

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.

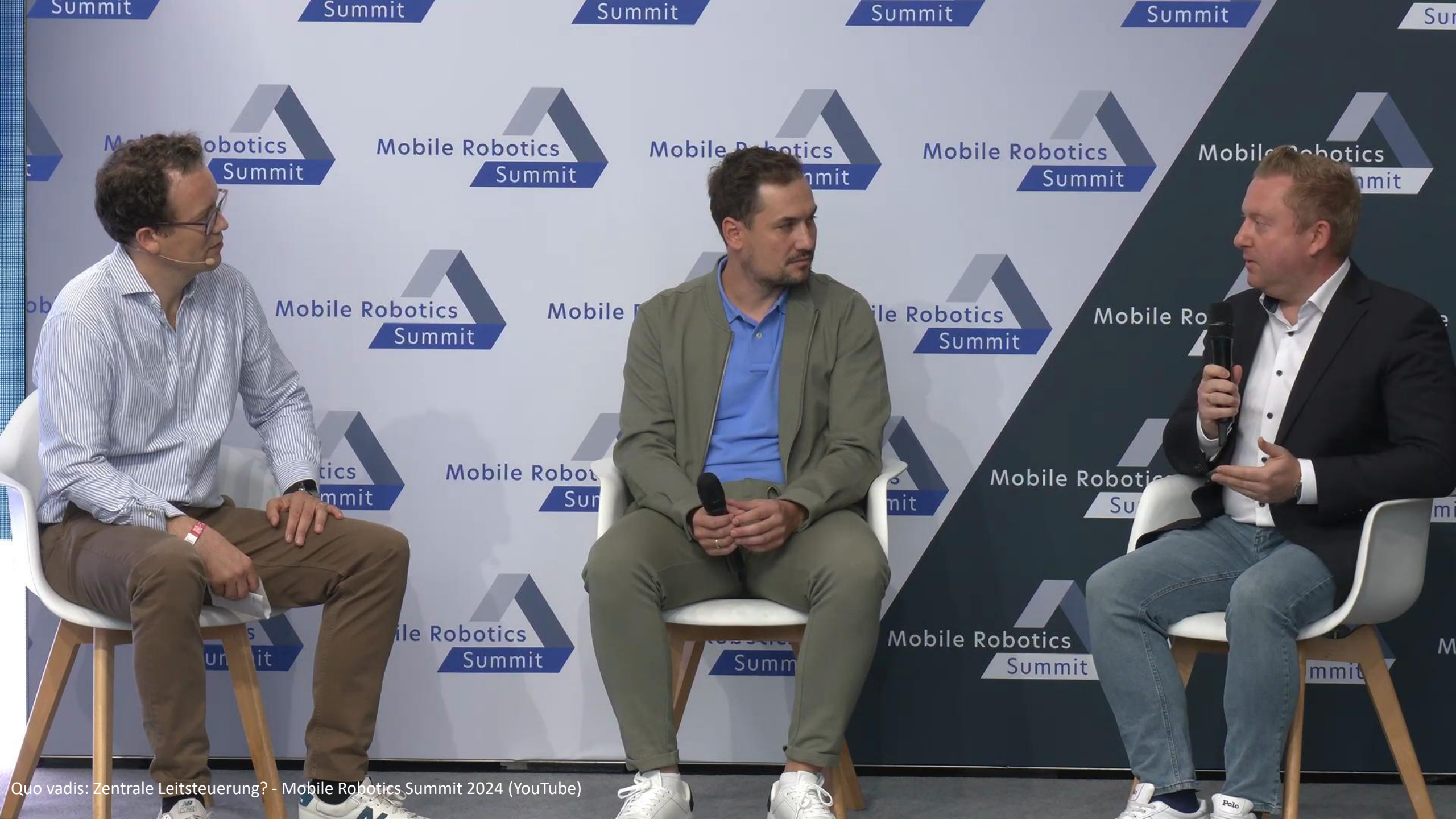
Er bestellt drei automatisierte LKW.



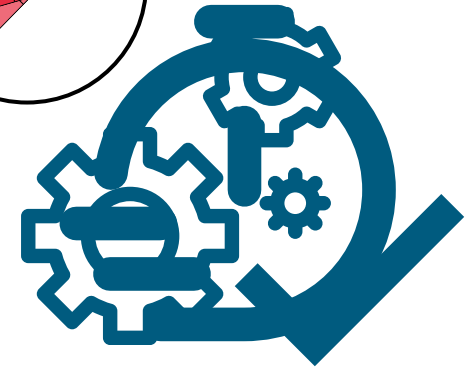




Randol White – Overhead view of Waymo honking problem in San Francisco parking lot (YouTube)







Prioritized Planning Algorithms for Trajectory Coordination of Multiple Mobile Robots

Michal Ciep, Peter Novák, Alexander Klotter, Marie Seitz

Abstract—This paper presents a prioritized planning algorithm for the trajectory coordination of multiple mobile robots. The algorithm is based on a prioritized planning approach that takes into account the global environment and the local environment of each robot. The algorithm is able to handle a large number of robots and can be used in a wide range of applications.

Index Terms—Mobile robots, trajectory coordination, prioritized planning, multi-robot systems.

1. INTRODUCTION
In recent years, several successful demonstrations of multi-robot systems have been reported. These systems are able to perform a wide range of tasks, from simple navigation to complex manipulation. The success of these systems is due to the development of new algorithms and hardware. This paper presents a prioritized planning algorithm for the trajectory coordination of multiple mobile robots. The algorithm is based on a prioritized planning approach that takes into account the global environment and the local environment of each robot. The algorithm is able to handle a large number of robots and can be used in a wide range of applications.

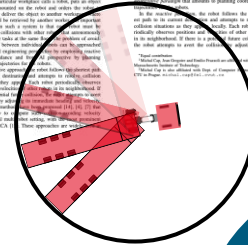
Provably Safe and Deadlock-Free Execution of Multi-Robot Plans under Delaying Disturbances

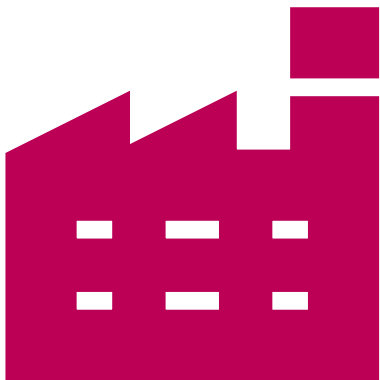
Michal Ciep^{1,2} and Peter Novák^{1,2} and Ehab El-Farouk^{1,2}

Abstract—This paper presents a provably safe and deadlock-free execution algorithm for multi-robot plans under delaying disturbances. The algorithm is based on a provably safe and deadlock-free execution approach that takes into account the global environment and the local environment of each robot. The algorithm is able to handle a large number of robots and can be used in a wide range of applications.

