AGV-Tanz mit LKW?
Wie man mit intelligenter Planung Deadlocks vermeidet

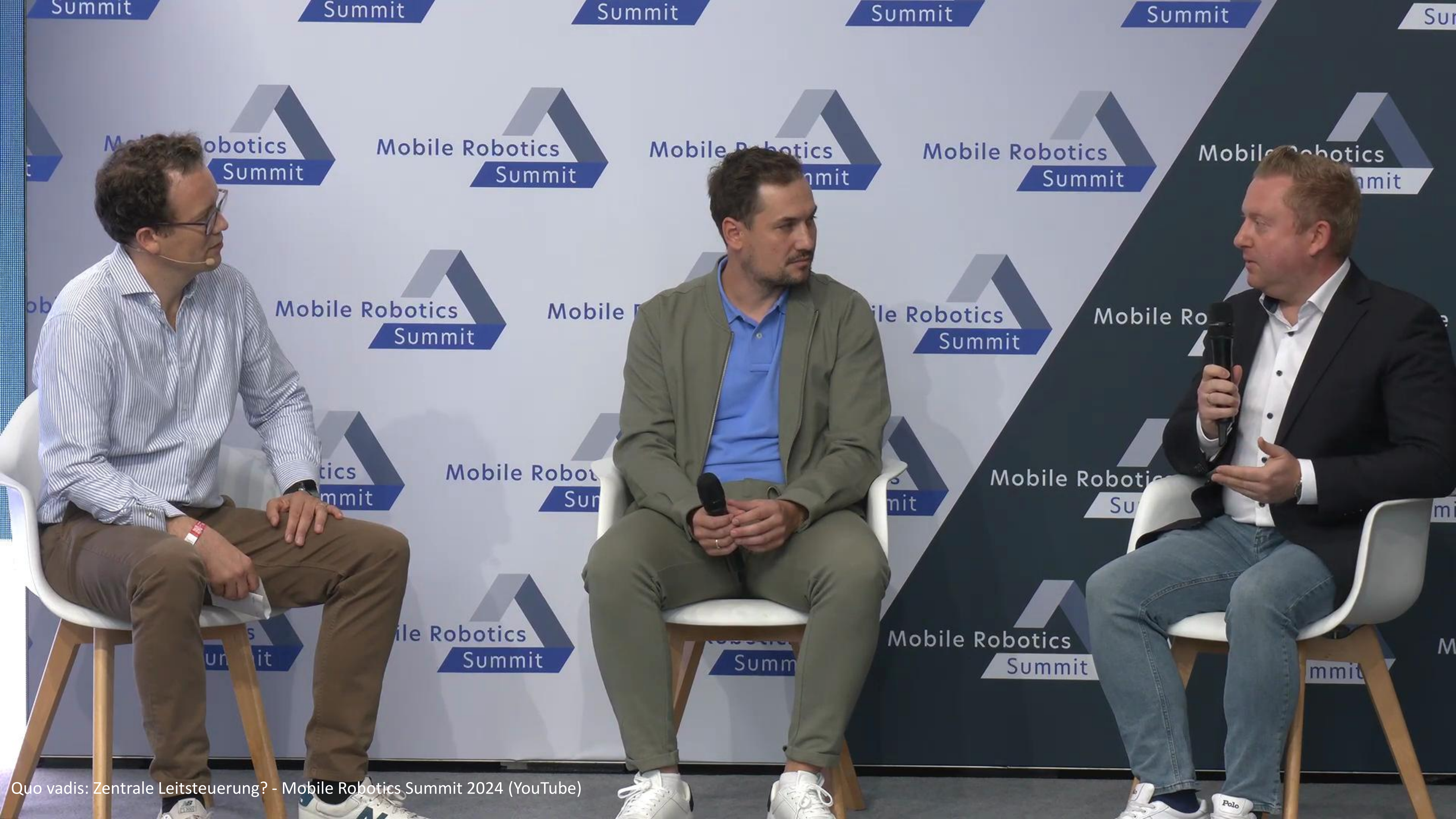
Dr.-Ing. Felix Keppler
Gruppenleiter Fahrzeugsteuerung und -sensorik
Fraunhofer-Institut für Verkehrs- und Infrastruktursysteme IVI
Dresden

Herr Gütermann leitet einen Logistikbetriebshof.

Er bestellt drei automatisierte LKW.

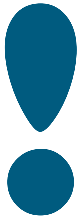

Hapag-Lloyd
www.ivi.fraunhofer.de

Randol White – Overhead view of Waymo honking problem in San Francisco parking lot (YouTube)



Quo vadis: Zentrale Leitsteuerung? - Mobile Robotics Summit 2024 (YouTube)

ek robotics GmbH – Healthcare AGV (Wikimedia)

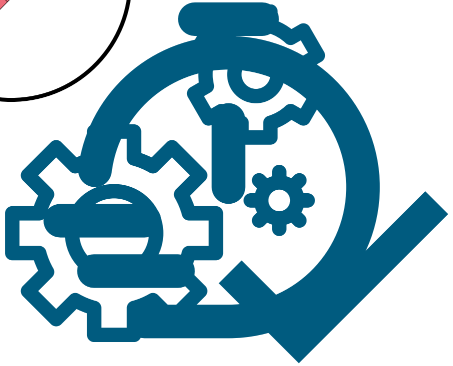


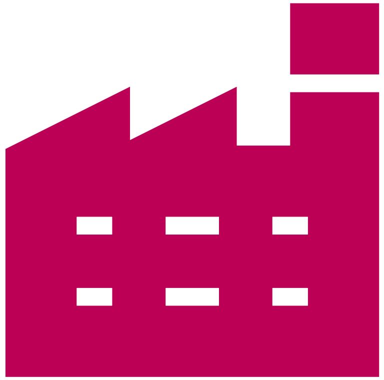
Prioritized Planning Algorithms for Trajectory Coordination of Multiple Mobile Robots

Michal Čáp, Peter Novák, Alexander Kleiner, Martin Selecký

Provably Safe and Deadlock-Free Execution of Multi-Robot Plans under Delaying Disturbances

Michal Čáp and Jean Gregoire and Emilio Frazzoli





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Prioritized Planning Algorithms for Trajectory Coordination of Multiple Mobile Robots

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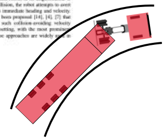
Provably Safe and Deadlock-Free Execution of Multi-Robot Plans under Delaying Disturbances



Multi-robot Trajectory Coordination for Complex Vehicle Combinations

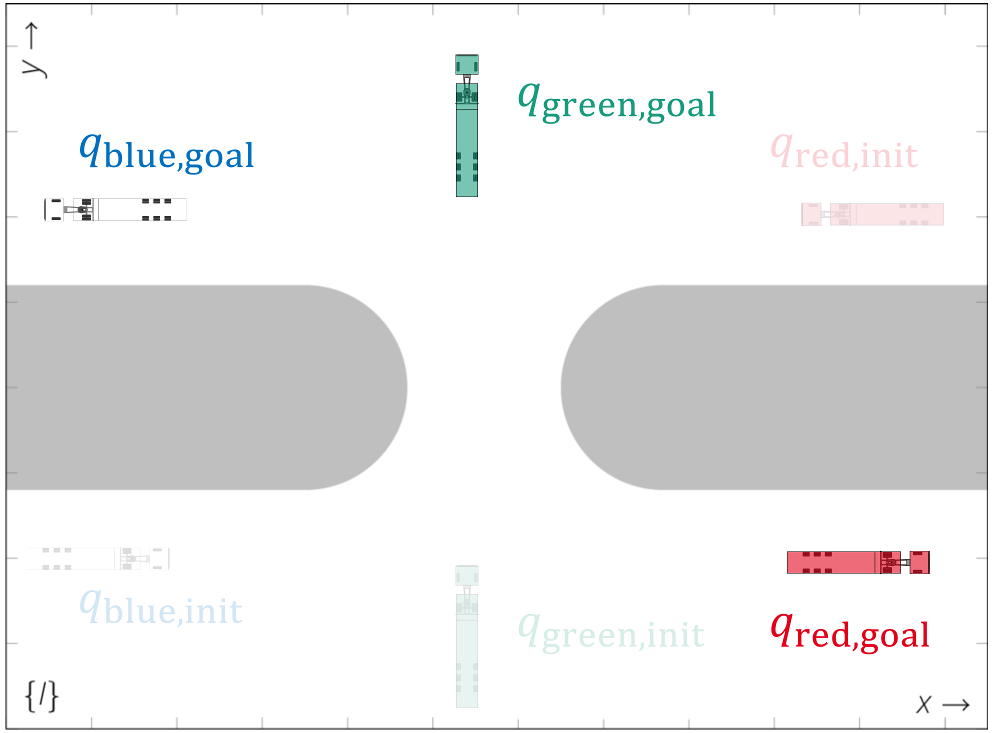
Research Objective

Given

- Initial robot configurations q_{init}
- Robot kinematics and geometry
- Static obstacle map
- Goal configurations q_{goal}

Desired Outcome

- Coordinated trajectories avoiding obstacles, mutual collisions and deadlocks
- Robustness against disturbances
- Practical deployability



