERN

Overview

- Motivation
- Trustworthy AI and Dependability
- Dependability of Dynamical Systems
- Production Scenarios
  - Production Level 4
  - Multi-Agent AI Systems and Behavior Decomposition
  - Collaborative Robotics
  - Fault-Tolerant Control
  - Hybrid Modelling
- Conclusion
- Future Research

Motivation: Development of Safety-Critical Applications

Source: Prevent

Automotive

Source: http://www.huffingtonpost.de

Production

complex
distributed
dynamical
collaborative
autonomous

Source: Boeing Dreamliner

Avionics

Source: Klinikum Jena

Medical Technology

Trustworthy AI and Dependablity

Ethical Principles

- (i) Respect for human autonomy
- (ii) Prevention of harm
- (iii) Fairness
- (iv) Explicability

Technical Requirements

- Technical robustness and safety
- Resilience to attack and security
- Fallback plan and general safety
- Accuracy
- Reliability and Reproducibility

} **Dependability**

European Commission, Directorate-General for Communications Networks, Content and Technology, *Ethics guidelines for trustworthy AI*, Publications Office, 2019, https://data.europa.eu/doi/10.2759/177365

Dependability of Dynamical Systems - Linguistic

What is Dependability?

- [Carter, 1982]: A system is dependable if it is trustworthy enough that reliance can be placed on the service it delivers
- [Laprie, 1992]: Dependability is that property of a computing system which allows reliance to be justifiably placed on the service it delivers
- [Dubrova, 2013]: Dependability is the ability of a system to deliver its intended level of service to its users

Dynamical (autonomous mobile robot) Systems

- **[Rüdiger, 2007]: Dependability in general is the capability of a system to successfully and safely fulfil its mission.**

[Carter, 1982] Carter, W.: A time for reflection. In Proc. 12th Int. Symp. on Fault Tolerant Computing (FTCS-12). IEEE Computer Society Press Santa Monica

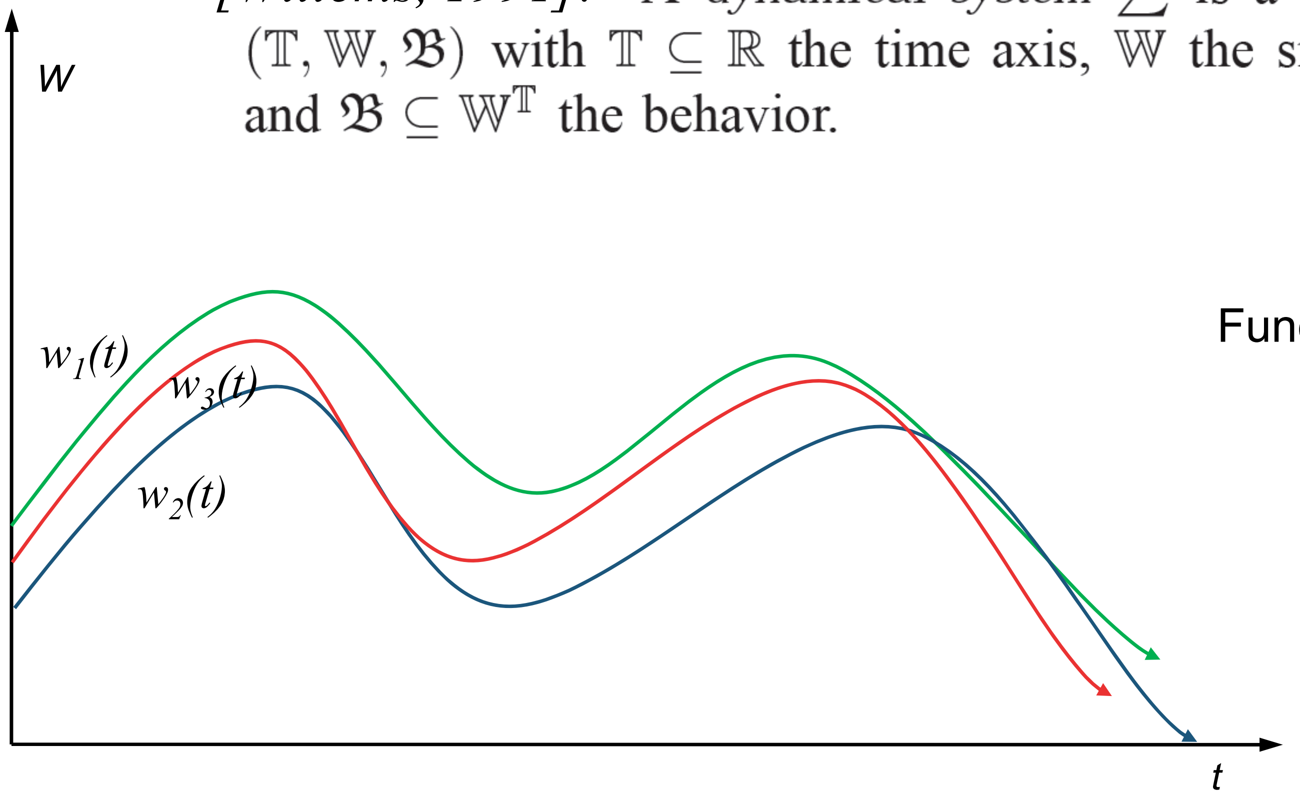
[Laprie, 1992] Laprie, J. C.: Dependability. Basic Concepts and Terminology. Ed. Springer Verlag.

[Dubrova, 2013] Dubrova, E.: Fault tolerant design: An introduction. Springer, DOI 10.1007/978-1-4614-2113-9

[Rüdiger, 2007] Rüdiger, J., Wagner, A., and Badreddin, E.: Behavior based definition of dependability for autonomous mobile systems. In European Control Conference 2007 (July 2-5), pp. 4146–4151.

Dynamical System – Behavior Description

[Willems, 1991]: A *dynamical system* $\sum$ is a triple $\sum = (\mathbb{T}, \mathbb{W}, \mathfrak{B})$ with $\mathbb{T} \subseteq \mathbb{R}$ the time axis, $\mathbb{W}$ the signal space, and $\mathfrak{B} \subseteq \mathbb{W}^{\mathbb{T}}$ the behavior.