Index Terms—Multi-robot systems, provably safe, deadlock-free, trajectory coordination, multi-robot systems.

1. INTRODUCTION
In recent years, several successful demonstrations of multi-robot systems have been reported. These systems are able to perform a wide range of tasks, from simple navigation to complex manipulation. The success of these systems is due to the development of new algorithms and hardware. This paper presents a provably safe and deadlock-free execution algorithm for multi-robot plans under delaying disturbances. The algorithm is based on a provably safe and deadlock-free execution approach that takes into account the global environment and the local environment of each robot. The algorithm is able to handle a large number of robots and can be used in a wide range of applications.





Fraunhofer

IVI



Prioritized Planning Algorithms for Trajectory Coordination of Multiple Mobile Robots

Michal Čip, Peter Novák, Alexander Kleuser, Martin Šelocký

Algorithms to approximate multi-robot systems out of the constraints is hard to present in particular the individual robot's position. One approach to this problem involves finding coordinated trajectories from start to destination for all the robots and then applying these trajectories to the robots.

A widely used practical method for finding such coordinated trajectories is "velocity" prioritized planning, where robots plan their trajectories in order of their priority. This method is effective in practice, but it is infeasible (i.e., there are schedule problem instances that the algorithm fails to solve) and it has a high computational complexity. In this paper, we propose a method guaranteed to succeed. Further, prioritized planning is a centralized algorithm, which makes the method unsuitable for

computed by the revised prioritized planning approach. This paper briefly characterizes the problem instances for which the method is guaranteed to succeed.

Further, we propose a new asynchronous decentralized algorithm for finding coordinated trajectories. This decentralized method can be used in multi-robot systems without a central server. This technique may be used to find coordinated trajectories past obstacles in a multi-robot system without a central server. The individual robots. The paper provides an analysis showing that the asynchronous decentralized implementation of classical algorithms can be used to find coordinated trajectories in a multi-robot system. The paper also provides a comparison of the experimental comparison of performance of different versions of centralized and decentralized algorithms.

The contributions of this work are in an adapted version of classical prioritized planning called *revised prioritized planning* (RPP) and in the development of a new algorithm, called *revised heuristic prioritized planning* (RHPP), which is provably reliable in this algorithm and is an exponentially decelerated version of both classical and revised prioritized planning. Together with a formal modular decomposition algorithm, RHPP can be used to synthesize a set of control algorithms for robotic components properties from its controlled components.

Finally, a simulation performed in a standard on real-time laboring mode shows that at the critical version of prioritized planning reliable under a wide class of scenarios on which RPP and RHPP are applicable, the algorithm is faster than the algorithm based on the heuristic prioritized planning (HPP) and that the exponentially decelerated implementation of classical and revised prioritized planning (RPP) is faster than the algorithm based on the heuristic prioritized planning (HPP).

Such conditions can change substantially with the push or threat and enticement by autonomous mobile robots. One way to deal with possible collisions between the robot and its human co-workers is to have the robot detect the presence of a human and then stop or slow down. However, such a robot could also be programmed to detect the presence of a human and then speed up or change direction to avoid a collision. Such a robot could be programmed to detect the presence of a human and then speed up or change direction to avoid a collision. Such a robot could be programmed to detect the presence of a human and then speed up or change direction to avoid a collision.

that make them more difficult to model. The ability to use such coordination problem as an analogue to precise coordination problems is a key feature of the proposed and computationally-efficient approach in which robots gain their own responsibility under other members' preselected policies. The proposed approach is computationally efficient because the problem is solved in a distributed manner. In this paper, we show that a simple algorithm of coordination problem can be used to solve a more general problem of coordination problem. The proposed approach is generated to find collision-free trajectories for a well-defined coordination problem. The proposed approach is also suitable for multi-robot systems in which robots have local-to-global information by requiring the start and destination position of each robot and some sensor data about the environment. The proposed approach is suitable to provide a solution. For instance, in our previous work [10], we have shown that the proposed approach can be used to find collision-free trajectories for a well-defined coordination problem. The proposed approach is also suitable for multi-robot systems in which robots have local-to-global information by requiring the start and destination position of each robot and some sensor data about the environment. The proposed approach is suitable to provide a solution. For instance, in our previous work [10], we have shown that the proposed approach can be used to find collision-free trajectories for a well-defined coordination problem.

Provably Safe and Deadlock-Free Execution of Multi-Robot Plans
under Delaying DisturbancesMichel Cap^{a,1,2} and Jean Gregoire^{a,2} and Emilio Frenkel^b[illegible]

5. Introduction

The advantages of reducing the total lead time lead to the attainment of production objectives. Multi-order systems consist of a large number of cooperating modules. One of the prime concerns in the warehouse management systems developed by Kiva Systems (now Amazon Robotics) is that multiple robots in stock picking for human warehouse workers. To introduce the problem, the robots in such systems typically operate in a dedicated lane, excluded area. The further impact of robots in manufacturing, can however research is focused on the

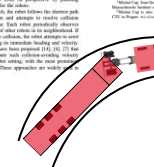
volvement of robots that can safely share their work with human workers. One of the challenges posed by mixed human-robot teams is how to control the motions of the robots given that their motions can be disturbed by humans.

The problem of coordinating motions of multiple robots can be approached either from a control engineering perspective by employing a reactive paradigm or from an AI perspective by employing a deliberative paradigm that amounts to planning coordinated trajectories for the robots.

From a control engineering perspective, the solution can be very difficult in high-dimensional systems, and the control must be designed to adapt to spatial growth caused by the number of robots. This is why heuristic techniques such as potential planning [31, 32] are often used in practice. In fact, the multi-robot coordination is so-called well-formulated subproblems, a solution to which can be obtained by decomposing the global problem using decoupled planning techniques [33, 34].

The main drawback of the deliberative paradigm is that robots are guaranteed to reach their goals only if they do not move.

² In the *structure paradigm*, the robot follows the shortest path to the goal, and attempts to avoid obstacles and collision situations as they appear, locally. Each robot periodically observes positions and velocities of other robots in its neighborhood. If there is a potential future collision the robot attempts to avert the collision by adjusting its velocity.