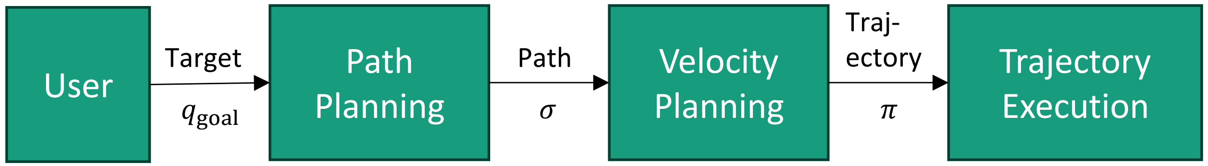
felix.keppler@ivi.fraunhofer.de

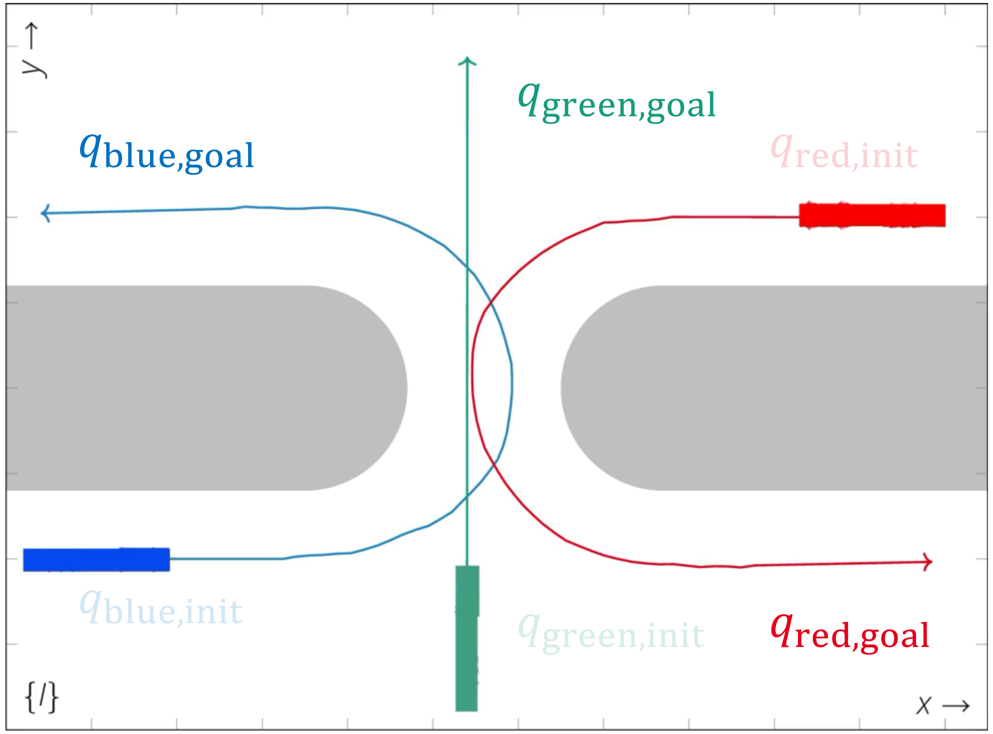
Related Work

Trajectory Coordination

Path-Velocity-Decomposition[Kant 1986]

- Planning in composite statespace is computationally intractable
- Decouple problem into path planning and velocity planning





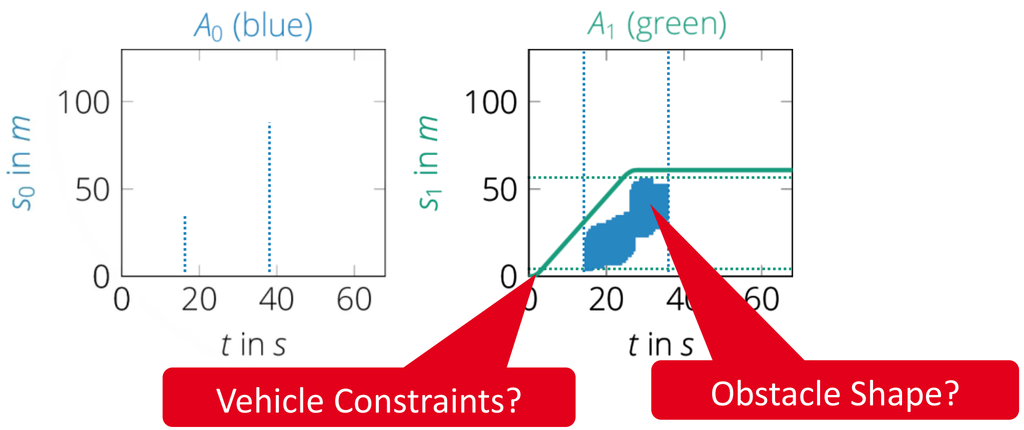
[Kant 1986] K. Kant and S. W. Zucker, "Toward Efficient Trajectory Planning: The Path-Velocity Decomposition," The International Journal of Robotics Research, vol. 5, no. 3, pp. 72–89, Sep. 1986

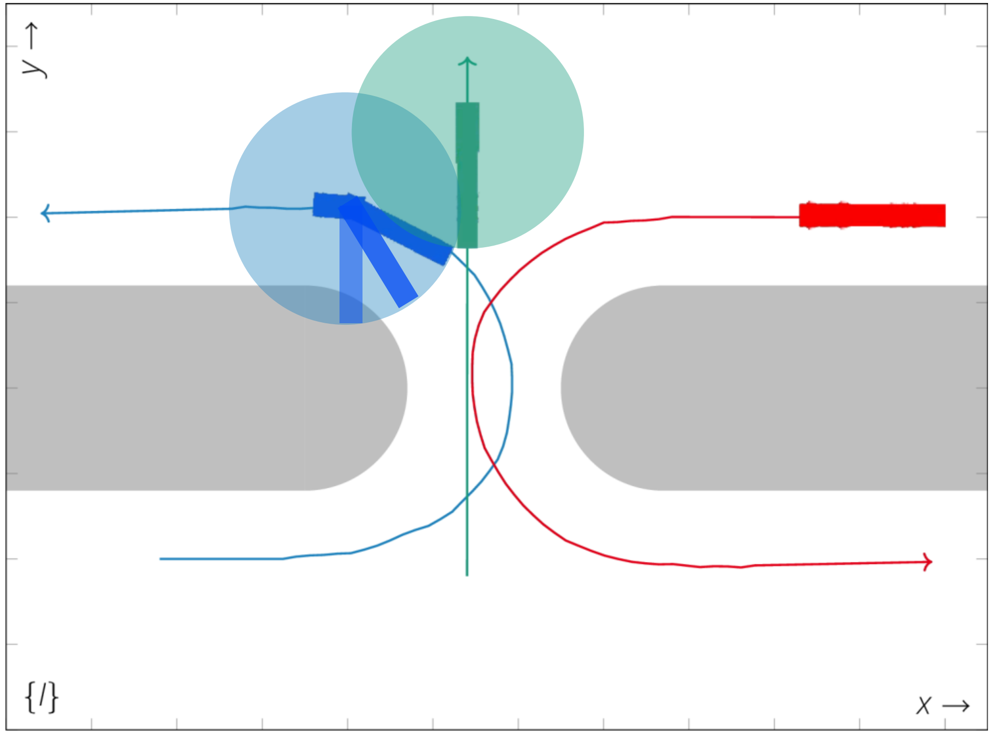
Related Work

Velocity Planning

Prioritized Planning [Erdmann 1987, Čáp 2015]

- Use heuristics to assign priorities, e.g.,
  priority A_0 (blue) > priority A_1 (green) > priority A_2 (red)
- Sequential velocity planning





[Erdmann 1987] M. Erdmann and T. Lozano-Pérez, "On multiple moving objects," Algorithmica, vol. 2, no. 1, p. 477, 1987

[Čáp 2015] M. Čáp, P. Novák, A. Kleiner, and M. Selecký, "Prioritized Planning Algorithms for Trajectory Coordination of Multiple Mobile Robots," IEEE Transactions on Automation Science and Engineering, vol. 12, no. 3, 2015

