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Centralized Robotic Fleet Coordination and Control

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Agenda

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- Main objective and general assumptions
- Conventional approaches to robotic fleet coordination
- Why to centrally guide robotic fleets
- System architecture and design
- Implementation detail
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- Conclusion
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- Outlook - 5G testbed in DFKI Kaiserslautern

Background

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- Fleets of mobile platforms and mobile manipulators for various use cases
  - Warehousing and (intra-) logistics
  - Healthcare
  - Manufacturing among many others
- Driver for value creation with certain success factors [1]:
  - Productivity
  - Availability
  - Flexibility
  - Predictability

[1] G. Fragapane, D. Ivanov, M. Peronet, et al., “**Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics**”, Annals of operations research, pp. 1–19, 2020.

Main objective and general assumptions

- Considering a use case that is closely related to an **integrated**, **modular** and highly **automated** production/warehouse facility
- **Sporadically** incoming transportation tasks are served by centrally guided, mobile robots
- Developing a software system that enables **efficient**, **deterministic** and **flexible** management of transportation tasks
- Leveraging capabilities of current and next generation communication networks in terms of latency and reliability, e.g. running safety-critical applications on the edge server
- Condensing majority of sensors and computing units within infrastructure, only downlink communication for vehicle control → **minimize energy** consumption of the devices
- Minimal on-board sensor setup only; instead **infrastructure-based positioning** is assumed to be given (as a Black Box)
- Initially considering kinematics of differential drive robots, but not limited to such
- **Infrastructure database**, which enables the user to construct a **grid-based road network** (statically, for now)

Conventional approaches to robotic fleet coordination

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- Two common approaches for application of mobile robots in industrial environments
  - Guided robots, following static paths, e.g. rail-based or based on infrastructure embedded in the ground
    - ➢ Safe and predictable but inflexible
  - Fully autonomous robots, mostly relying on information obtained by on-board sensors and processed by on-board computing resources (e.g. Simultaneous Localization and Mapping (SLAM)) and using negotiation strategies to solve critical situations, e.g. road intersections
    - ➢ Flexible but hard to predict and relatively high energy consumption

Why to centrally guide robotic fleets

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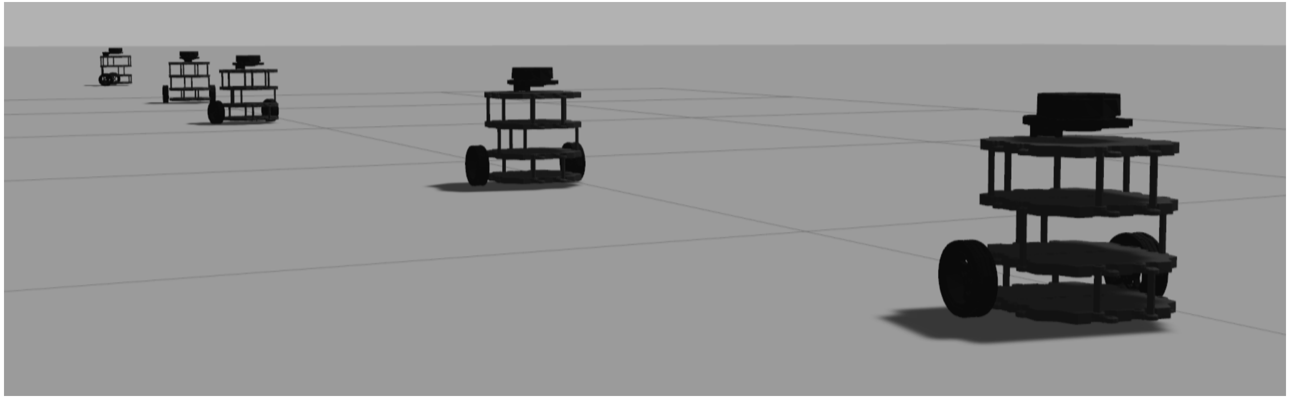
- Easily run **controllers** on machines that are **located spatially distinct** to the actual **device** or even use **migration strategies** to dynamically adapt to changing circumstances
- Central unit to aggregate overall system information → obtain optimal solutions for planning processes
- Enable cooperation, e.g. platooning, even without sidelink communication
- Potentially **Single Point of Failure**?