Multi-robot Trajectory Coordination for Complex Vehicle Combinations

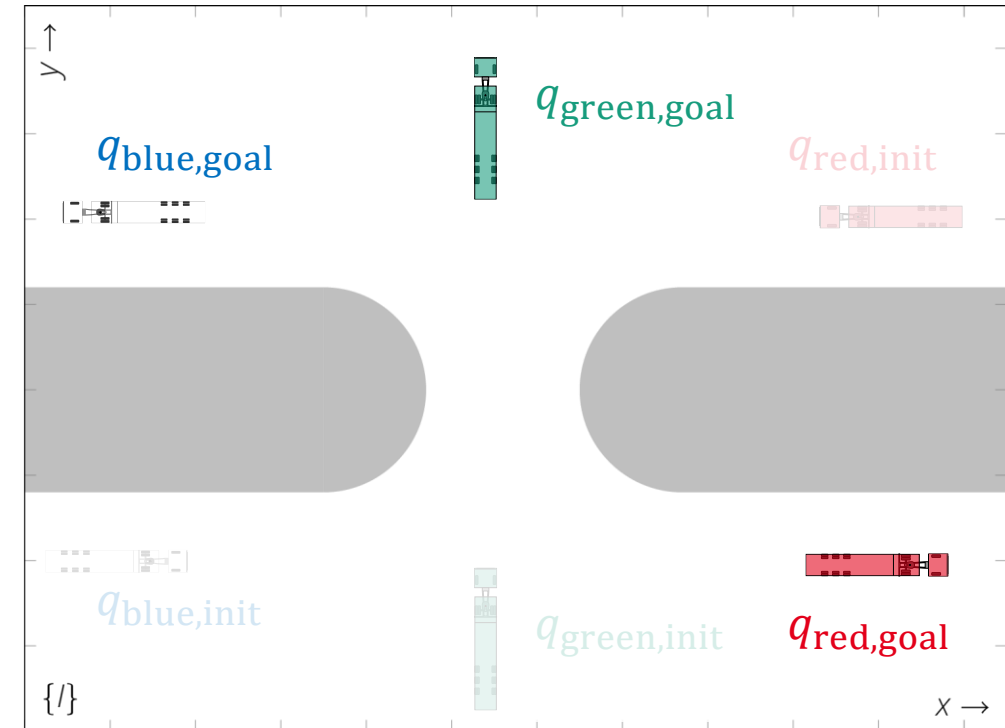
Research Objective

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

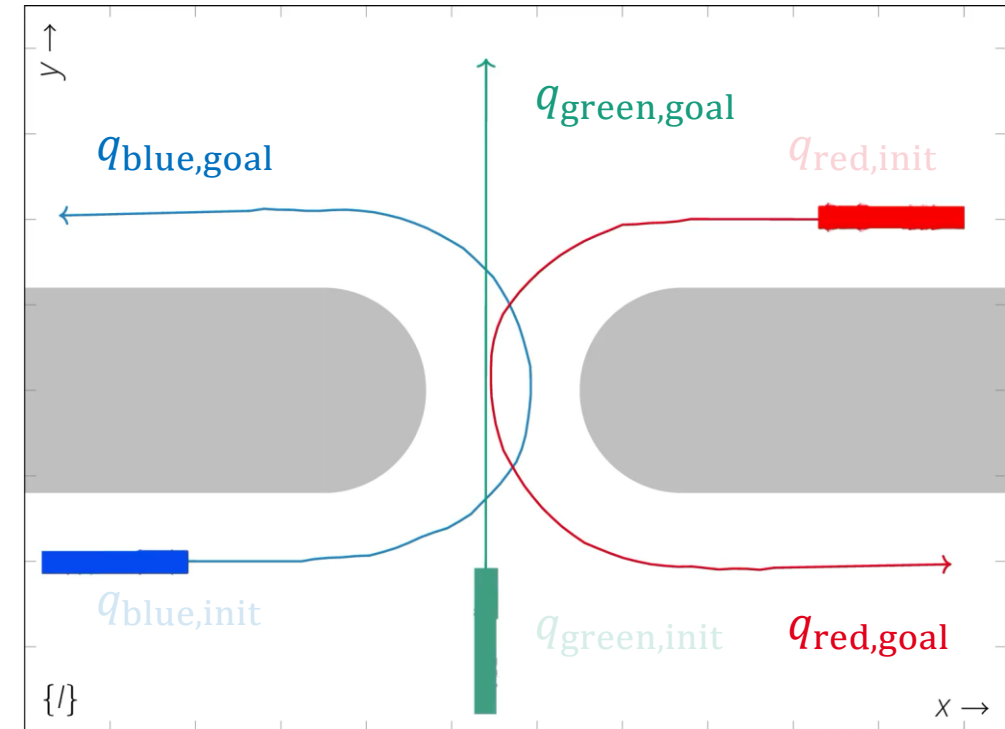
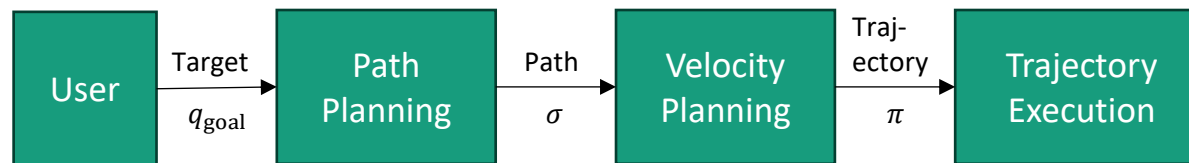


Related Work

Trajectory Coordination

Path-Velocity-Decomposition^[Kant 1986]