Related Work

Path Planning for Complex Vehicles at Fraunhofer IVI

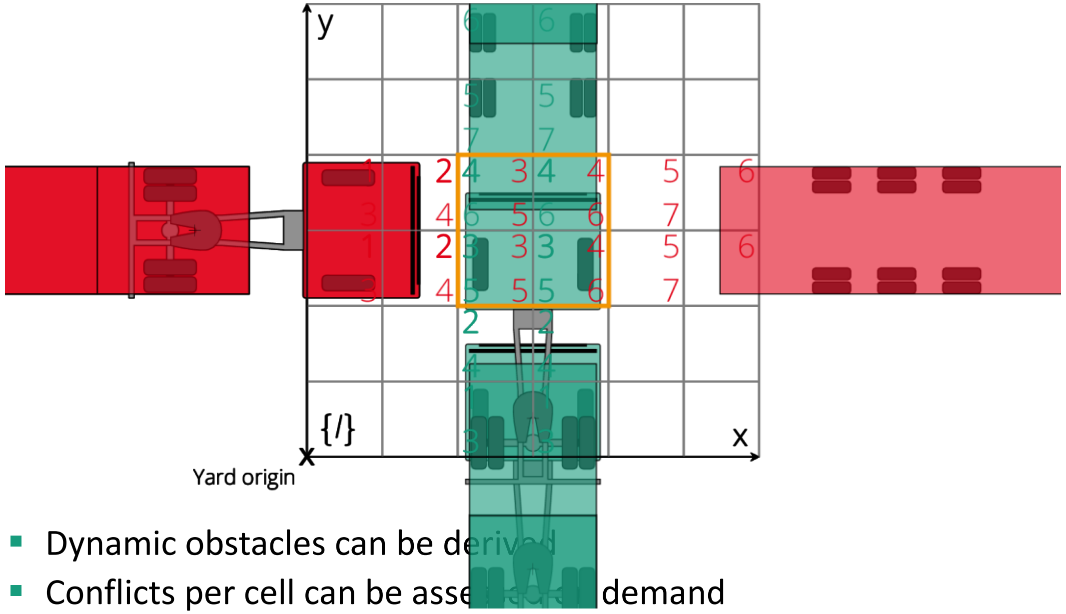
Fraunhofer IVI

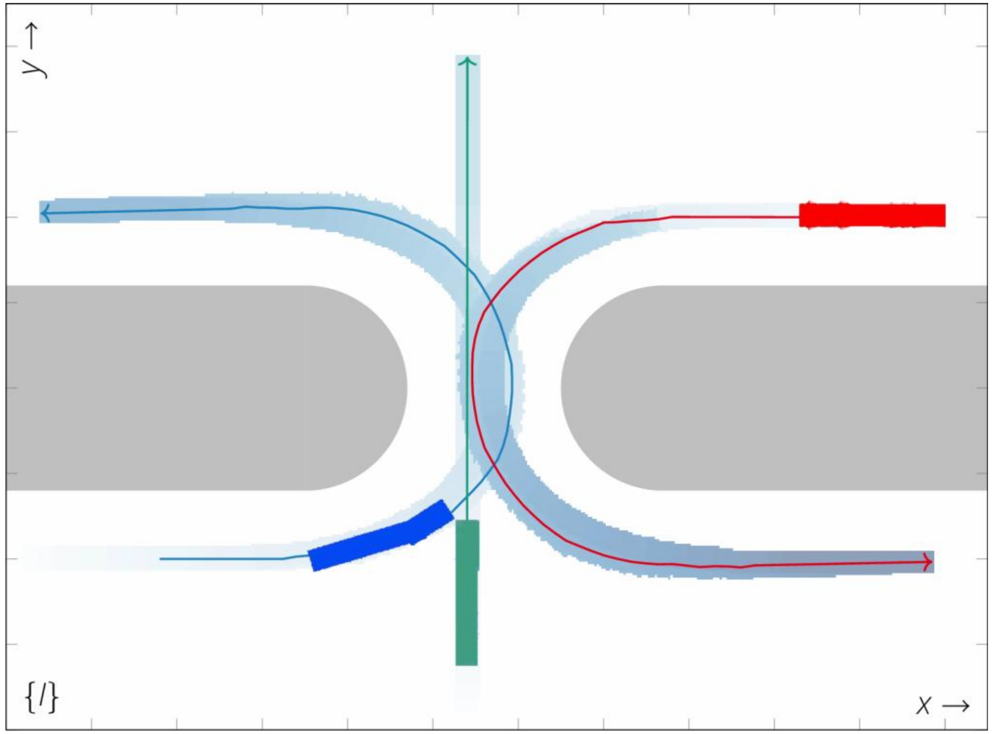
Approach

Deriving Dynamic Obstacles

Spatiotemporal Occupancy Tracking[Keppler 2020]

- Kinematic simulation to register occupancy intervals of the swept vehicle geometry in a grid map representing the workspace



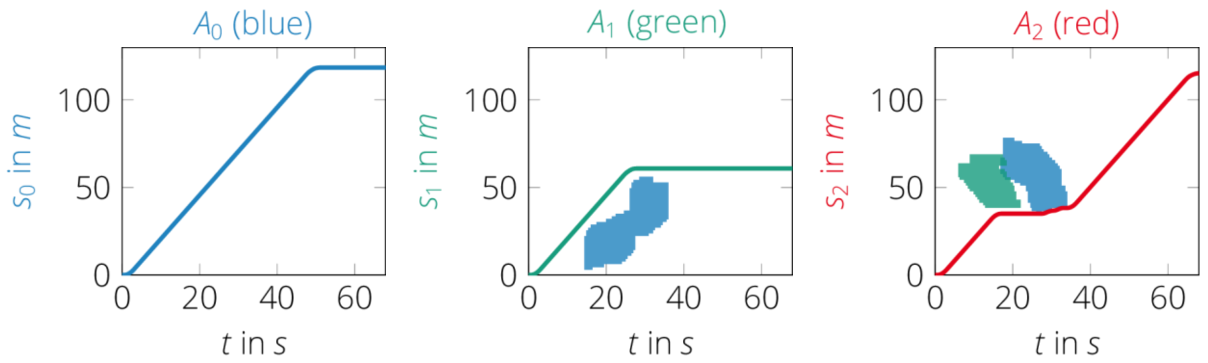


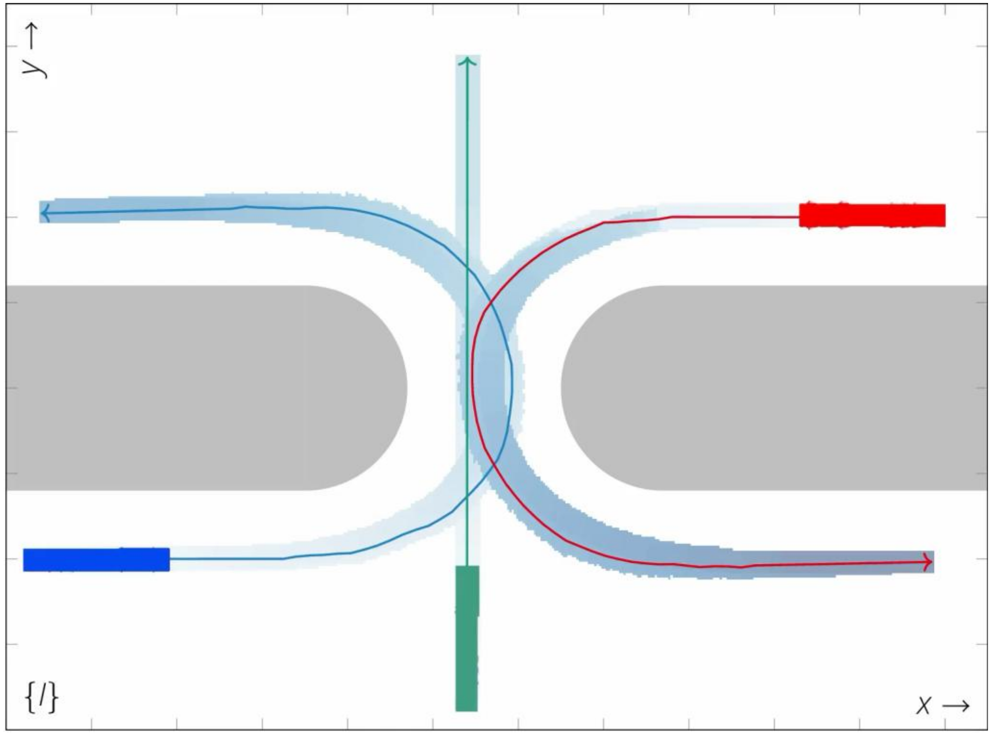
- Dynamic obstacles can be derived
- Conflicts per cell can be assessed on demand

[Keppler 2020] F. Keppler and S. Wagner, “Prioritized Multi-Robot Velocity Planning for Trajectory Coordination of Arbitrarily Complex Vehicle Structures,” in 2020 IEEE/SICE International Symposium on System Integration (SII), Honolulu, Hawaii, USA, Jan. 2020

Multi-robot Trajectory Coordination for Complex Vehicle Combinations

Results under Ideal Conditions





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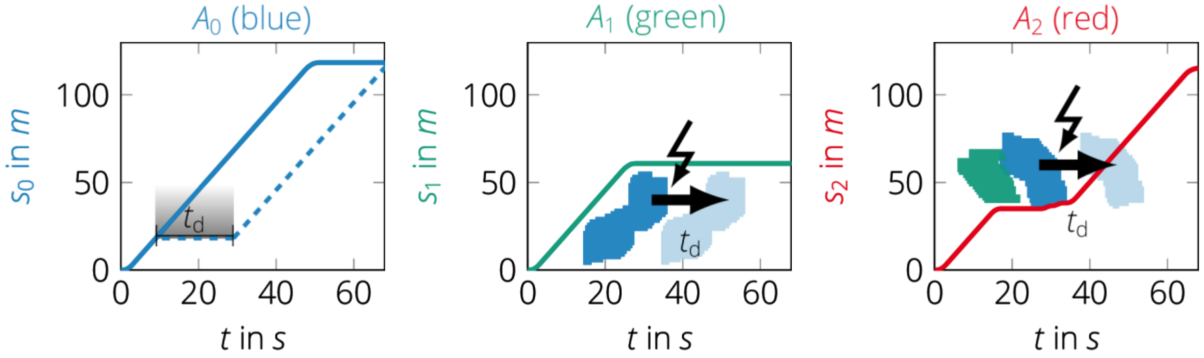
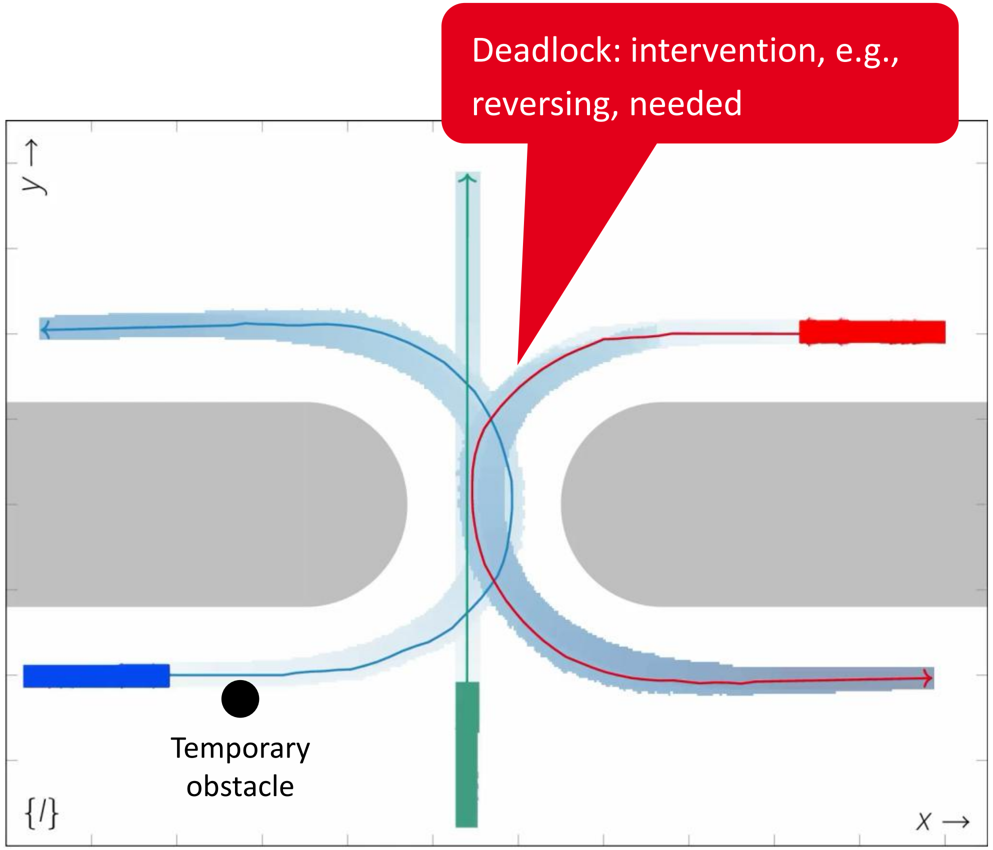
Multi-robot Trajectory Coordination for Complex Vehicle Combinations