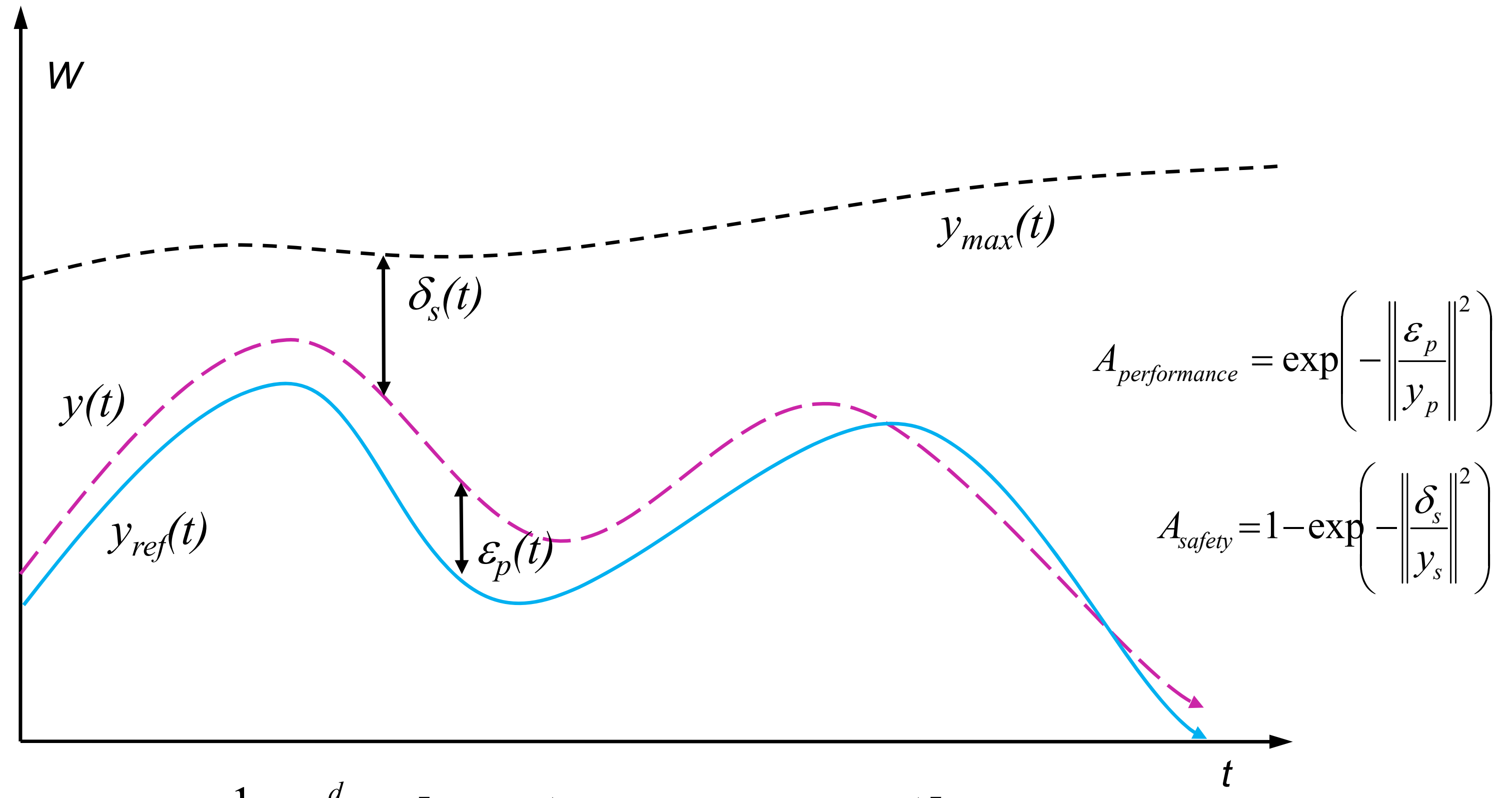
Functional representation

state space

$$\dot{x}(t) = f(x(t), u(t))$$
$$y(t) = g(x(t), u(t))$$
$$x(t_0) = x_0$$

J.C. Willems: Paradigms and puzzles in the theory of dynamical systems. *Automatic Control, IEEE Transactions on, 36(3):259-294, March 1991*

Dependability of Dynamical Systems - Formal

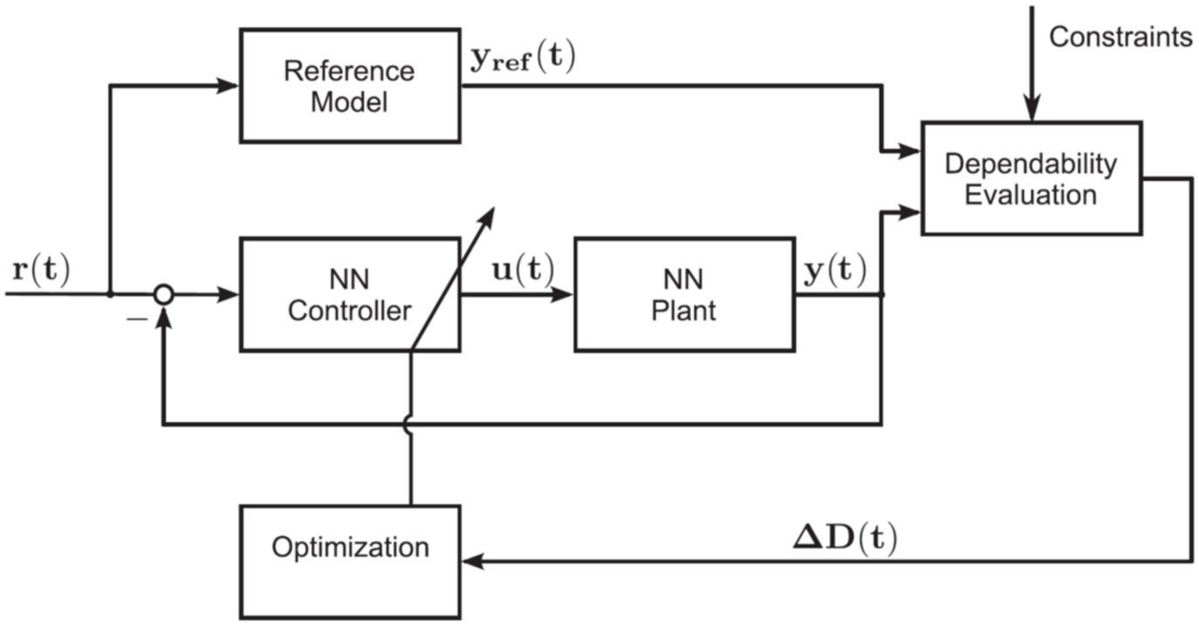


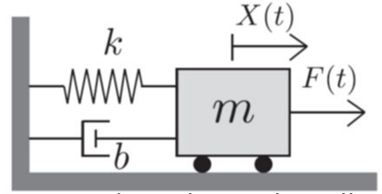
Dependability Measure

$$D(t) = 1 - \frac{1}{m}\int_0^t \sum_{j=1}^{d} a_j \left[1 - A_j\left(u(t), y_r(t), y(t), \Theta_j\right)\right] dt$$

Wagner (2018): : Modeling, Analysis, and Design of Dependable Systems with Application to Robotics and Assistance Technology. Verlag Dr. Hut 2018, ISBN 978-3-8439-3559-3.

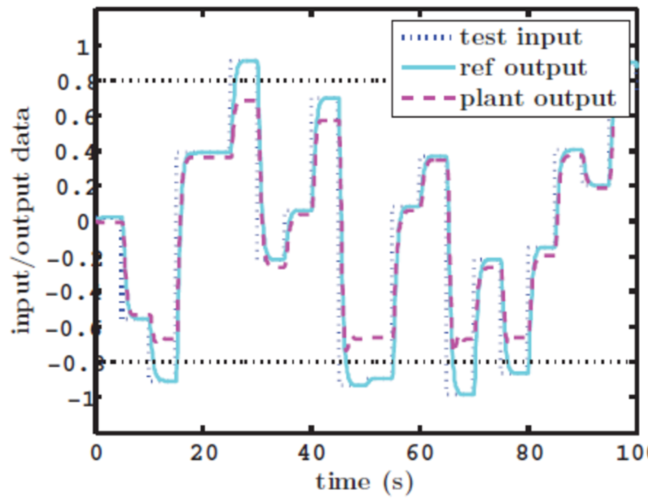
Dependability Optimization: Robot Control