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



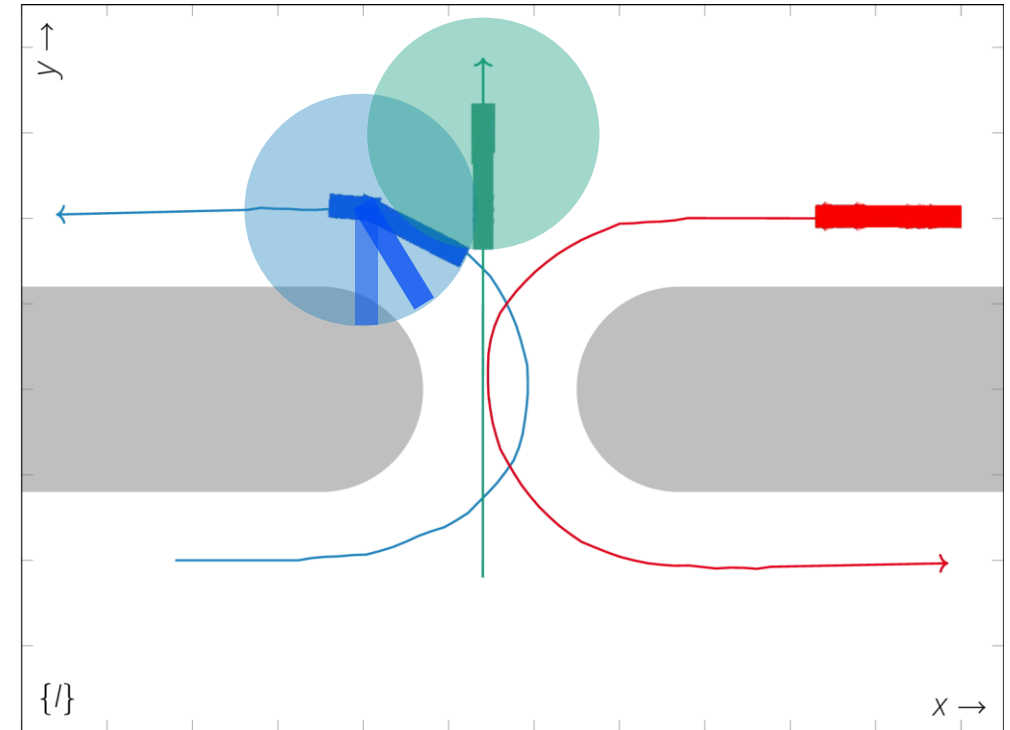
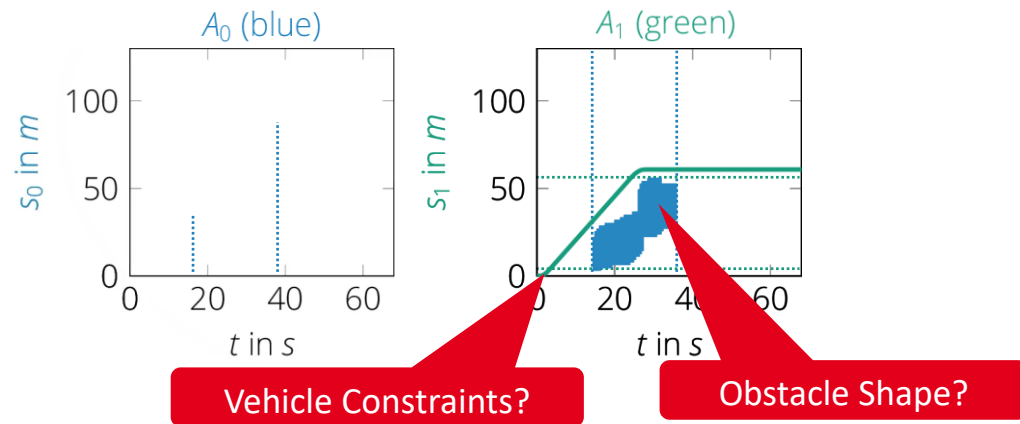
[Kant 1986] K. Kant and S. W. Zucker, "Toward Efficient Trajectory Planning: The Path-Velocity Decomposition," The International Journal of Robotics Research, vol. 5, no. 3, pp. 72–89, Sep. 1986