System architecture and design

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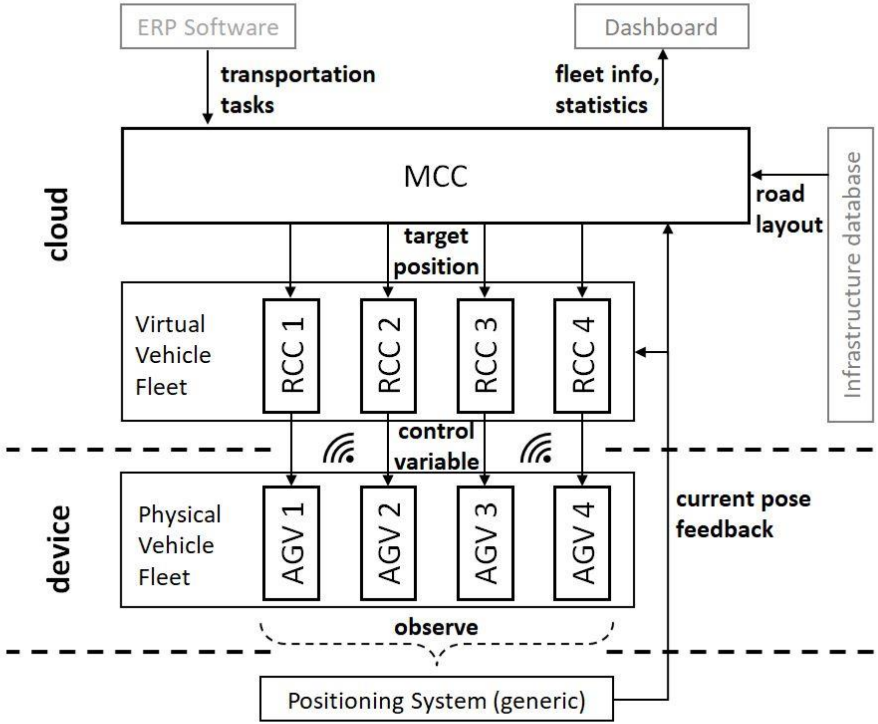
- Design aspects
  - Modular and scalable software solution implemented in C, C++ and Python
  - Set of mandatory modules that are required for basic tasks
  - Easily extendable with additional components for more sophisticated tasks
  - Decomposition of **planning** (fleet-level) and **control** (robot-level) tasks

- Key features
  - Integration of planning unit for **task scheduling** and **online task migration**, **resource allocation** and **trajectory planning** [2, 3]
  - **Collision detection** and **avoidance**, **deadlock detection** [2, 3]
  - Integration of ROS modules (e.g. navigation stack) and related tools (e.g. Gazebo) [3]

[2] M. Berndt, C. Fischer, and D. Krummacker, "**Real-Time Task Scheduling and Multi-Vehicle Navigation for Intralogistics**", in 2020 Workshop on Next Generation Networks and Applications (NGNA 2020), (Dec. 14–18, 2020), Kaiserslautern, Germany: Technische Universität Kaiserslautern, 2020.
[3] M. Berndt, C. Fischer, D. Krummacker and H. D. Schotten, "**Deterministic Planning for Flexible Intralogistics**", in The 26th IEEE International Conference on Automation and Computing 2021 (ICAC 21), (Sep. 2–4, 2021), Portsmouth, UK: IEEE, 2021.