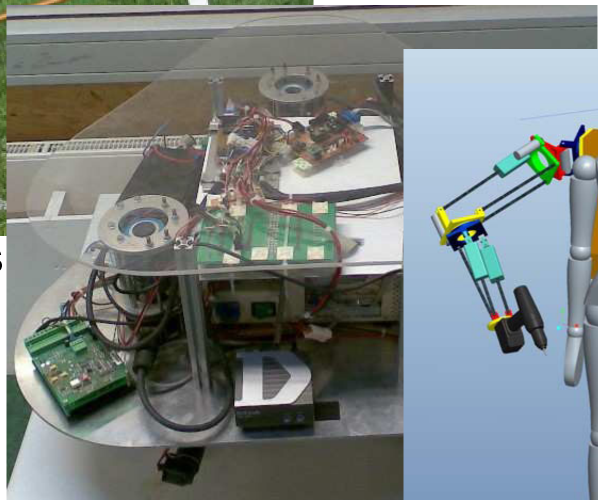


Damped mechanical oscillator

$y_p = 0.2$ $y_s = 0.08$, $y_{max} = 0.8$, $y_{min} = -0.8$,
$a_p = 0.4$, $a_{s+} = a_{s-} = 0.3$

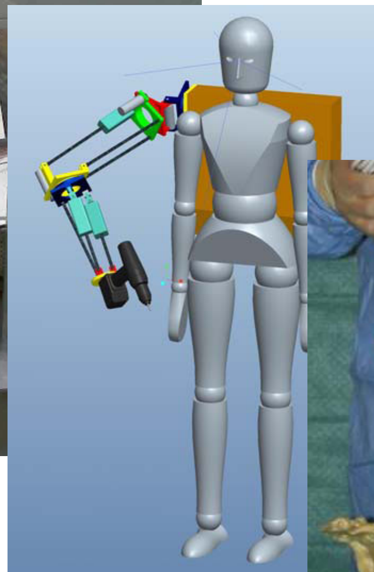


Dependable Robotics Research Group (Univ. Heidelberg): Autonomous Mobile Robots and Assistance Systems



Mobile Robots

Rehabilitation Systems



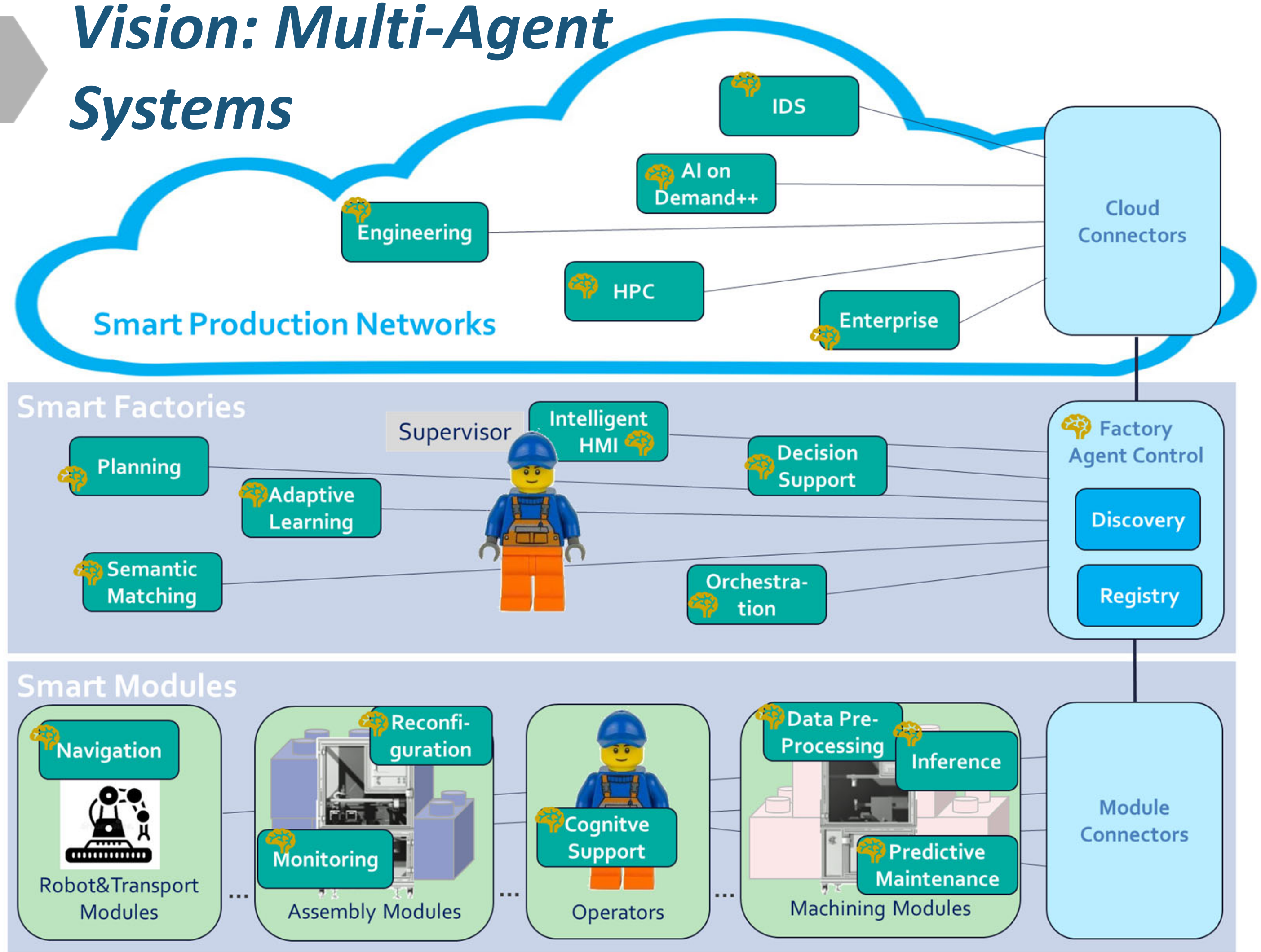
Bionic Exoskeletons

Surgical Robots

Production Level 4
(Autonomous Human-Centered Shared Production)