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

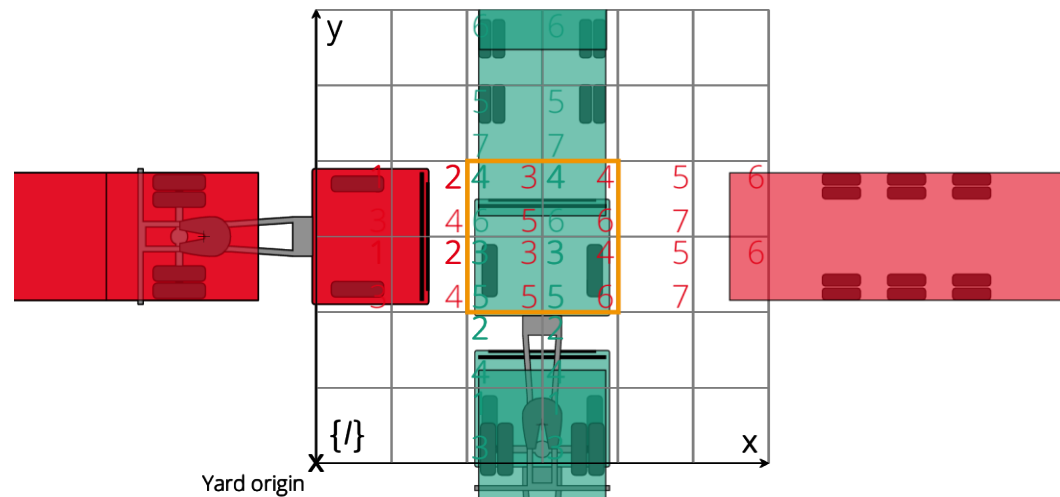


Approach

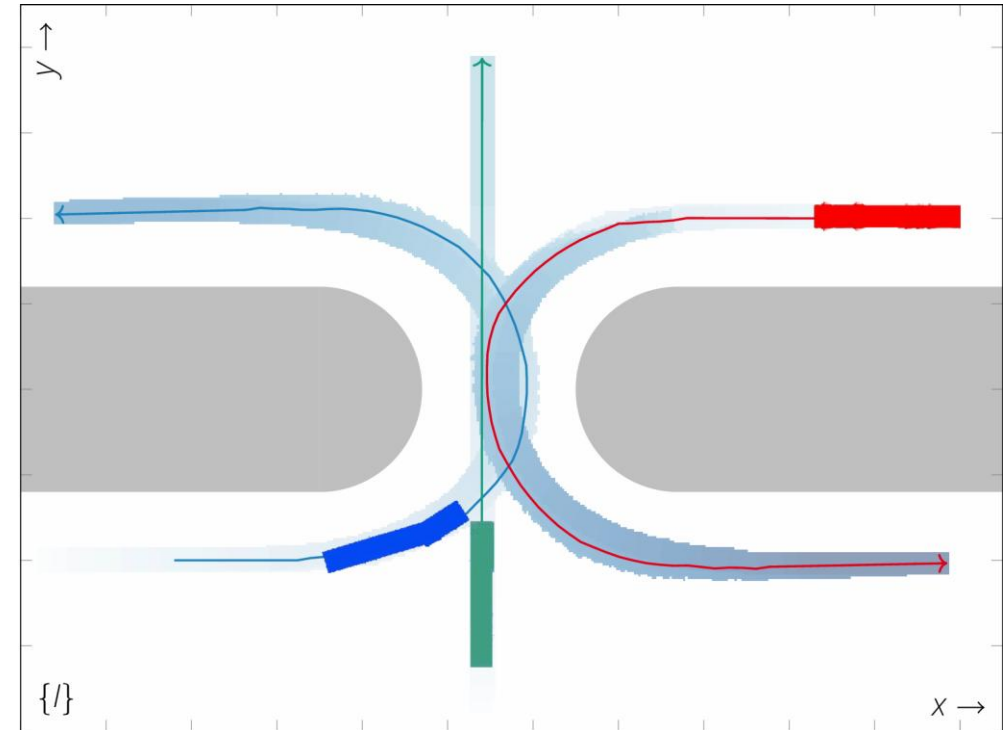
Deriving Dynamic Obstacles

Spatiotemporal Occupancy Tracking^[Keppler 2020]

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



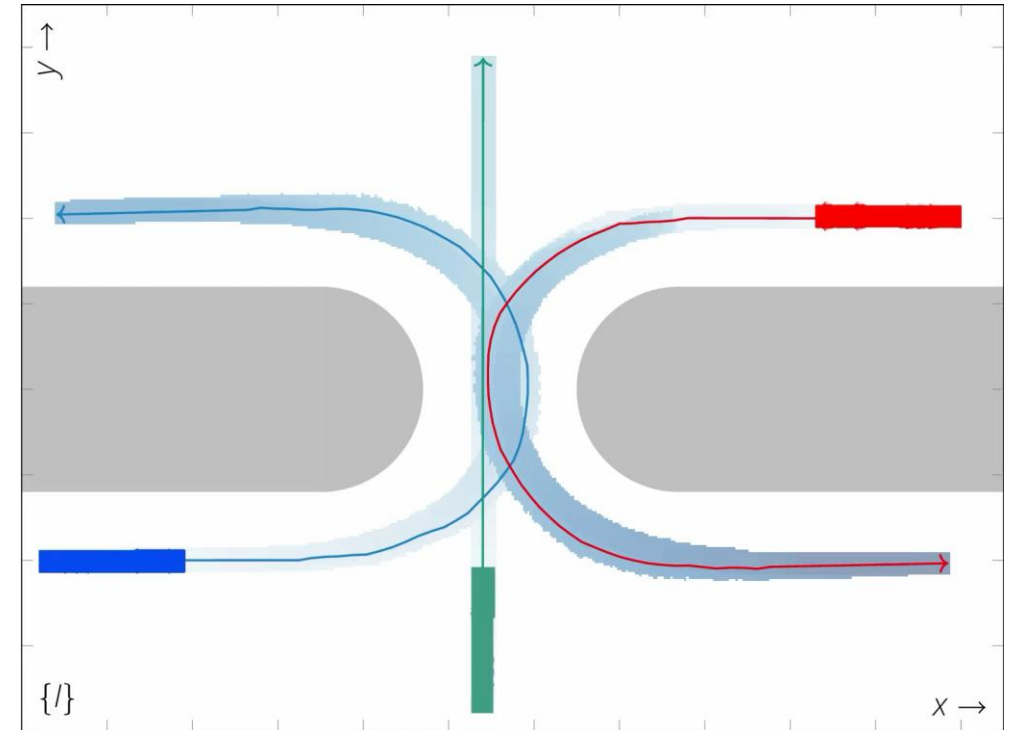
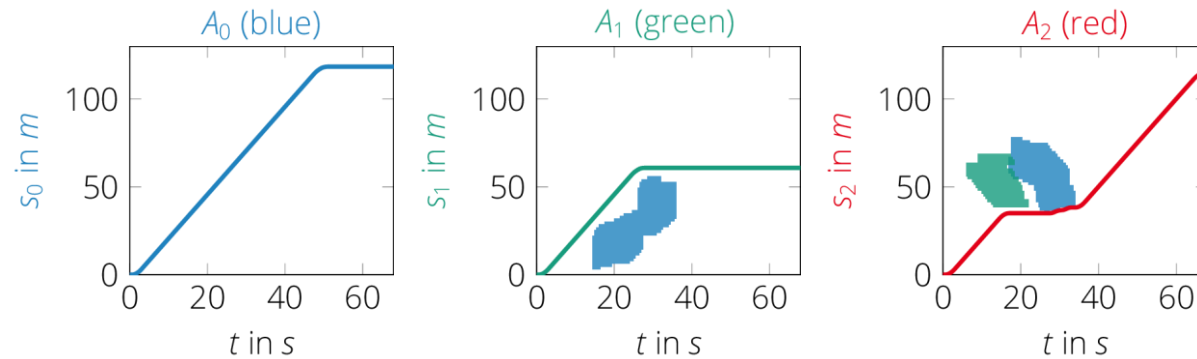
- Dynamic obstacles can be derived
- Conflicts per cell can be assessed and demand