Implementation detail

- Mission Control Center (MCC)
    - global mission planning
- Robot Control Center (RCC)
    - robot-specific motion control
- Infrastructure database
    - used-defined road layout, constraints, …
- Dashboard (GUI)
- Positioning System (generic)
    - simulated ground-truth data only
    - to be extended to multi-technology localization framework
- ERP Software interface
    - to receive incoming tasks in future versions



Gazebo simulation

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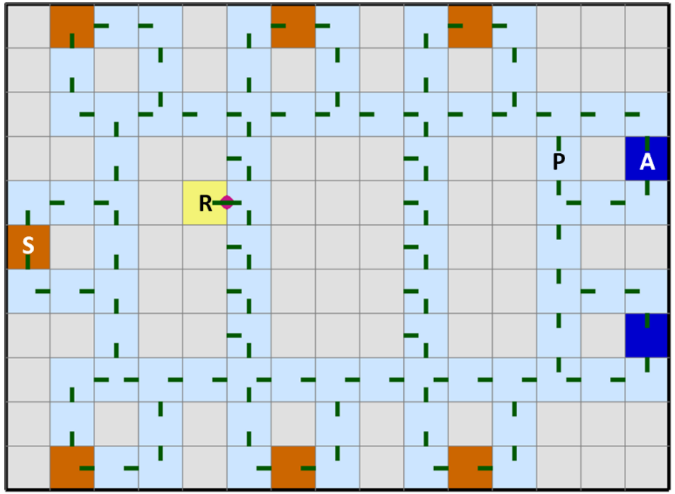
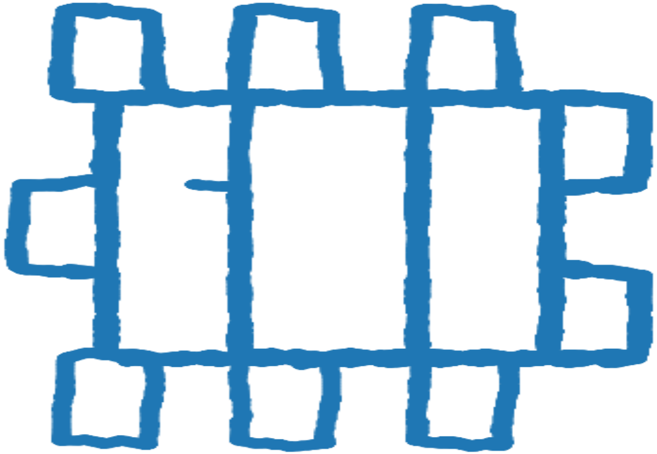
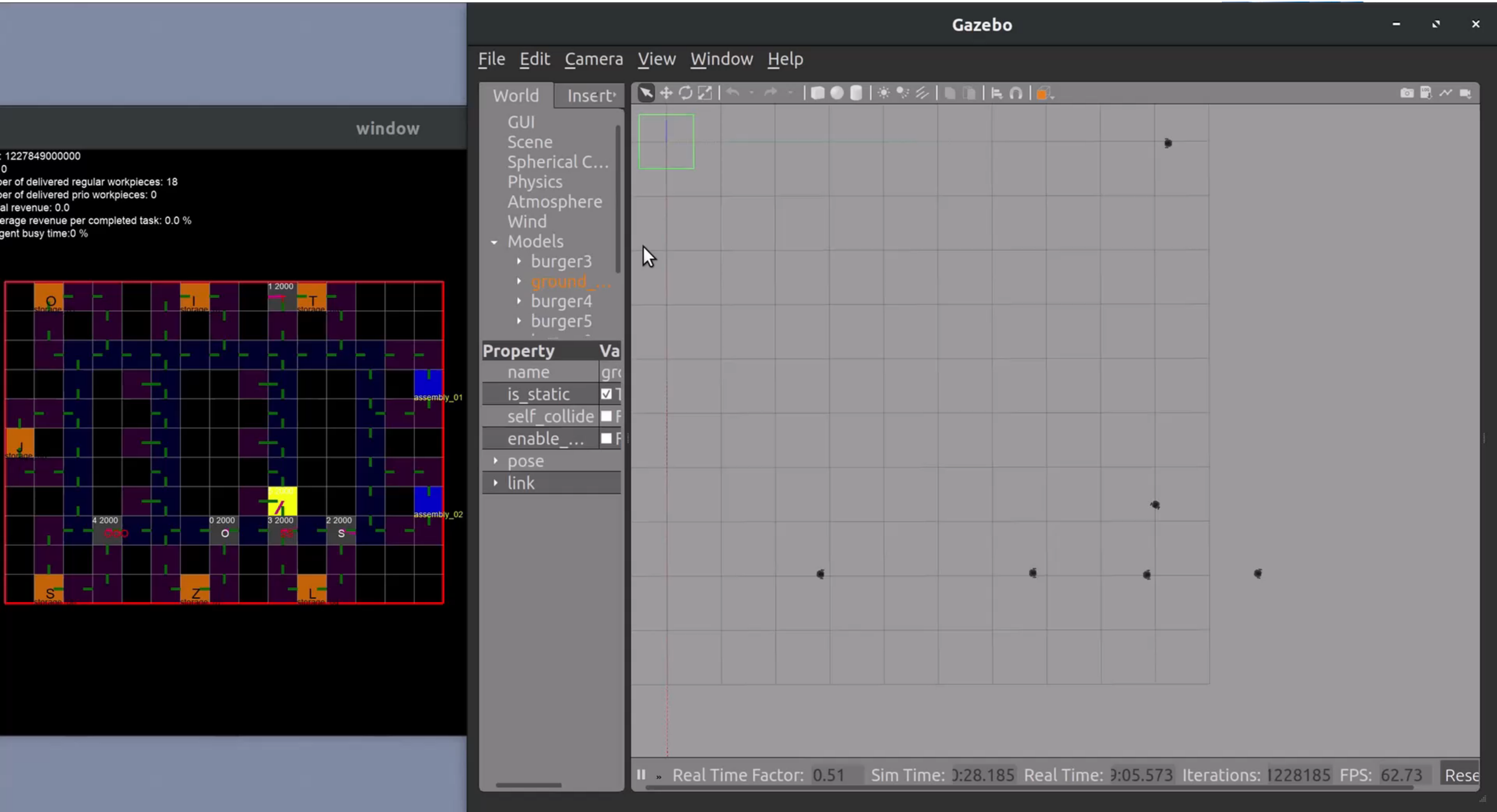
- Single robot: path following capability