Source: SmartFactory-KL

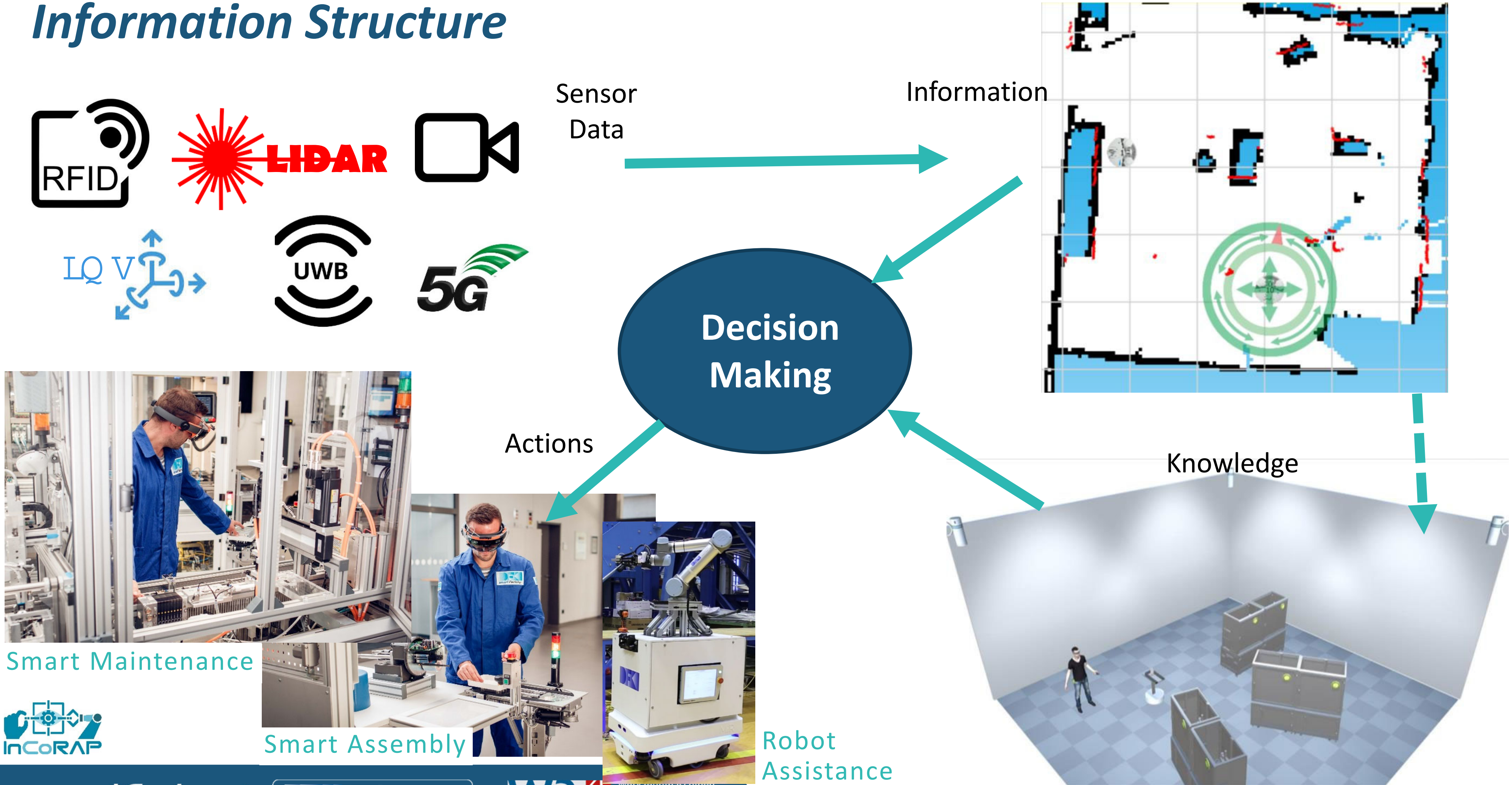
Vision: Multi-Agent Systems



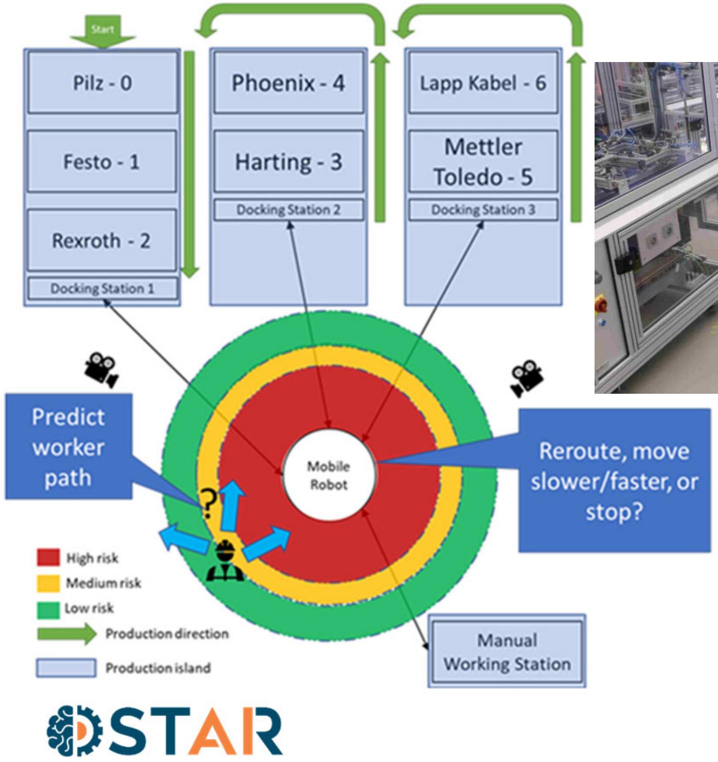
MAS4AI

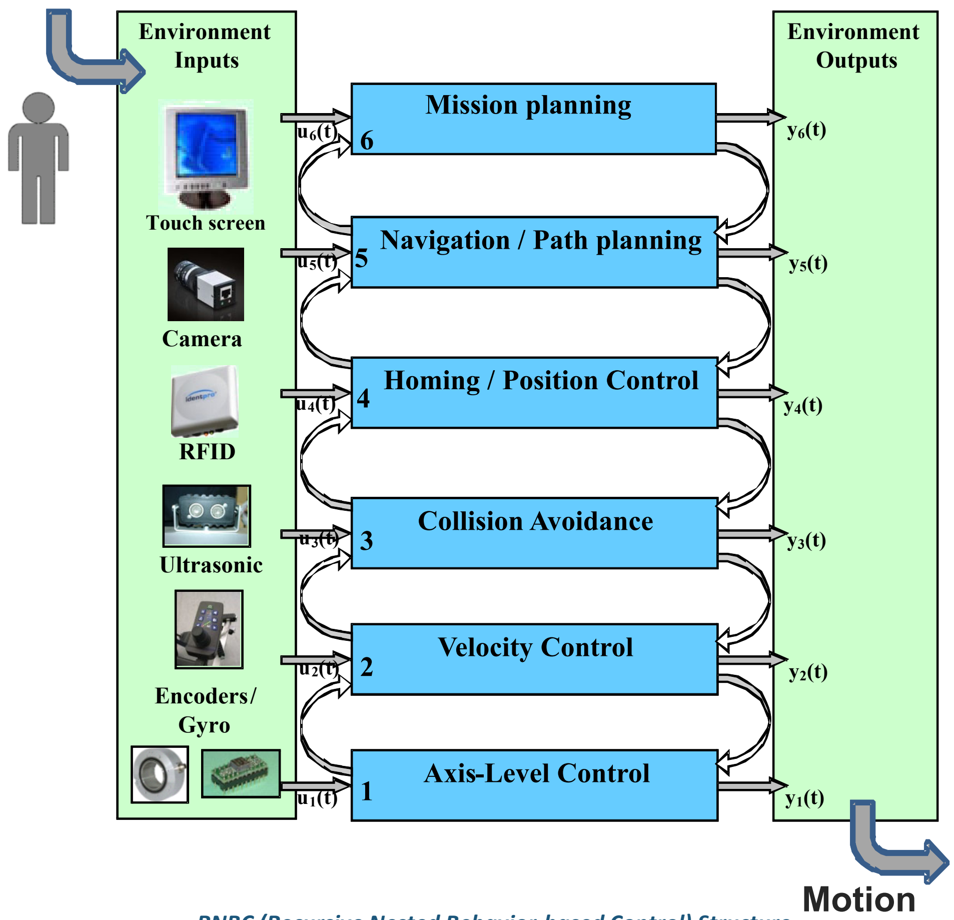
- **Multi-agent AI systems**
  - Diverse AI technologies and combinations: knowledge-based, hierarchical planning and model-based machine learning
  - AI components in different hierarchy layers
  - Unified, reusable and scalable solutions
- **Autonomous modular production**
  - Semantic Self-description capabilities of technical modules, optimization of configurations and processes
  - Human assistance with awareness of human capabilities
  - Highly reactive and safe solutions