[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

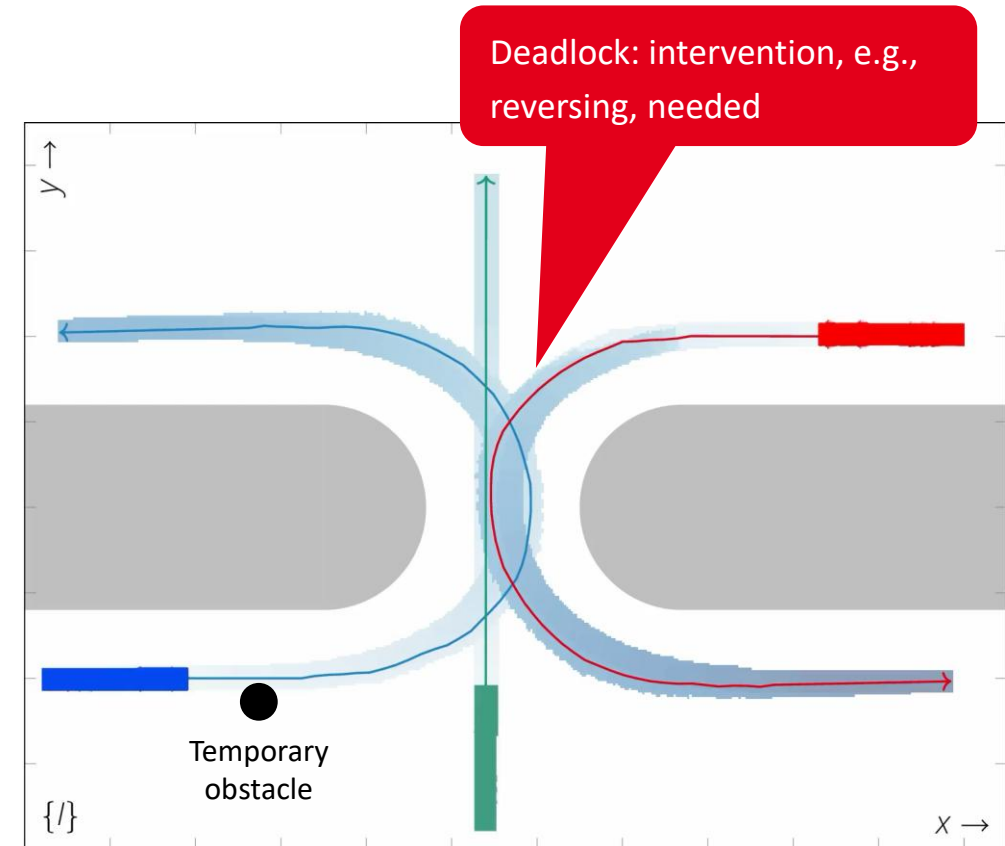
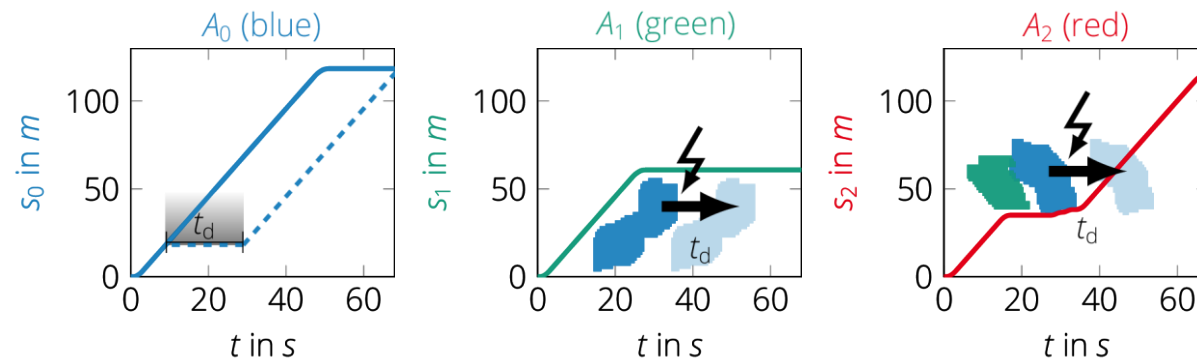
Multi-robot Trajectory Coordination for Complex Vehicle Combinations

Results under Ideal Conditions



Multi-robot Trajectory Coordination for Complex Vehicle Combinations

Delaying Disturbances

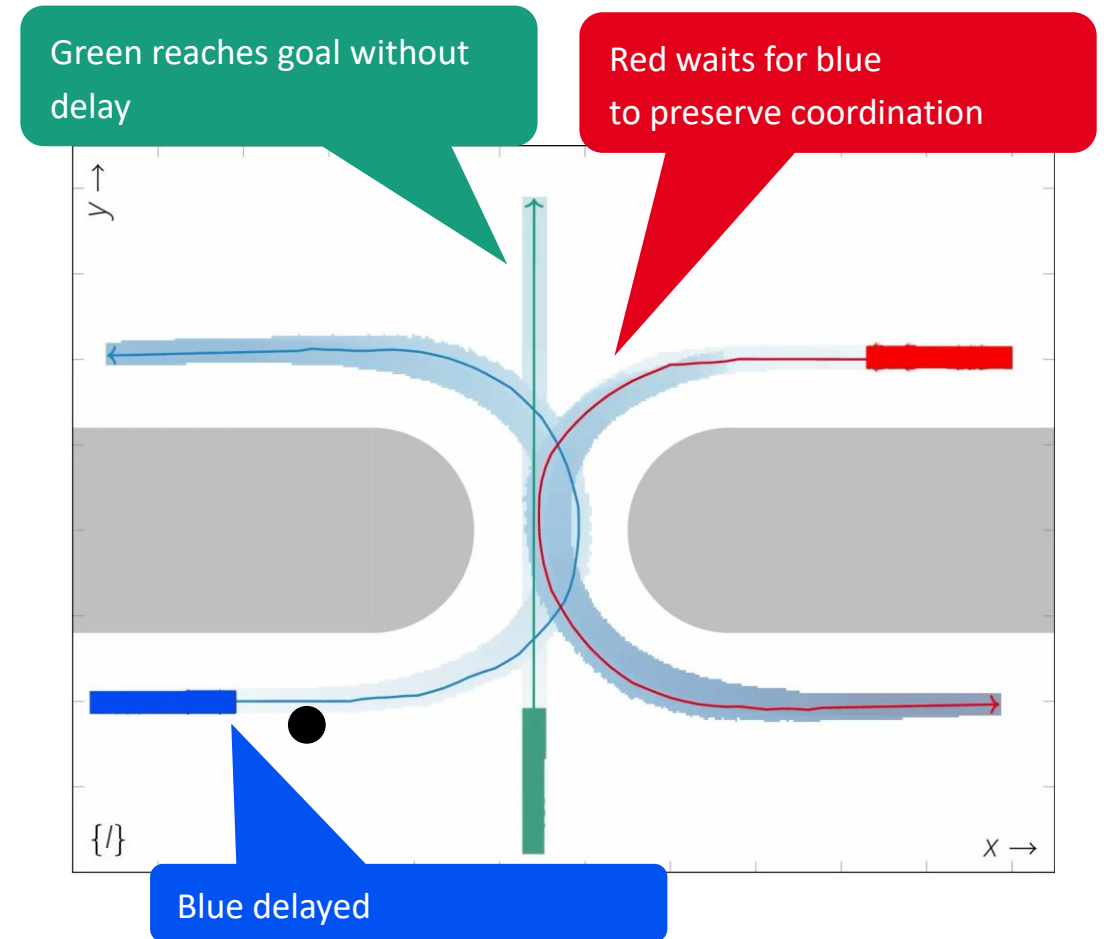


Multi-robot Trajectory Coordination for Complex Vehicle Combinations

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 Leitstandssysteme



 **Automation Suite XY**

helyOS framework.org

Open Source on GitHub

Aufgabe	Microservices
Schwerlasttransport A nach B	

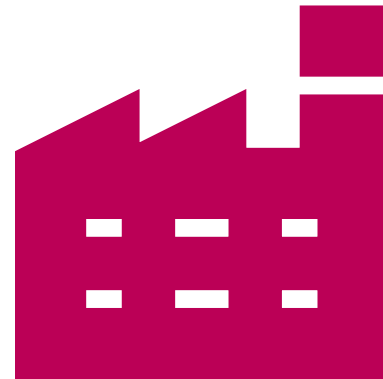


VDA5050







Fraunhofer
IVI

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!