Delaying Disturbances





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Multi-robot Trajectory Coordination for Complex Vehicle Combinations

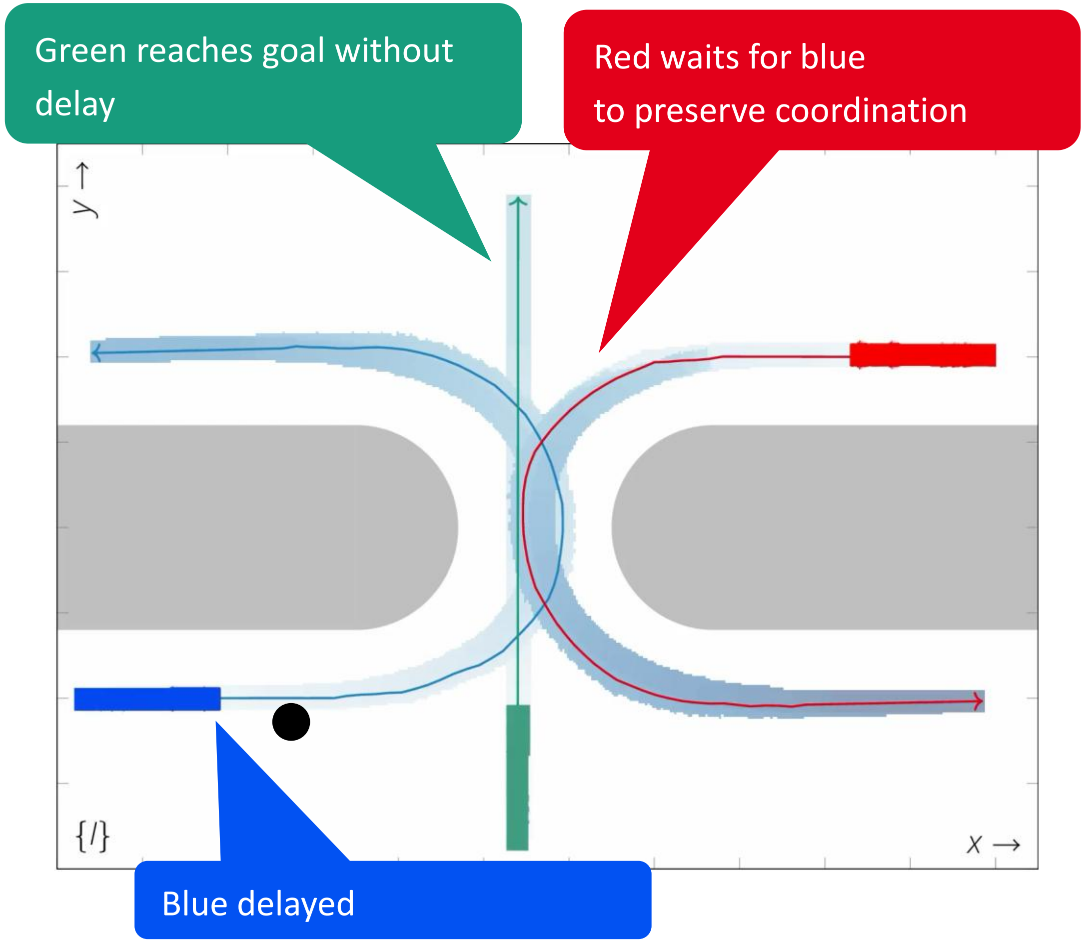
Delaying Disturbances

RMTRUCK control law[Schäfer 2023]

- Inspired by RMTRACK[Čáp 2016]
- Preserves traversing order defined by prioritized planning

- Extended for non-circular robots
- Braking and acceleration instead of velocity jumps

- Provably deadlock-free
- Number of affected agents can be reduced



[Schäfer 2023] J. Schäfer, F. Keppler, S. Wagner, and K. Janschek, “RMTRUCK: Deadlock-free Execution of Multi-robot Plans under Delaying Disturbances,” in 26th International IEEE Conference on Intelligent Transportation Systems (ITSC), Bilbao, Spain, Sep. 2023

[Čáp 2016] M. Čáp, J. Gregoire, and E. Frazzoli, “Provably safe and deadlock-free execution of multi-robot plans under delaying disturbances,” in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, South Korea, Oct. 2016

Wir bringen Forschung in die Anwendung – als Module für Produkte

Und vernetzen herstellerneutral mit dem helyOS®-Framework für Leitstandsysteme

TruckTrix Pfadplanung

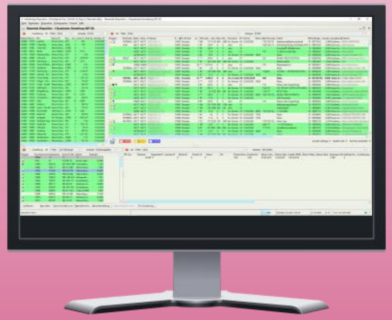
OrchesTruck Koordination

FarmTrix Pfadplanung

...

Web-App

Farm-/Yard-Management



Automation Suite XY

helyOS framework.org

Open Source on GitHub

Aufgabe	Microservices
Schwerlasttransport A nach B	●

VDA5050

Regelung

E/E System Integration

Lokale Planung

Megawatt Laden

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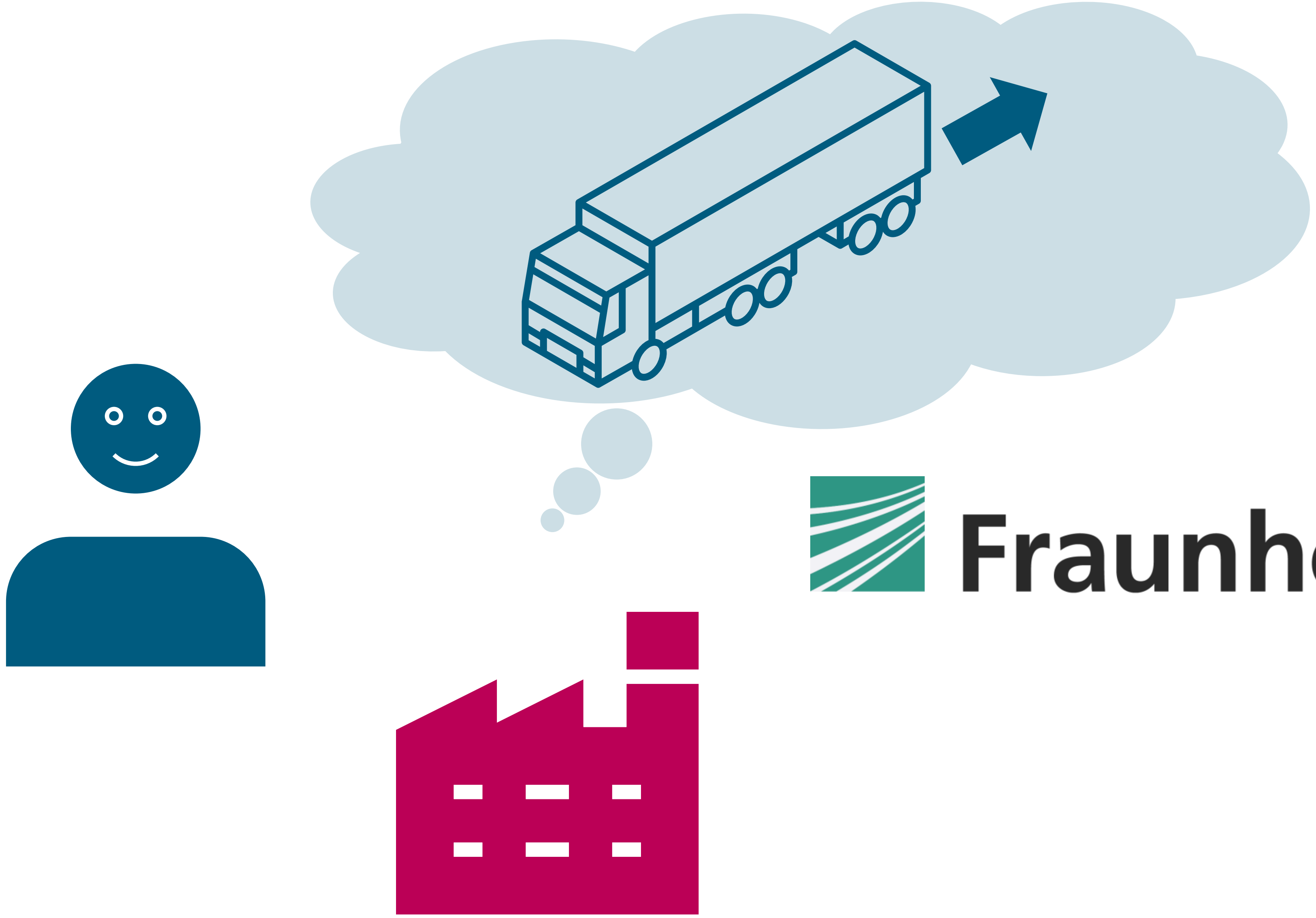
Hapag-Lloyd
www.ivi.fraunhofer.de


M ZH 3020



Fazit

Auf dem Weg zum automatisierten Betriebshof ohne AGV-Tanz

- Automatisiertes Fahren im Betriebshof für viele Anwendungsfälle heute technisch möglich & wirtschaftlich sinnvoll

- Für einige Anwendungsfälle bleiben spannende Forschungsfelder mit großem Innovationspotenzial
  - Koordination mehrerer Fahrzeuge auf engem Raum
  - Automatisiertes Koppeln von (Bestands-) Trailern
  - Rückwärts rangieren mehrgliedriger Fahrzeuge
  - Zertifizierbare Umfeldsensorik an / hinter (Bestands- & Fremd-) Trailern

- Jetzt die Basis schaffen: Steer-by-Wire-fähige Fahrzeuge und Projekte für Innovationen Made in Europe

Koordination, Leitstand, Rückwärtsfahrt…

Ihr Use-Case?