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Conclusion

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- Considering use case w.r.t. current trends in Industry 4.0, (I)IoT, particularly intralogistics
- Proposing an architecture and corresponding, possible implementation for robotic fleet coordination and control system
- Design concept enabling user to deploy a fleet **flexibly** and **efficiently**
- Ensuring **determinism** of mission planning process by design, obtain optimal solutions for planning problems
- **Modular design** approach to facilitate integration and exchange of various software components
- Increasing availability of robots by reducing **on-board sensor** setup to a bare **minimum**
- Increasing flexibility by enabling the user to integrate new (infrastructure-based) positioning technologies and sensor moduls during runtime without interruption of service
- Demonstrating system feasibility by conducting extensive tests in 3D simulation environment
- Showing relevant features, e.g. path and collision avoidance

Future work

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- Simulation still lacks real-world application to prove feasibility under realistic circumstances
- Tests have to be conducted using private 5G network to investigate the suitability of 5G NR for these purposes, especially with regard to reliability and latency
- Centralization by itself not necesarilly optimal in all situations
  - Very high requirements on communication infrastructure
  - Hybrid/hierarchical approaches should also be considered
  - Enable on-line process migration, e.g. controllers running on the edge server or on the device at different points in time
  - Adaptively react to changing circumstances (communication control co-design)
- Transferring from a general ROS-based system design towards a more flexible approach
  - Enable combinations of different frameworks, e.g. ROS + ROS2