Dr.-Ing. Felix Keppler
felix.keppler@ivi.fraunhofer.de
+49 351 4640 662



www.ivi.fraunhofer.de



Fraunhofer IVI

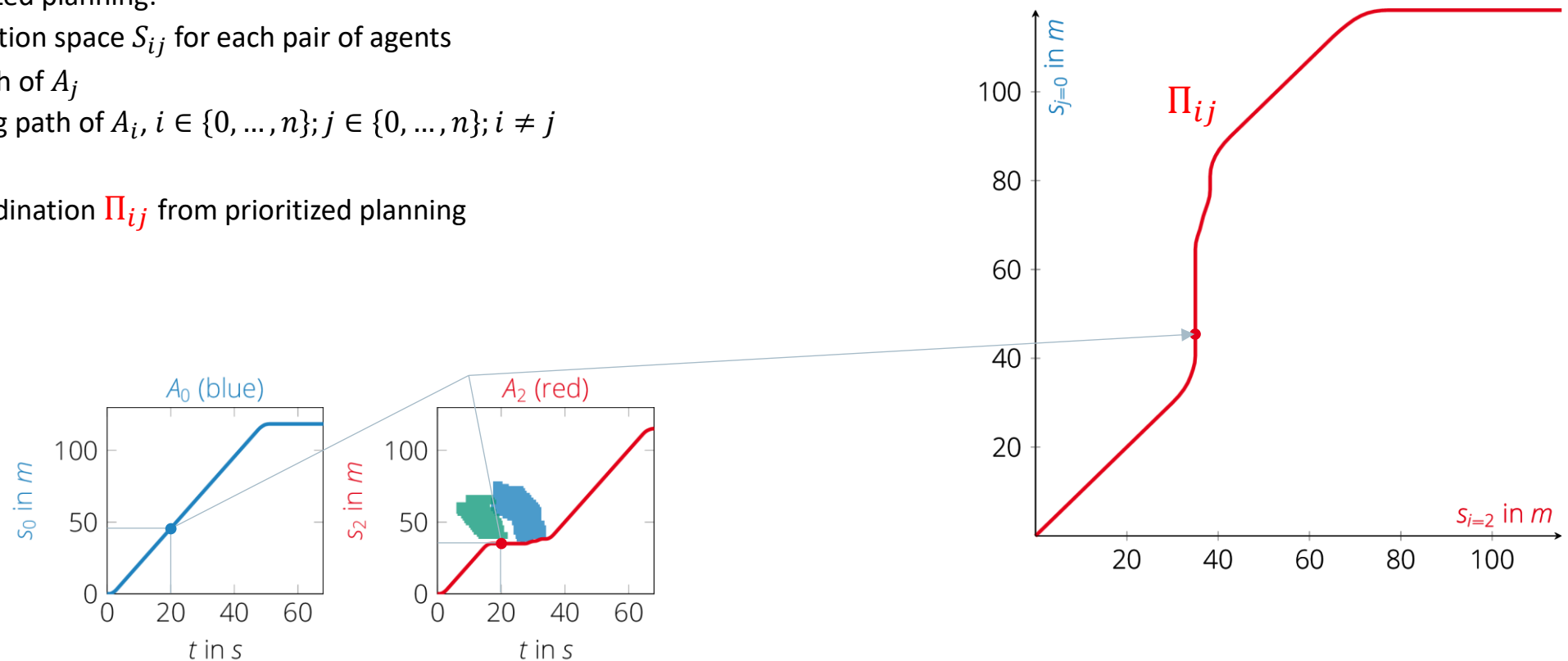


RMTRUCK

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

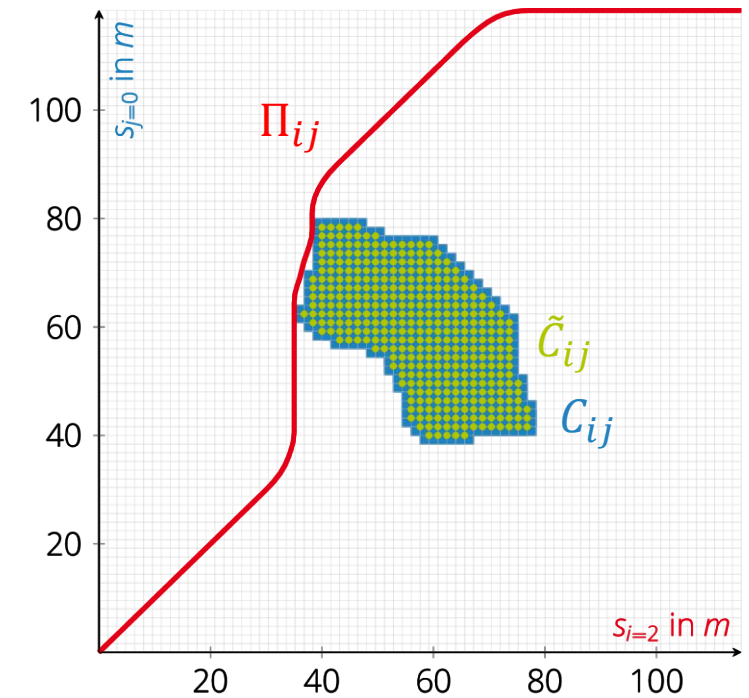


RMTRUCK

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]: $(s_i(t), s_j(t))$ 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