Information Structure



Behavior Decomposition for Autonomous Mobile Robot



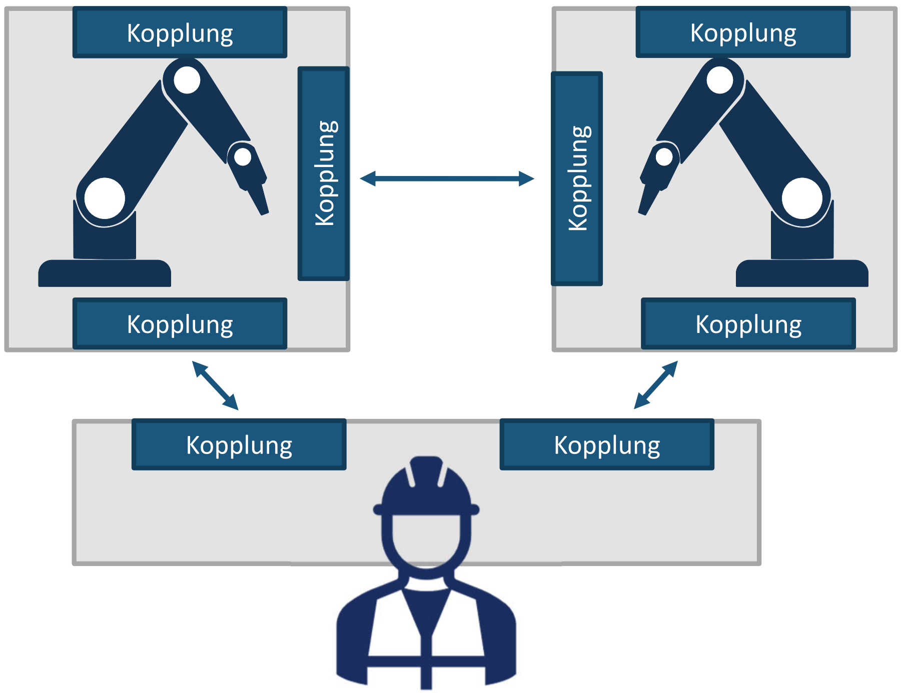


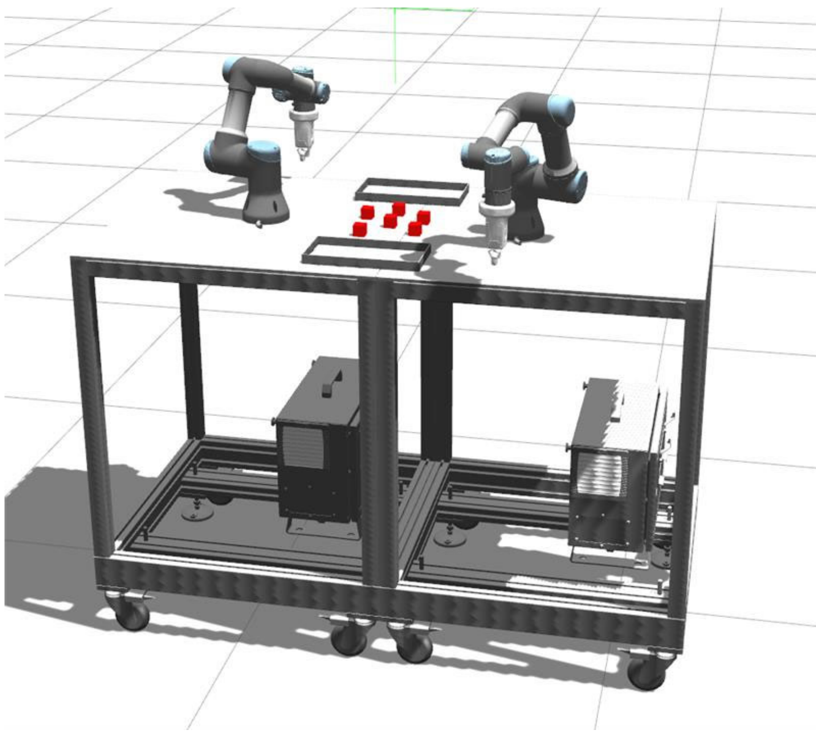
RNBC (Recursive Nested Behavior-based Control) Structure

Badreddin1989; Bartolein2007; Wagner2010; Wagner2016

Collaborative Robots

KoKoBot

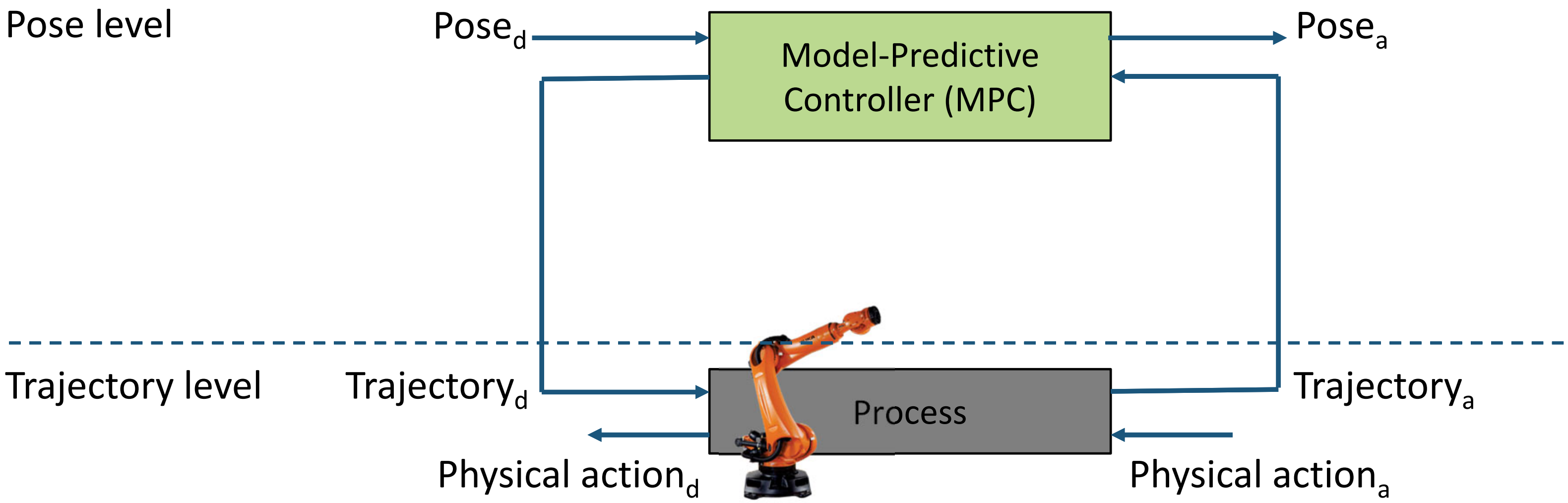




Nigora Gafur et al., 2021

Planning und Model-Predictive Control

$$J_i(\mathbf{x}_i^k, \mathbf{u}_i^k) := (\mathbf{x}_i^{N_\mathrm{p}} - \mathbf{x}_i^\mathrm{f})^T \mathbf{Q}_i^\mathrm{f} (\mathbf{x}_i^{N_\mathrm{p}} - \mathbf{x}_i^\mathrm{f}) + \sum_{k=0}^{N_\mathrm{p}-1} ((\mathbf{x}_i^k - \mathbf{x}_i^\mathrm{f})^T \mathbf{Q}_i^x (\mathbf{x}_i^k - \mathbf{x}_i^\mathrm{f}) + \mathbf{u}_i^{k\,T} \mathbf{R}_i^\mathrm{u} \mathbf{u}_i^k + (\mathbf{u}_i^{k+1} - \mathbf{u}_i^k)^T \mathbf{R}_i^\mathrm{d} (\mathbf{u}_i^{k+1} - \mathbf{u}_i^k))$$