Vielen Dank für Ihre Aufmerksamkeit!

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+49 351 4640 662

Mobile Robotics Summit

IN KOOPERATION MIT Logistics Summit

w www.ivi.fraunhofer.de

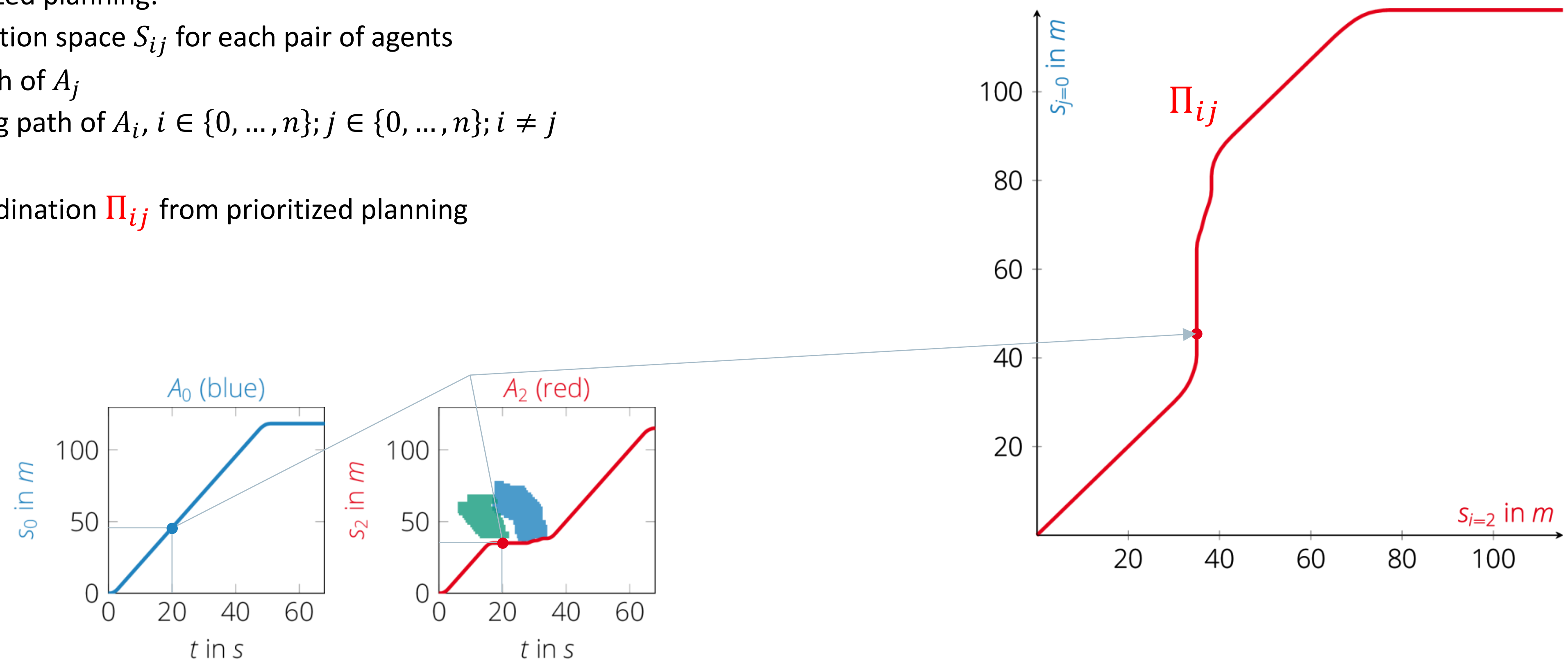
in Fraunhofer IVI

RMTRUCK
Phase A (Offline)

Offline, once after prioritized planning:

- Definition of a coordination space S_{ij} for each pair of agents
  - Distance s_j along path of A_j
    over distance s_i along path of A_i, $i \in \{0, \dots, n\}; j \in \{0, \dots, n\}; i \neq j$

- Original trajectory coordination Π_{ij} from prioritized planning

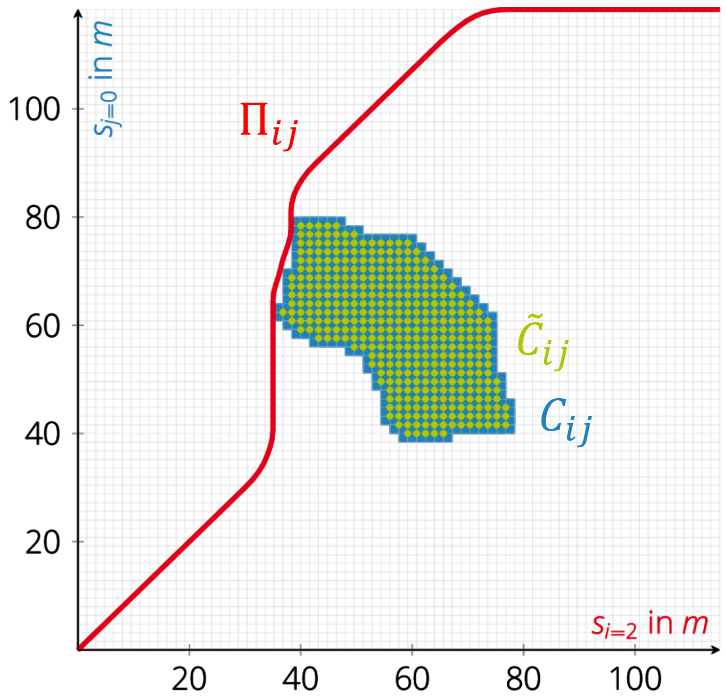


RMTRUCK

Phase A (Offline)

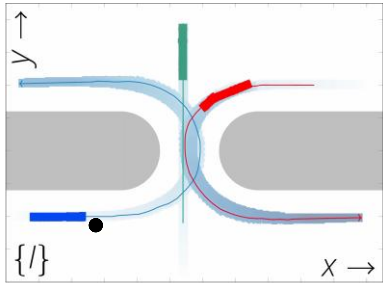
Offline, once after prioritized planning:

- Determination of a collision set $\tilde{C}_{ij}$ with (s_i, s_j), where collisions would occur (known from planning)
- Dilation to collision region C_{ij} covering region between two discrete path steps



RMTRUCK

Phase B (Online)



Online on each agent:

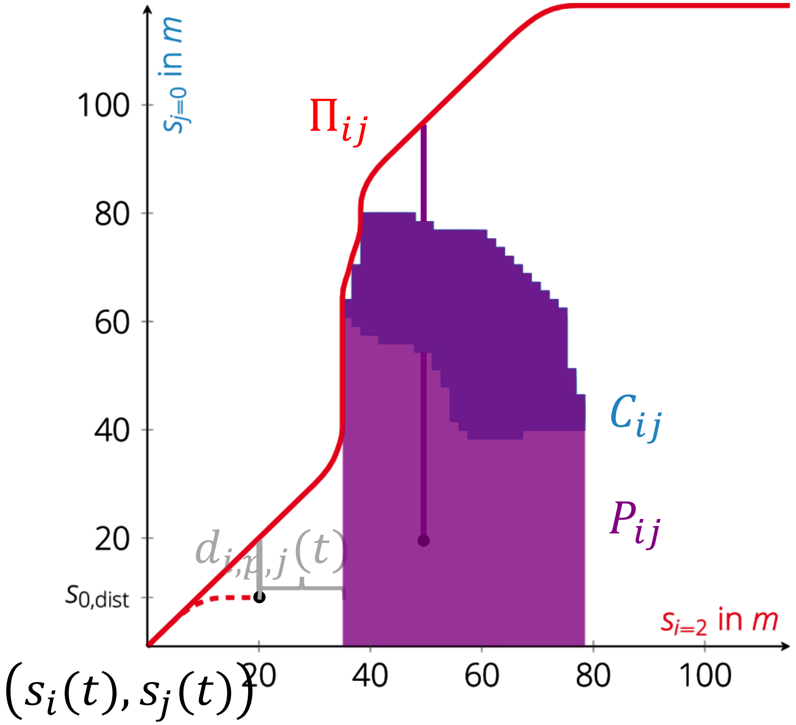
- Deviations from planned s-t-profiles lead to deviations in S_{ij}
- Adopted from RMTRACK[Čáp 2016]: $\left(s_i(t), s_j(t)\right)$ may deviate from Π_{ij} as long as it is possible to return to Π_{ij} via a vertical or horizontal line in positive direction without crossing a collision region
- Otherwise, the point $\left(s_i(t), s_j(t)\right)$ is called prohibited:

$$C_{ij} \cap \left(\{s_i(t)\} \times \{s_j(t), \dots, \Pi_{ij}(s_i(t))\}\right) \neq \emptyset \qquad \left(p_{i,j}(s_i, s_j)\right)$$

- Thus, a prohibited area is defined as:

$$P_{ij} \coloneqq \{(s_i, s_j) \mid p_{i,j}(s_i, s_j)\}$$

- Distance to prohibited area $d_{i,p,j}(t)$ governs maximum allowed velocity



[Čáp 2016] M. Čáp, J. Gregoire, and E. Frazzoli, "Provably safe and deadlock-free execution of multi-robot plans under delaying disturbances," in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, South Korea, Oct. 2016

