Intelligent Dependable Autonomous Systems

DFKI Research Fellow Talk
Achim Wagner
2022-03-17
Overview

• Motivation
• Trustworthy AI and Dependability
• Dependability of Dynamical Systems
• Production Scenarios
  o Production Level 4
  o Multi-Agent AI Systems and Behavior Decomposition
  o Collaborative Robotics
  o Fault-Tolerant Control
  o Hybrid Modelling
• Conclusion
• Future Research
Motivation: Development of Safety-Critical Applications

Automotive

Production

complex
distributed
dynamical
collaborative
autonomous

Avionics

Medical Technology

Source: Prevent

Source: Boeing Dreamliner

Source: Klinikum Jena

Source: http://www.huffingtonpost.de
Trustworthy AI and Dependability

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 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.
**Dynamical System – Behavior Description**

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

![Graph showing dynamical system behavior with function $w_1(t)$, $w_2(t)$, and $w_3(t)$ on the y-axis and time $t$ on the x-axis.]

Functional representation

- State space
  
  \[
  \dot{x}(t) = f(x(t), u(t))
  \]

- Output
  
  \[
  y(t) = g(x(t), u(t))
  \]

- Initial condition
  
  \[
  x(t_0) = x_0
  \]
Dependability of Dynamical Systems - Formal

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

\[ A_{\text{performance}} = \exp \left( - \frac{\varepsilon_p}{y_p} \right) \]

\[ A_{\text{safety}} = 1 - \exp \left( - \frac{\delta_s}{y_s} \right) \]

**Dependability Optimization: Robot Control**

$$y_p = 0.2, y_s = 0.08, y_{max} = 0.8, y_{min} = -0.8, \ a_p = 0.4, a_{sp} = a_s = 0.3$$

**Damped mechanical oscillator**

$X(t) = \frac{k}{m} \cdot s^3 + \frac{b}{m} \cdot s^2 + \frac{m}{m} \cdot s$
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**

- **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

- RFID
- LIDAR
- Camera
- LOV
- UWB
- 5G

Sensor Data

Information

Decision Making

Actions

Knowledge

Smart Maintenance

Smart Assembly

Robot Assistance
Behavior Decomposition for Autonomous Mobile Robot

RNBC (Recursive Nested Behavior-based Control) Structure
Badreddin1989; Bartolein2007; Wagner2010; Wagner2016
Collaborative Robots

Nigora Gafur et al., 2021
Planning und Model-Predictive Control

\[ J_i(x_i^k, u_i^k) := (x_i^{N_p} - x_i^f)^T Q_i^f (x_i^{N_p} - x_i^f) + \sum_{k=0}^{N_p-1} ((x_i^k - x_i^f)^T Q_i^x (x_i^k - x_i^f) + u_i^k R_i^u u_i^k + (u_i^{k+1} - u_i^k)^T R_i^d (u_i^{k+1} - u_i^k)) \]
Planning und Model-Predictive Control

\[ J_i(x_i^k, u_i^k) := (x_{i+1}^{N_p} - x_i^f)^T Q_i^f (x_{i+1}^{N_p} - x_i^f) + \sum_{k=0}^{N_p-1} ((x_i^k - x_{i+1}^f)^T Q_i^x (x_i^k - x_{i+1}^f) + \\
( u_i^k R_i^u u_i^k + (u_i^{k+1} - u_i^k)^T R_i^u (u_i^{k+1} - u_i^k)) \]

Pose level

Trajectory level

Pose_d → Pose_model → Pose_a

Trajectory_d → Trajectory_model → Trajectory_a

Physical action_d → Physical action_model → Physical action_a

Model-Predictive Controller (MPC)

Process Model

Process State_model

Process

Trajectory_test
Planning und Model-Predictive Control

Piece Set level

Piece Set\(_{\text{d}}\) ➔ Planner ➔ Piece Set\(_{\text{a}}\)

Pose level

Pose\(_{\text{d}}\) ➔ MPC Loop Model (MPC – Process) ➔ Pose\(_{\text{model}}\) ➔ Pose\(_{\text{a}}\)

Trajectory level

Trajectory\(_{\text{d}}\) ➔ Model-Predictive Controller (MPC) ➔ Trajectory\(_{\text{model}}\) ➔ Trajectory\(_{\text{a}}\)

Process level

Physical action\(_{\text{d}}\) ➔ Process Model ➔ Process State\(_{\text{model}}\) ➔ Physical action\(_{\text{a}}\)
Robot Pick-and-Place with MPC and Collision Avoidance

Nigora Gafur et al., 2022
Fault-Tolerant Control

- Actuators
- Physical Process
- Sensors
- Products

Controller

FDD

- Nominal Model
  - Feature Generation
  - Change Detection
  - Fault Classification

Adaptation

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

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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

Worker assistance

Product Quality

Tracking/Visualization
Thank You for Attention!
References