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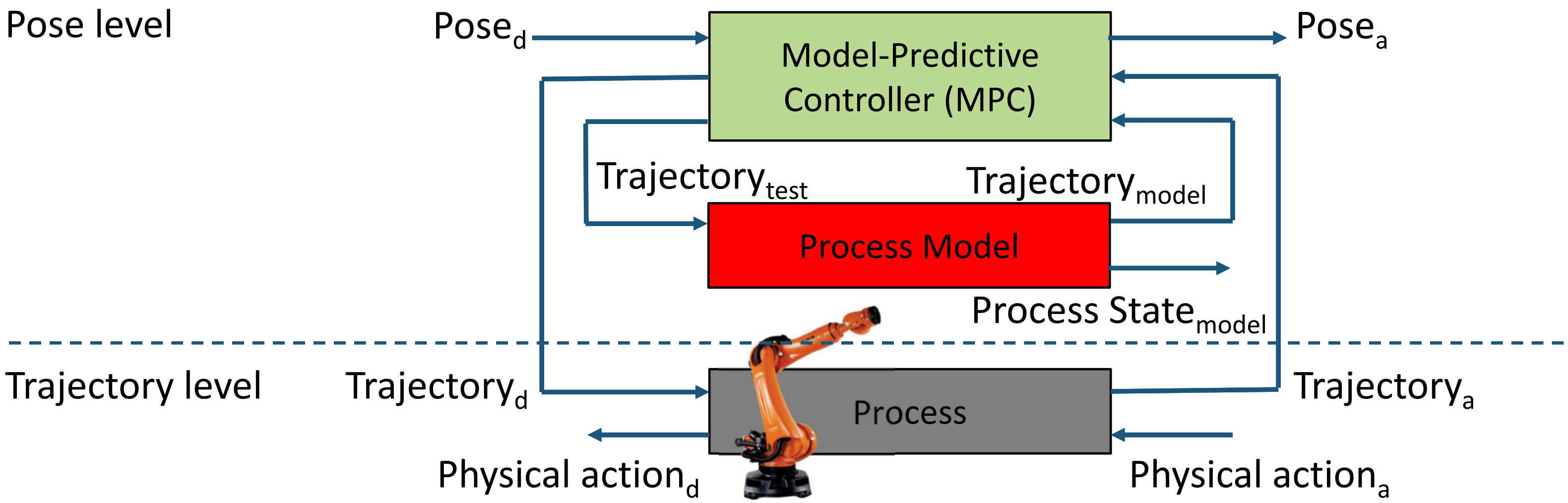
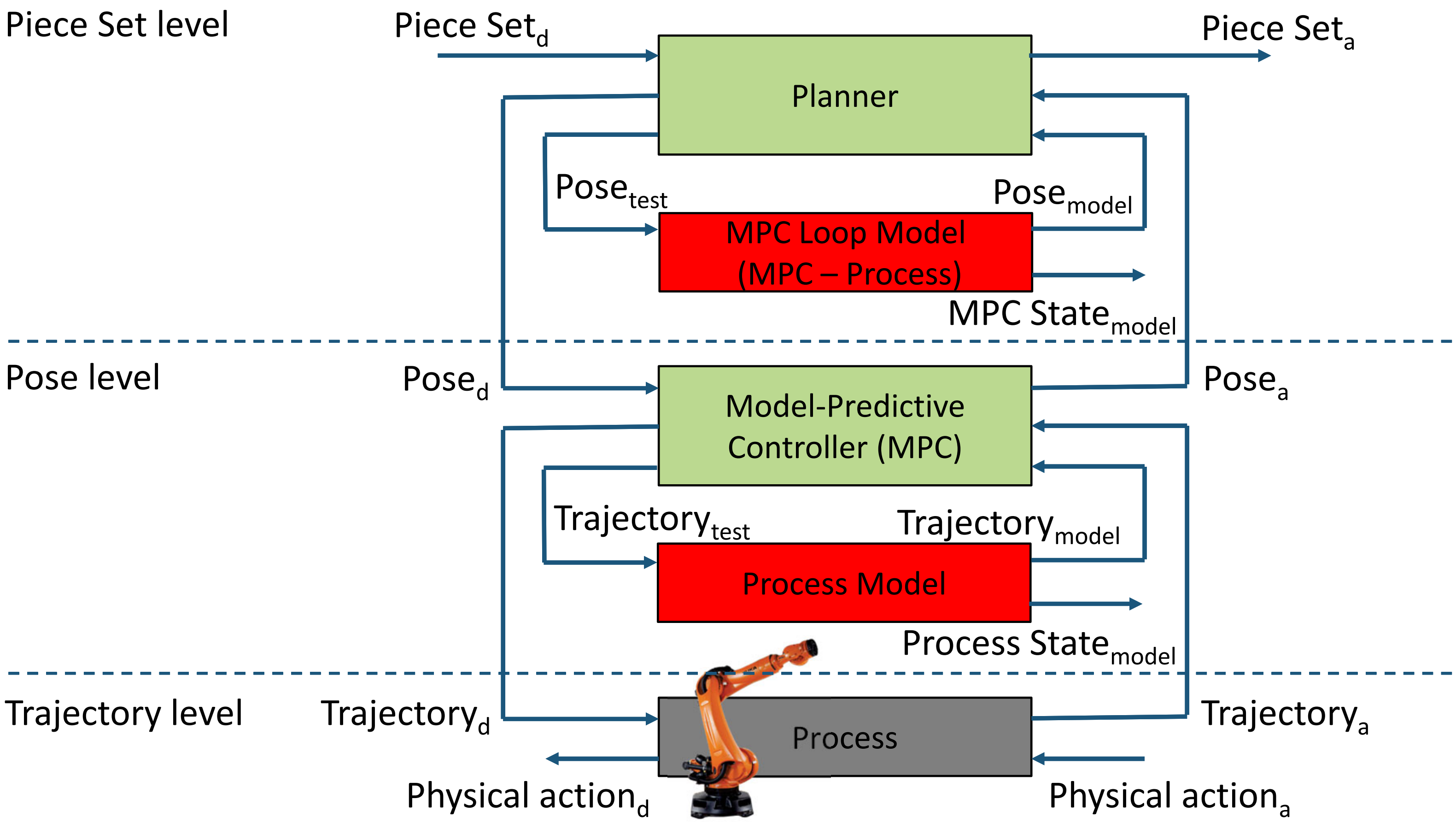
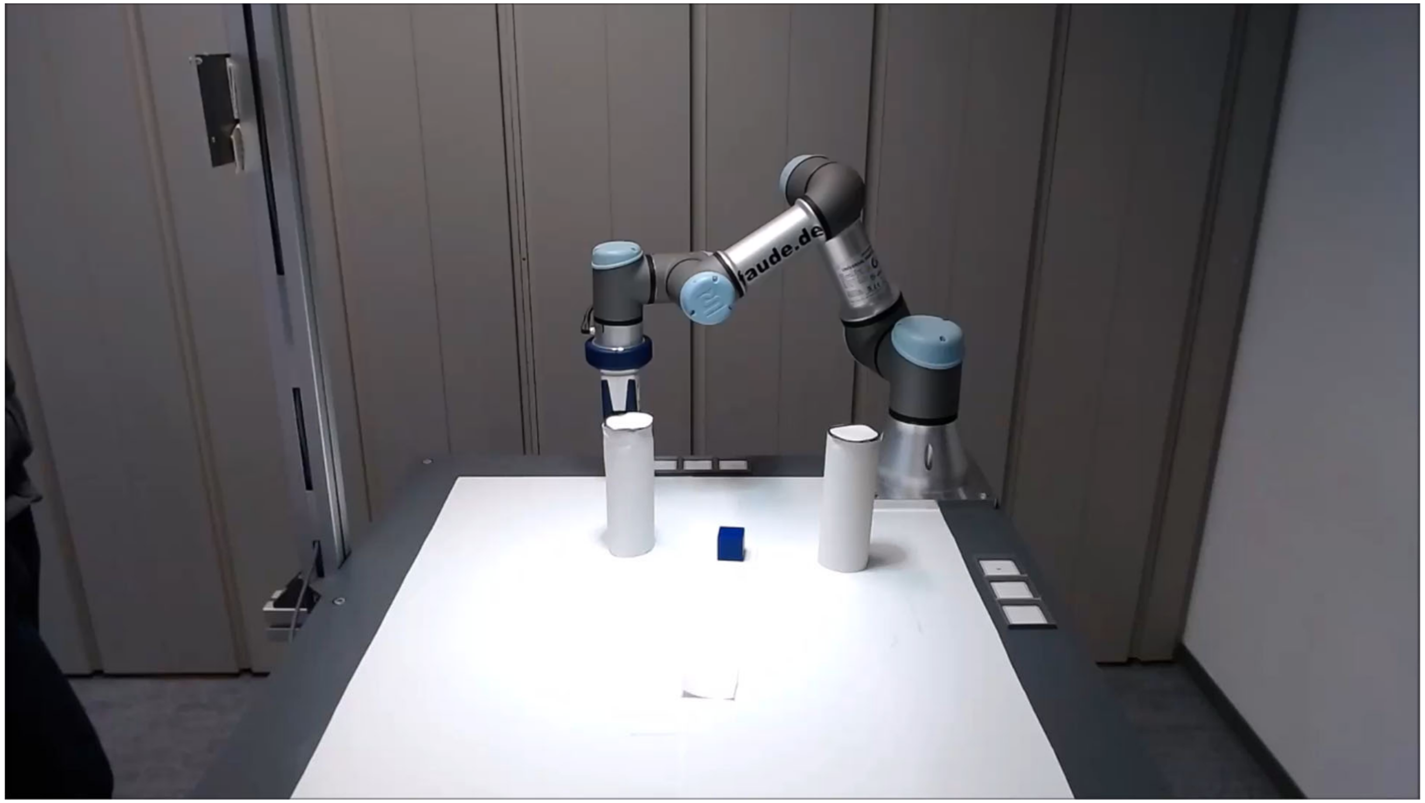