Future work

- Currently ground truth data assumed to be given → accurate and precise pose estimation is crucial - Integration of multi-technology localization platform using different approaches, e.g. camera- and radio-based systems
- Potentially using capabilities of mobile networks for positioning purposes
  - mmWave positioning with large BW, large antenny arrays, accurate timely synchronization, MPC-assisted positioning, JCaS, …
- Centrally aggregate and process this information to obtain a suitably well approximation, which might also enable application of sophisticated statistical methods
- Integrate additional sensor moduls, e.g. radar or lidar (on-board or infrastructure-based), to generate a highly dimensional digital twin of the entire factory floor
  - Extend Virtual Vehicle Fleet to an actual fleet of digital twins
  - Match positioning data of sensor nodes with time-dependent measurements
  - → Location aware sensor network

Outlook - 5G testbed in DFKI Kaiserslautern

- Wireless closed loop control
  - Robot motion control
- Wireless safety
  - Laser barriers that transmit emergency signal if triggered
- Camera-based positioning
  - Apriltags
  - Distributed stereo vision
- Radio-based positioning
  - UWB (also for communication)
  - 5G positioning
- Aggregation and fusion platform for heterogeneous sensor ndata
- Digital twin

Outlook - 5G testbed in DFKI Kaiserslautern

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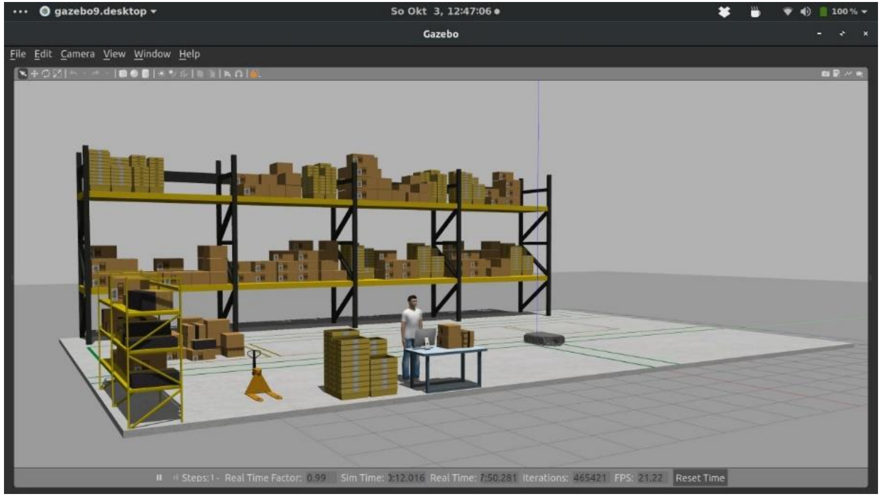
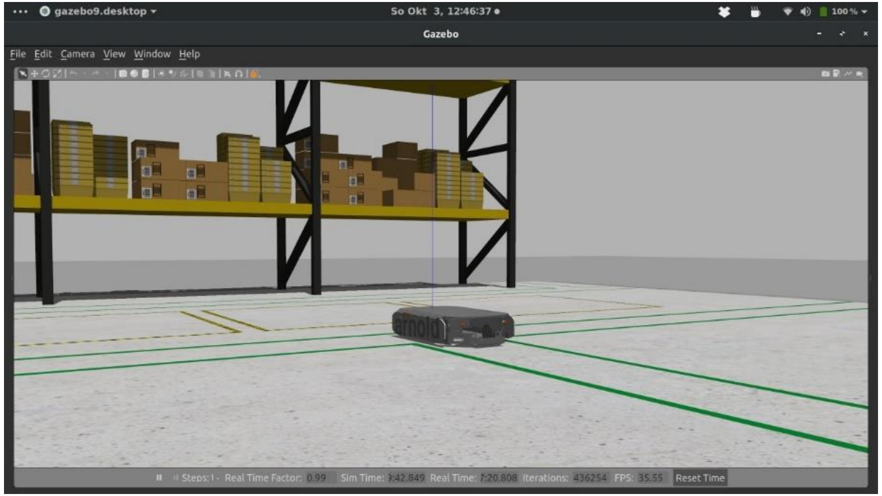
- Digital Twin





Contact information

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