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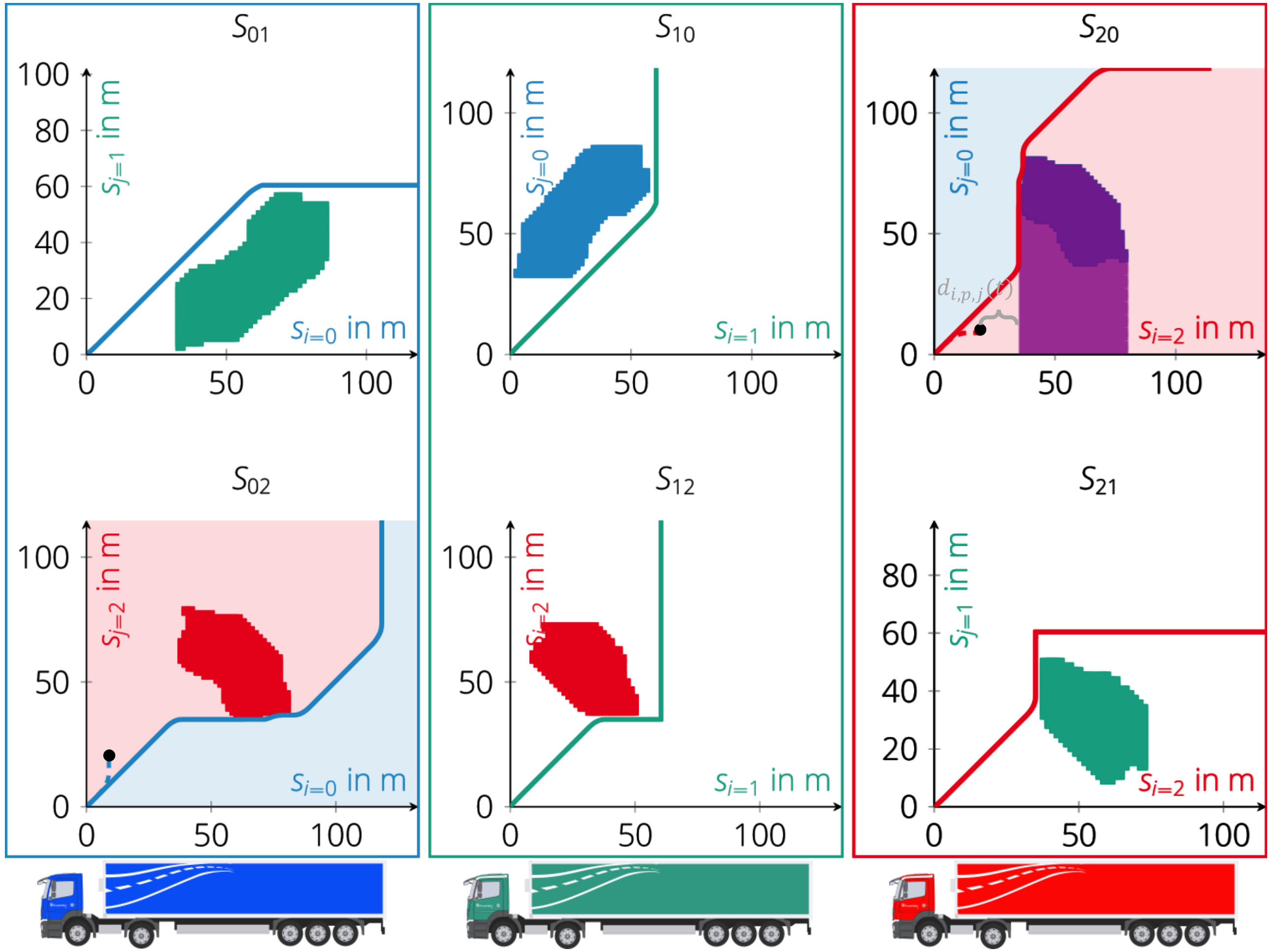
RMTRUCK

Phase B (Online)

- Each agent is responsible to maintain coordination w.r.t. all other agents
- Distance to closest prohibited area $\min(d_{i,p,j}(t)) \forall\, j$ governs maximum allowed velocity $v_{i,\max,\mathrm{RM}}(t)$, which limits controller output
- The coordination spaces S_{ij} and S_{ji} are symmetrical
  - Agent A_i can only influence the progress of s_i
  - Therefore, agent A_i is responsible for $(s_i(t), s_j(t))$ below Π_{ij}

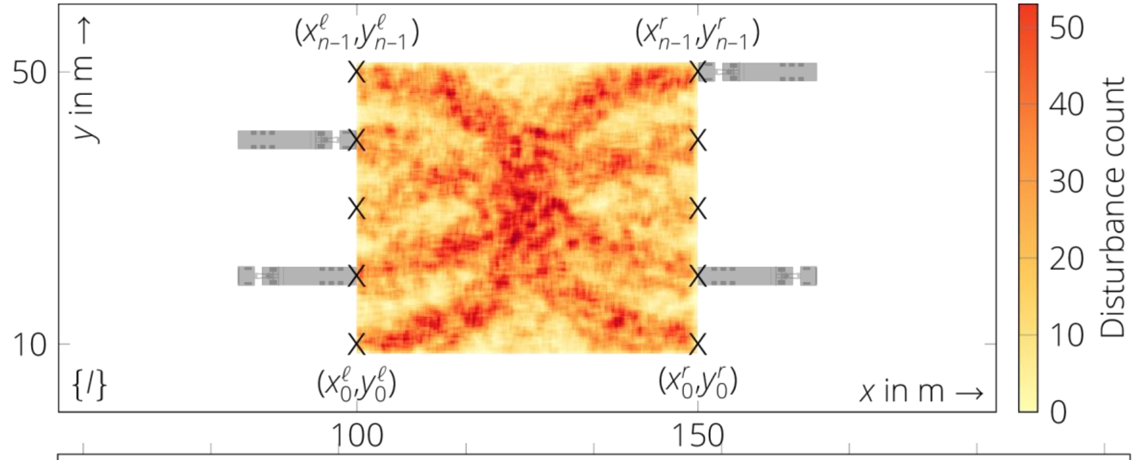


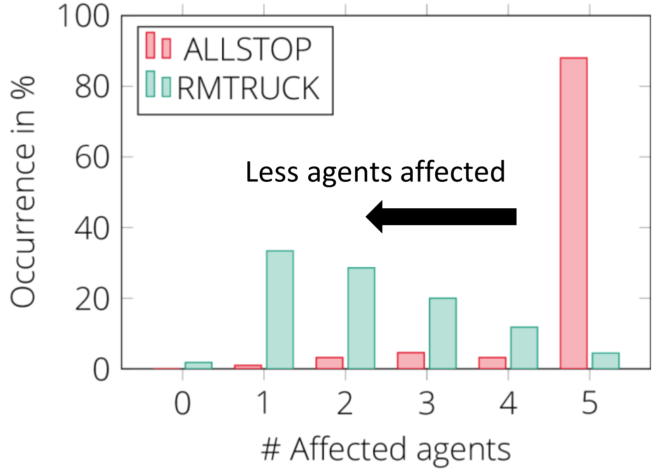
RMTRUCK

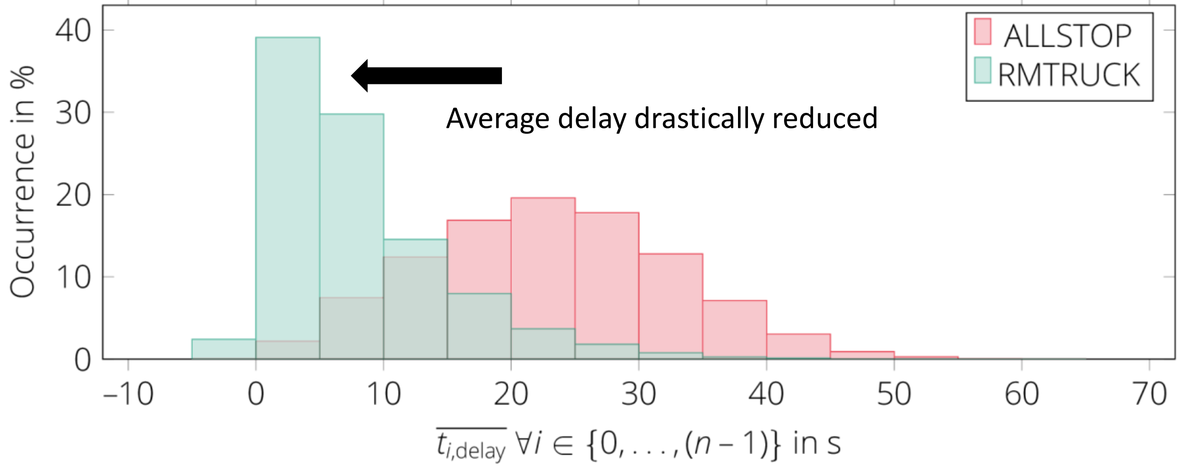
Benchmarking Results

Idealized simulation

- Randomized scenarios with five agents
- 20000 runs with one randomly scattered disturbance per run