Planning und Model-Predictive Control

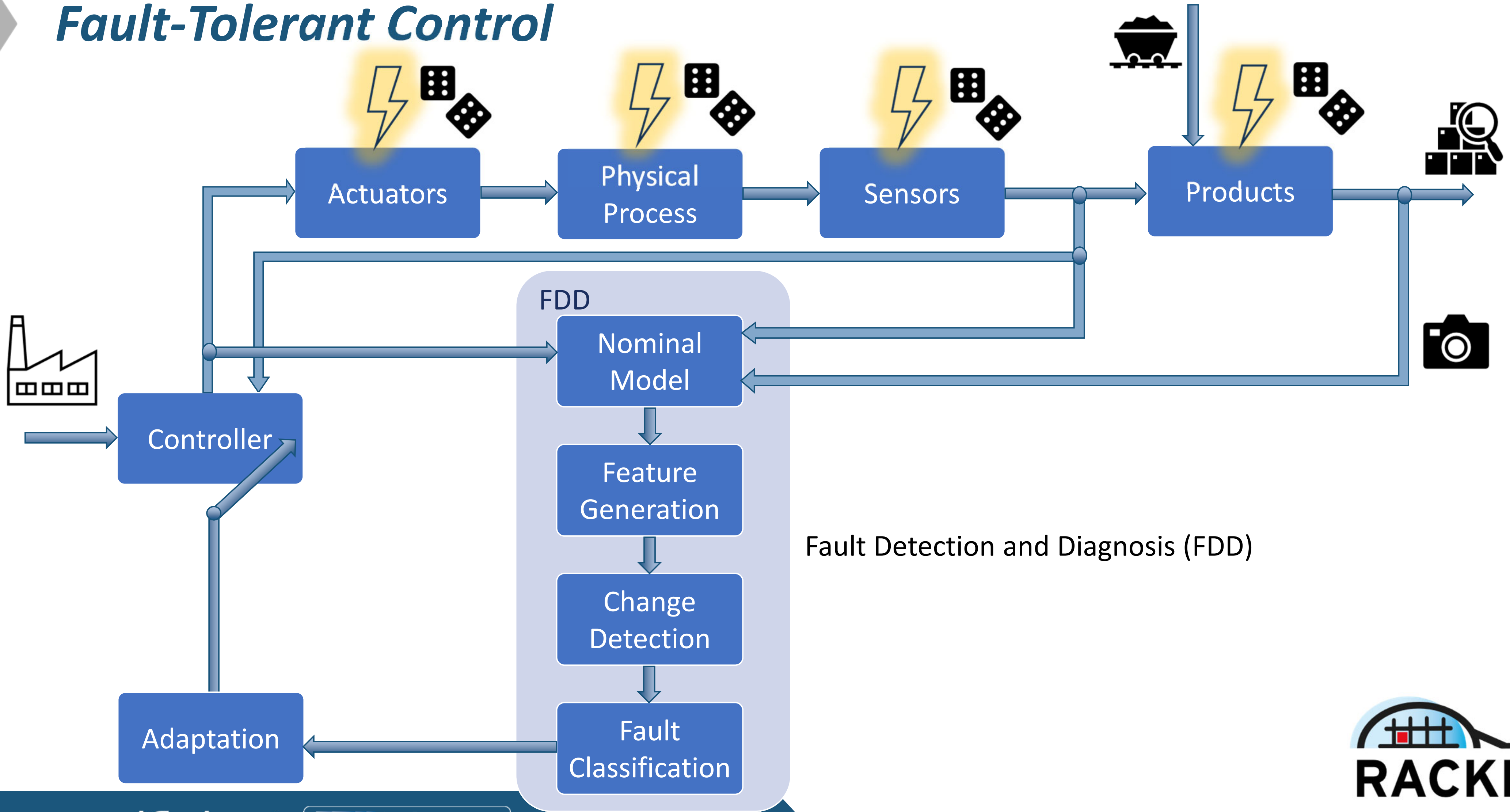


Robot Pick-and-Place with MPC and Collision Avoidance



Nigora Gafur et al., 2022

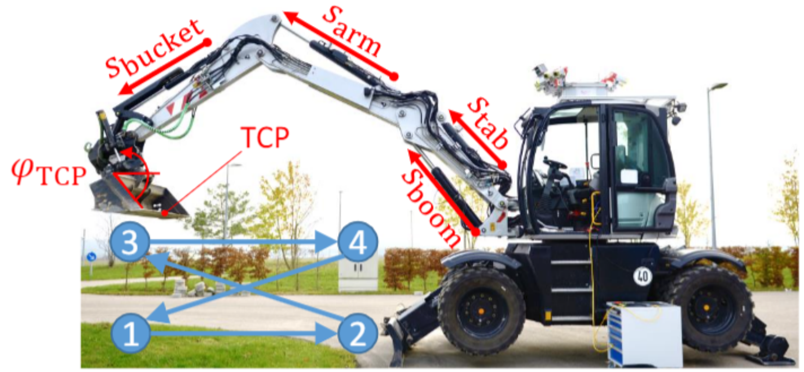
Fault-Tolerant Control

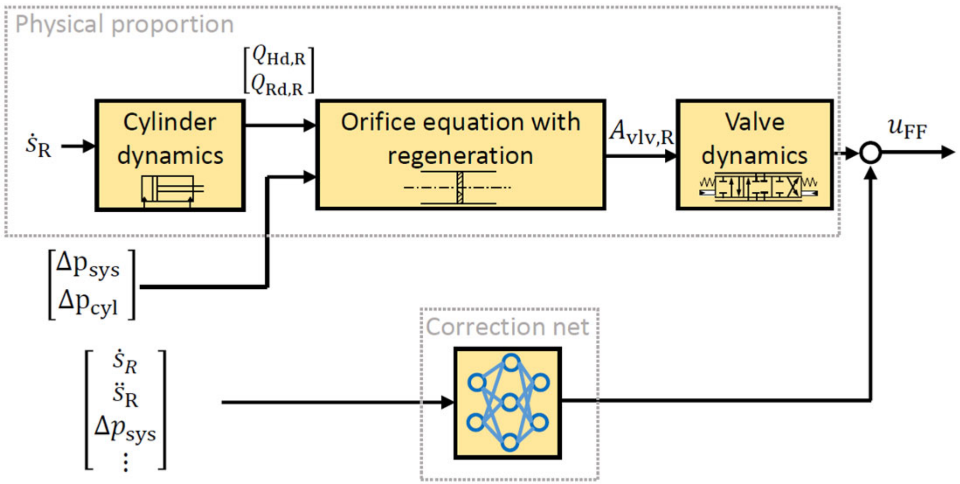


Fault Detection and Diagnosis (FDD)

Hybrid Data-Driven Modelling for Inverse Control of Hydraulic Excavators

- **Development of Hybrid models based on expert knowledge and data**
- Low effort system modelling
- Simplified general expert model available
- Only small set of experimental data available





4-Point-Cycle, without payload

	Boom Cylinder RMSE	Boom Cylinder R2	Arm Cylinder RMSE	Arm Cylinder R2
White Box	54.97	0.951	91.85	0.955
Hybrid 1	21.38	0.993	31.39	0.994
Hybrid 2	22.06	0.992	31.72	0.994
Black Box	21.27	0.993	31.21	0.994

4-Point-Cycle, with additional 1000 kg

	Boom Cylinder RMSE	Boom Cylinder R2	Arm Cylinder RMSE	Arm Cylinder R2
White Box	102.58	0.951	127.38	0.975
Hybrid 1	31.11	0.994	37.35	0.995
Hybrid 2	33.26	0.994	36.72	0.995
Black Box	51.06	0.988	37.14	0.995

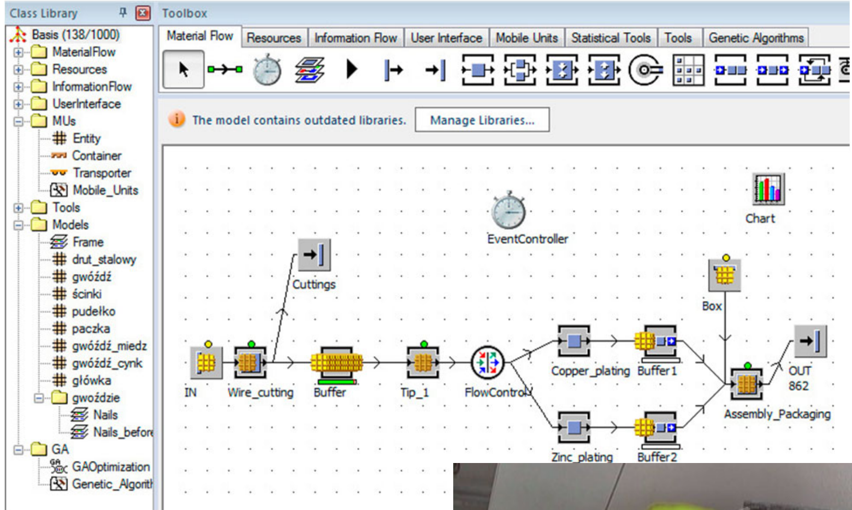
International Conference on Intelligent Robots and Systems (IROS, Weigand et al., 2021)