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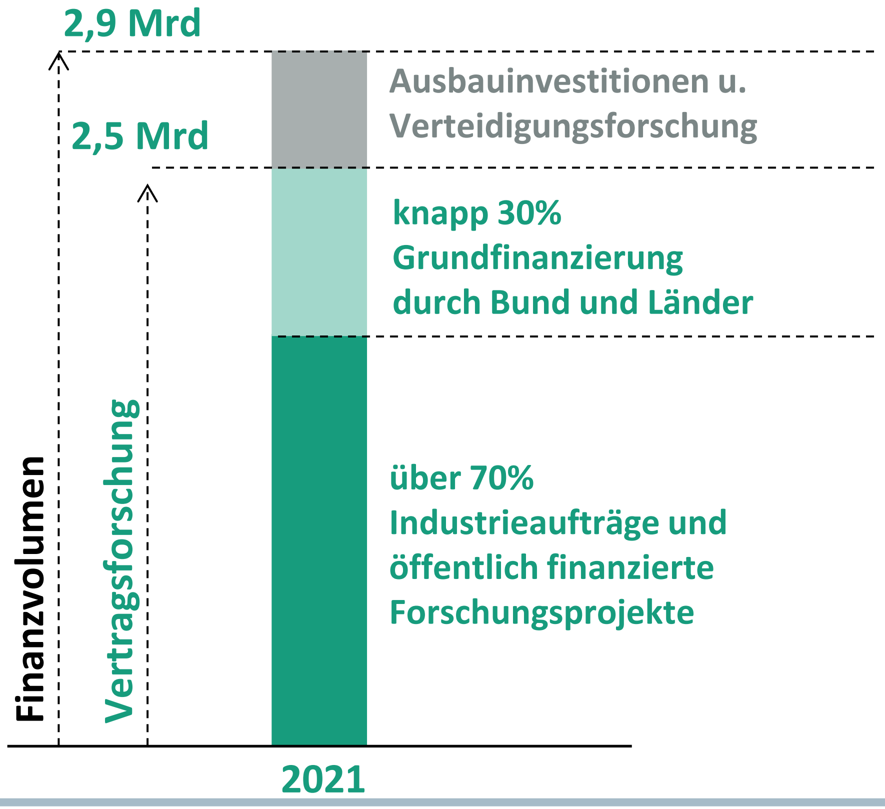
Die Fraunhofer-Gesellschaft

Auf einen Blick

Anwendungsorientierte Forschung mit Fokus auf zukunftsrelevante Schlüsseltechnologien sowie auf die Verwertung der Ergebnisse in Wirtschaft und Industrie. Wegweiser und Impulsgeber für innovative Entwicklungen.

~31 000 Mitarbeiterinnen und Mitarbeiter

76 Institute und Forschungseinrichtungen



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Fraunhofer-Gesellschaft

Internationales Netzwerk

- 8 selbstständige Fraunhofer-Auslandsgesellschaften
- Aktiv mit Partnern aus ca. 80 Ländern
- Representative Offices und Senior Advisors weltweit bilden die Brücke zu lokalen Märkten

Forschungsfelder

Kompetenzen

Intelligente Verkehrs- und Mobilitätssysteme

- Mobilitätsdienste und -daten
- Ticketing und Tarife

Fahrzeug- und Verkehrssicherheit

- funktionale Sicherheit
- Cybersicherheit
- Unfalldatenanalyse
- Verkehrspsychologie

Zivile Sicherheit

- Planung und Einsatzführung
- Infrastrukturmanagement

Risikobewertung

Energiesysteme

- autarke Versorgungssysteme
- stationäre Energiespeicher

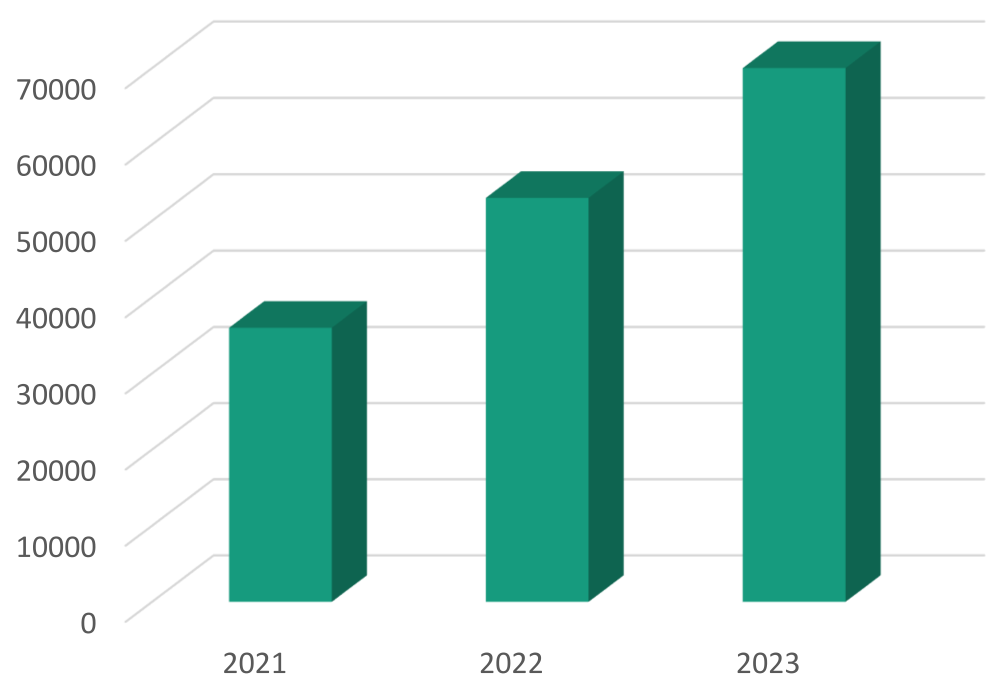
Elektromobilität

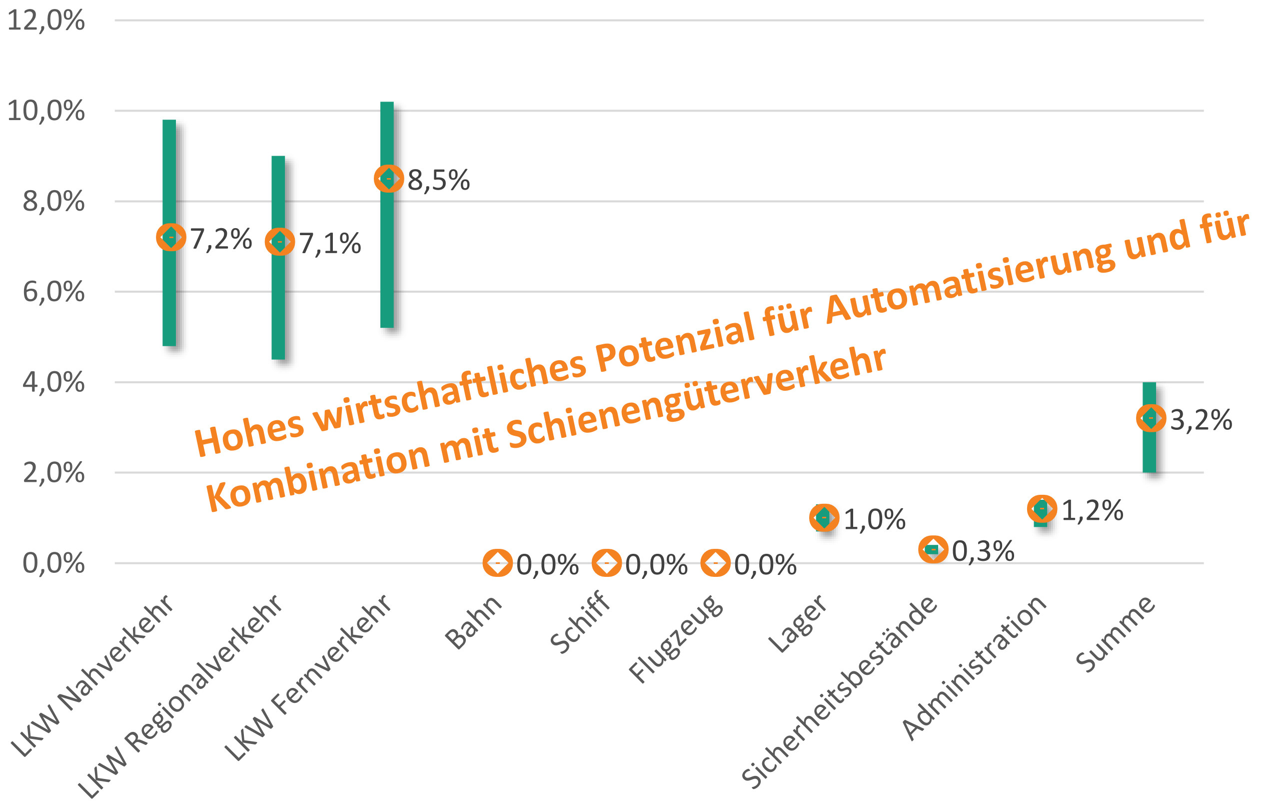
- Batterieentwicklung & -recycling
- Ladetechnologien
- Elektrobusse & E-Nutzfahrzeuge
- Brennstoffzellen / Wasserstofftechnologien

Fahrzeug- und Antriebstechnik

- Antriebstechnik, Mehrachslenkung und Spurführung
- autonomes Fahren und kooperative Fahrmanöver
- Feldrobotik und mobile Arbeitsmaschinen