Conclusion

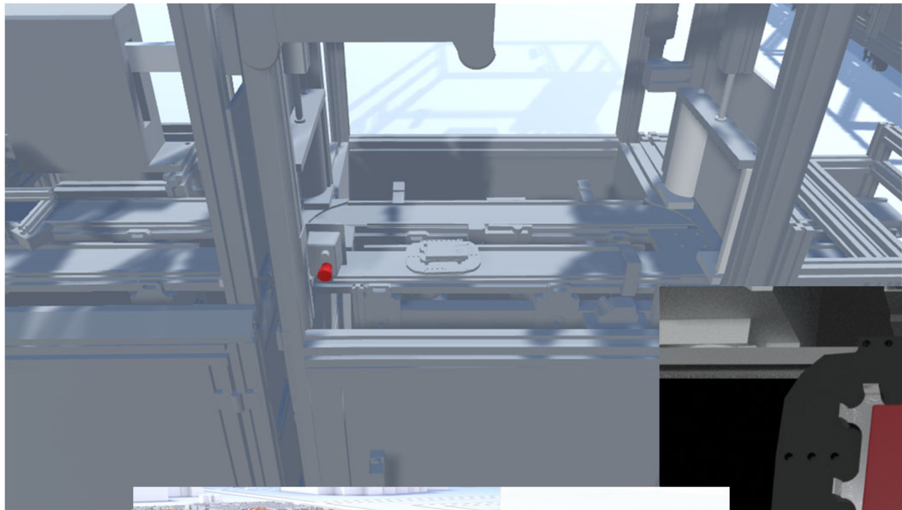
- Design of dependable production systems can be facilitated by design principles and a specific methodology
  - Formal specification of dependability properties and dependability measure
  - Explicit Description of *desired* and *not desired* system behavior
  - Information Structure is important factor for system design
  - Appropriate system decomposition for managing complexity
  - Identification of critical system variables and dependencies is challenging

- Role of Artificial Intelligence
  - Information extraction, knowledge representation, and decision making
  - Improving model accuracy and reducing effort by combining knowledge and data
  - Prediction of system behavior for optimal planning and control
  - Modelling of human behavior for advanced assistance

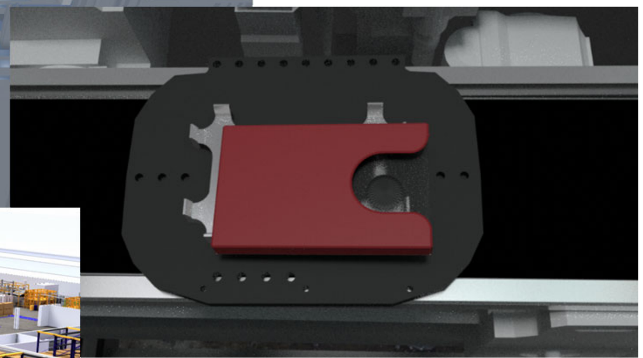
Future AI-Driven Dependability Research



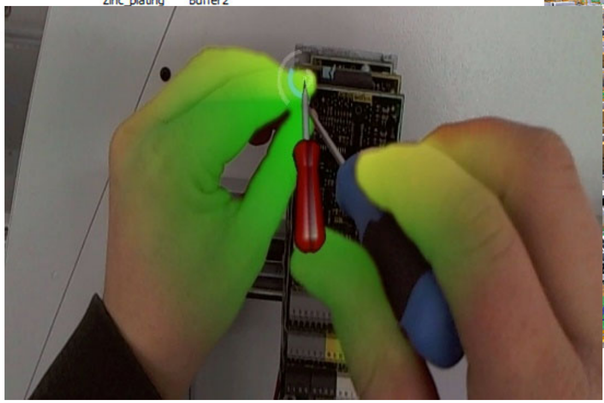
Production processes



Machine Behavior



Product Quality



Worker assistance

Tracking/Visualization

Thank You for Attention!

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