Automatisierung von LKW
Motivation: Fachkräftemangel



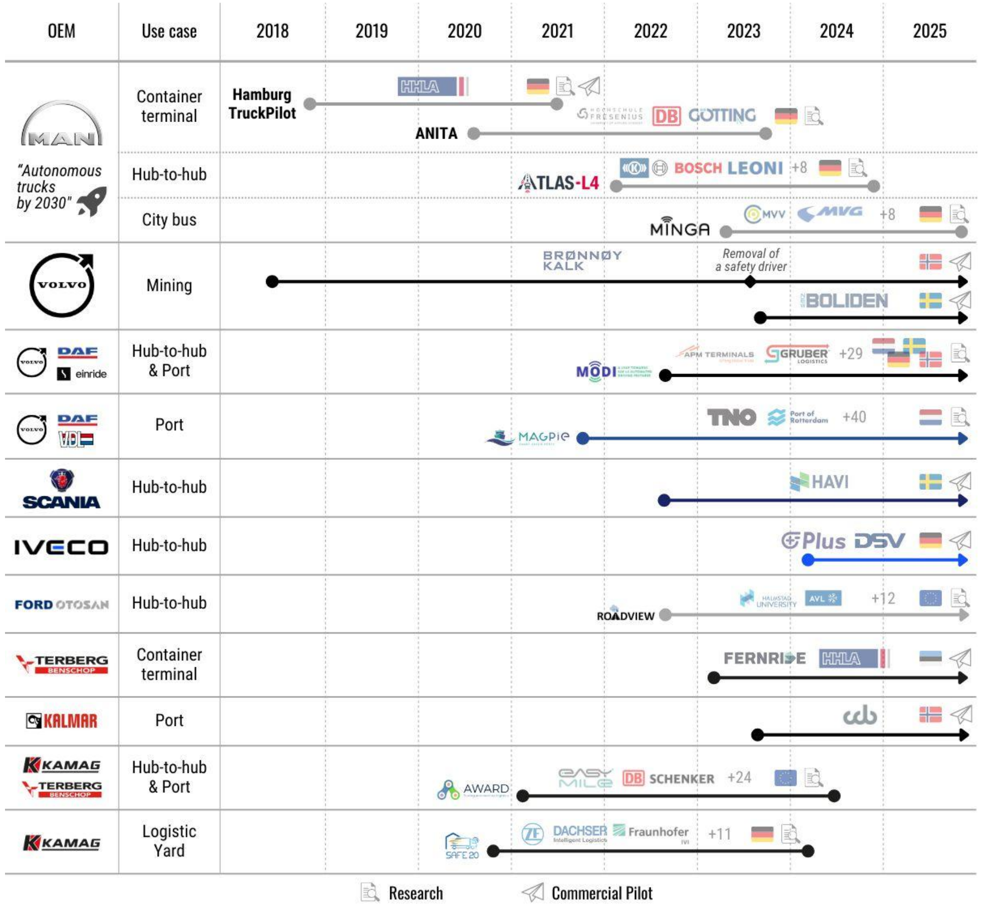


[1] Kille, Christian & Schmidt, Thorsten & Stölzle, Wolfgang & Häberle, Ludwig & Rank, Sebastian. (2023). Begegnung von Kapazitätsengpässen im Straßengüterverkehr – Fokus Personal

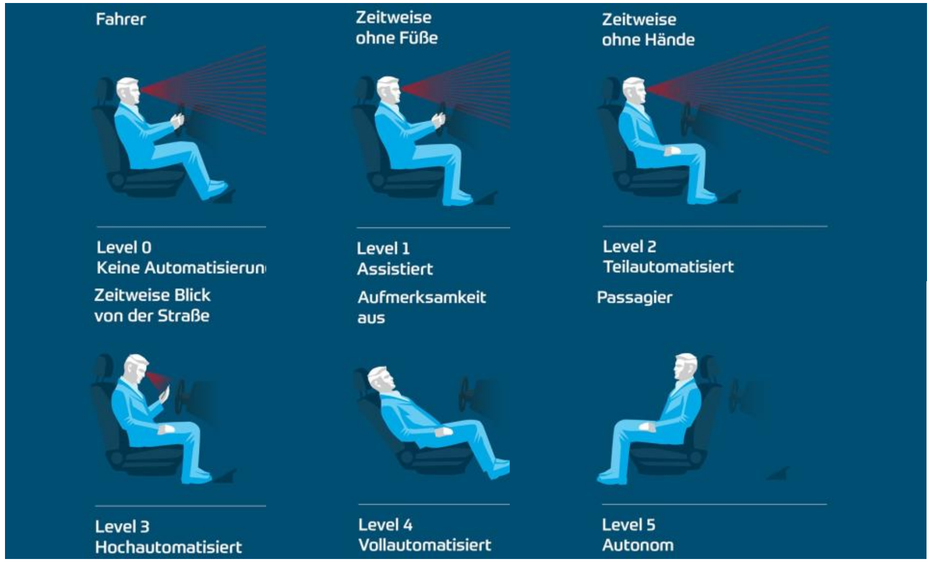
Automatisierung von LKW

Auf der Straße oder im Depot?

Autonomous Trucking Projects in Europe [1]



- Zahlreiche Aktivitäten namhafter Hersteller



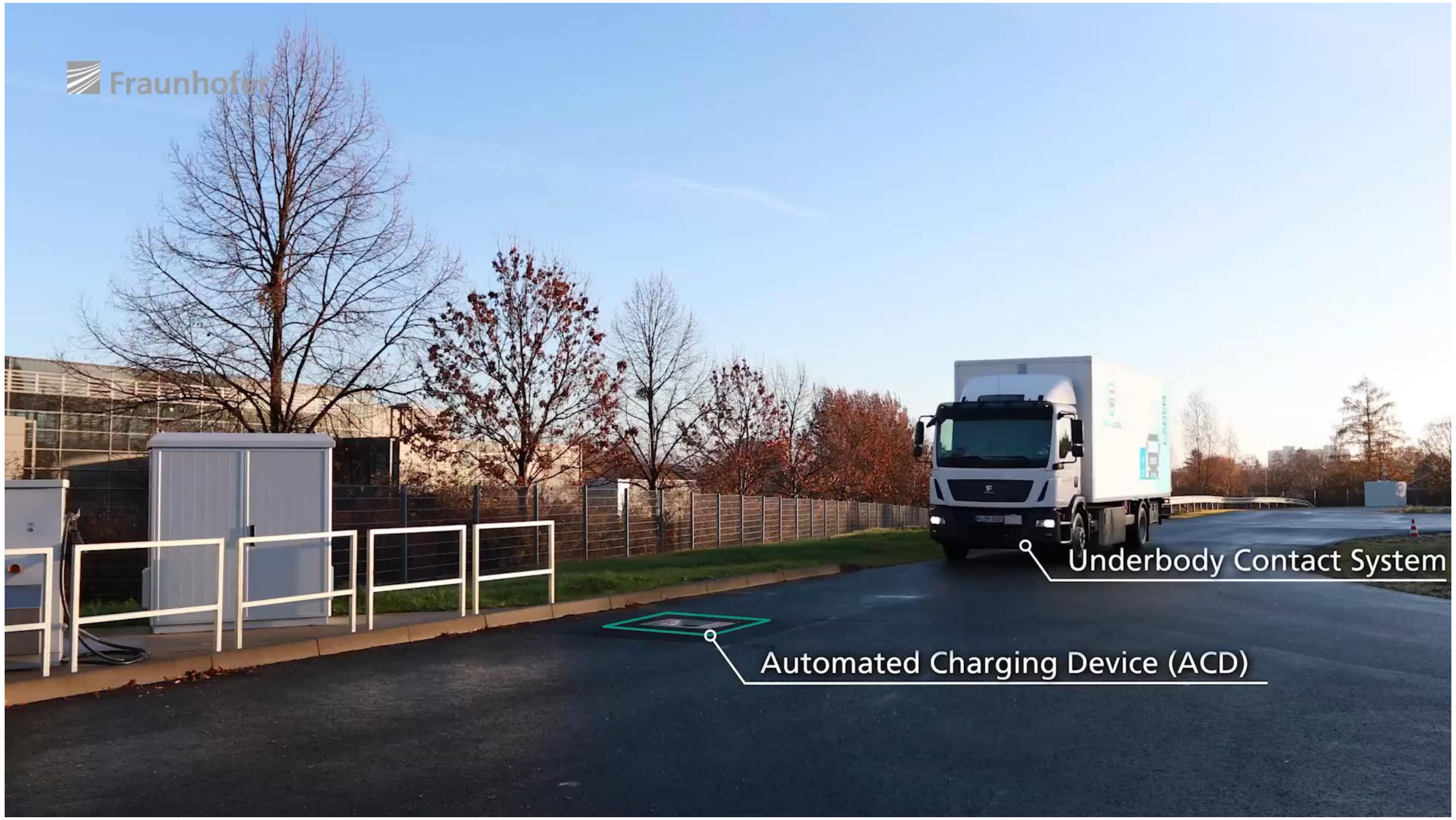
[2]

- Öffentlicher Verkehrsraum schwieriges Umfeld für Level 3+
  - Schwer kontrollierbares, hochveränderliches Umfeld
  - Fehlende regulatorische Bedingungen
- Hofautomatisierung bietet Chancen für zeitnahe Umsetzung

[1] Wojciech Siwik (ZF): Autonomous Trucking Projects in Europe, LinkedIn, 2024
[2] Jan Wienrich (ZF): Die Stufen zum selbstfahrenden Fahrzeug, ZF.com, 2024

Weitere Schritte

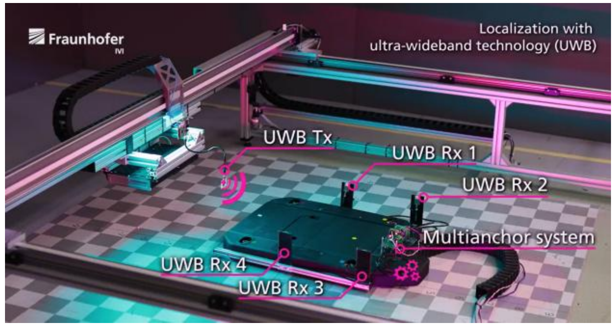
Vollautomatisches Nachladen im Megawatt-Bereich



- Projekt MEGA-LADEN
  - Bis 300 kW (Fahrzeug): 2024
  - > 1000 kW (Labor): 2023
  - Voll automatisierbar
  - Besonders nützlich bei beengten Platzverhältnissen, z.B. an Laderampen
- Nächste Schritte
  - > 1000 kW (Fahrzeug): bis 2027
  - Hochgenaue Positionierung mit UWB und Kamerasystemen
  - Übertrag auf KV-Anwendungen u.a.

Weitere Schritte

Fahren, Positionieren



Automatisiertes...	Fahren	Positionieren	Nachladen
Realisierung:	Straße: Zukunft Yard/Depot: seit 2019	bis 2027	Bis 300 kW (Fahrzeug): 2024 > 1000 kW (Labor): 2023
Aktuelle Forschung:	Präzise Rückwärtsfahrregelung, Lokale Bahnplanung zur Hindernisvermeidung	Hochgenaue Positionierung mit Kameras und UWB	> 1000 kW (Fahrzeug): bis 2027
Projekte:	AutoTruck, SAFE20, MAGPIE, COGNAC, Feldschwarm	Eigenforschung	GUW+, MEGA-LADEN, COGNAC