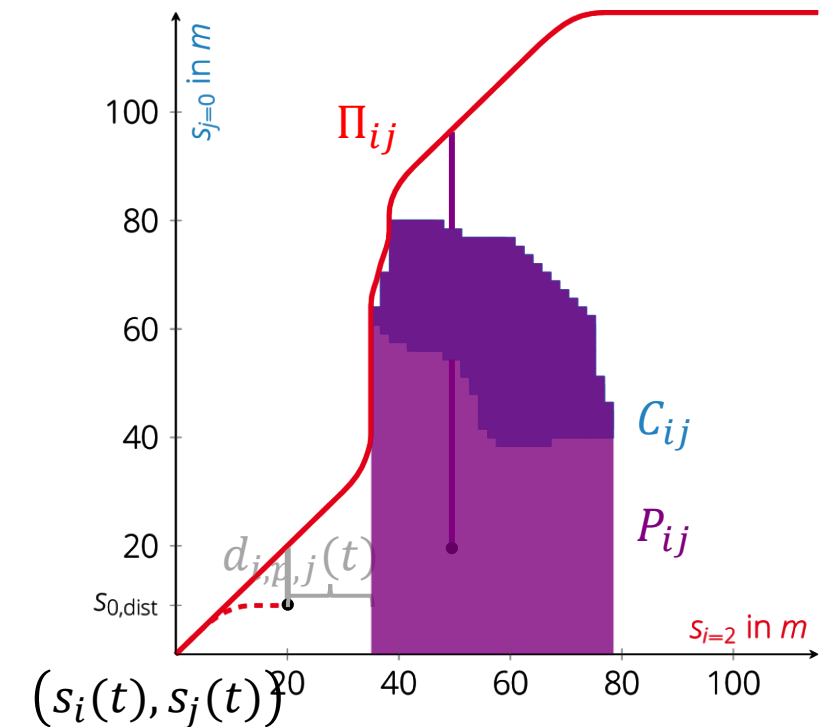
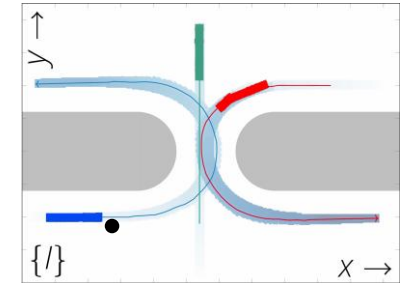
- Otherwise, the point $(s_i(t), s_j(t))$ is called prohibited:

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

- Thus, a prohibited area is defined as:

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

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

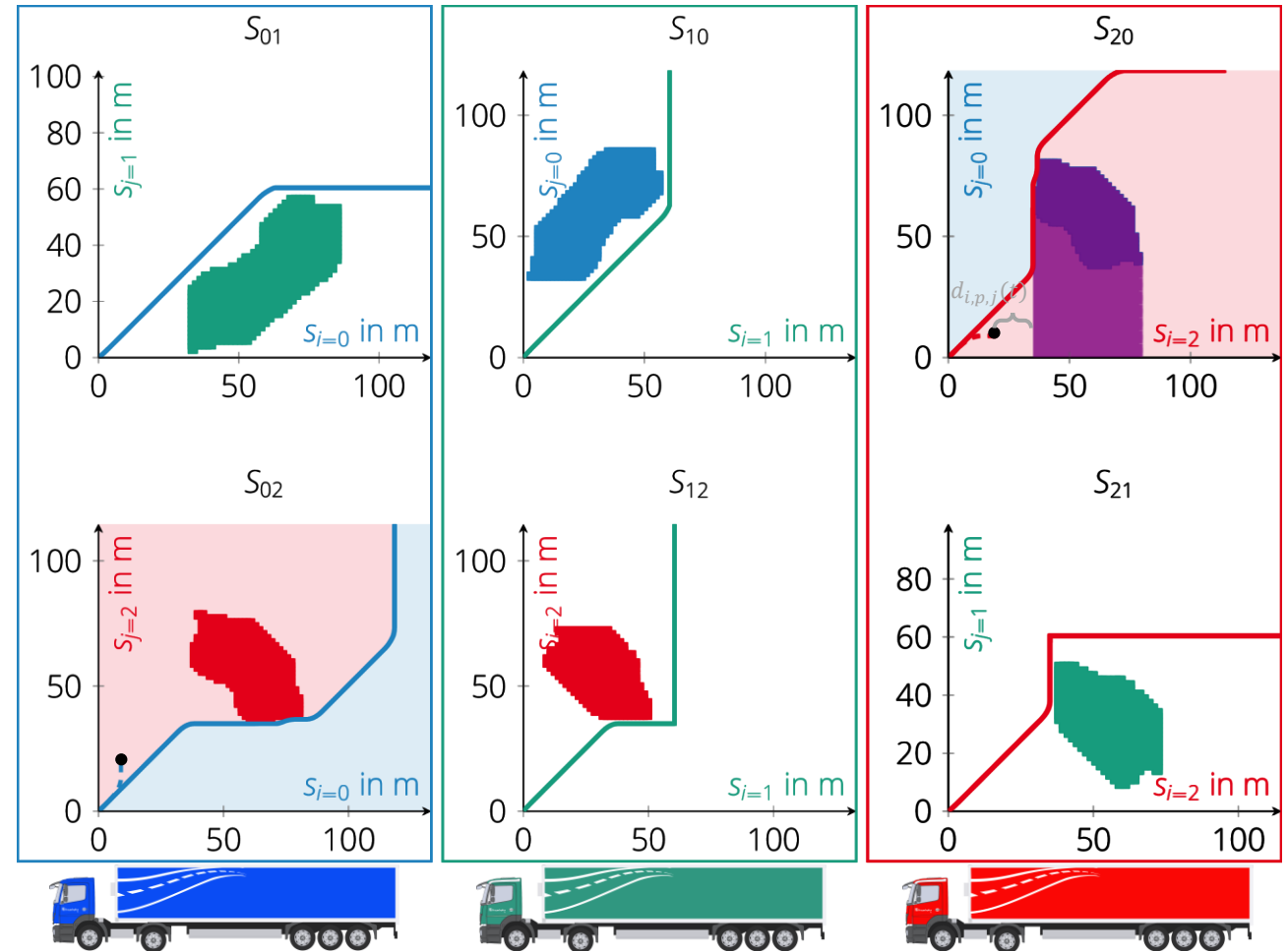


[Čáp 2016] M. Čáp, J. Gregoire, and E. Frazzoli, "Provably safe and deadlock-free execution of multi-robot plans under delaying disturbances," in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, South Korea, Oct. 2016

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 $v_{i,\max,\text{RM}}(t)$, 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}

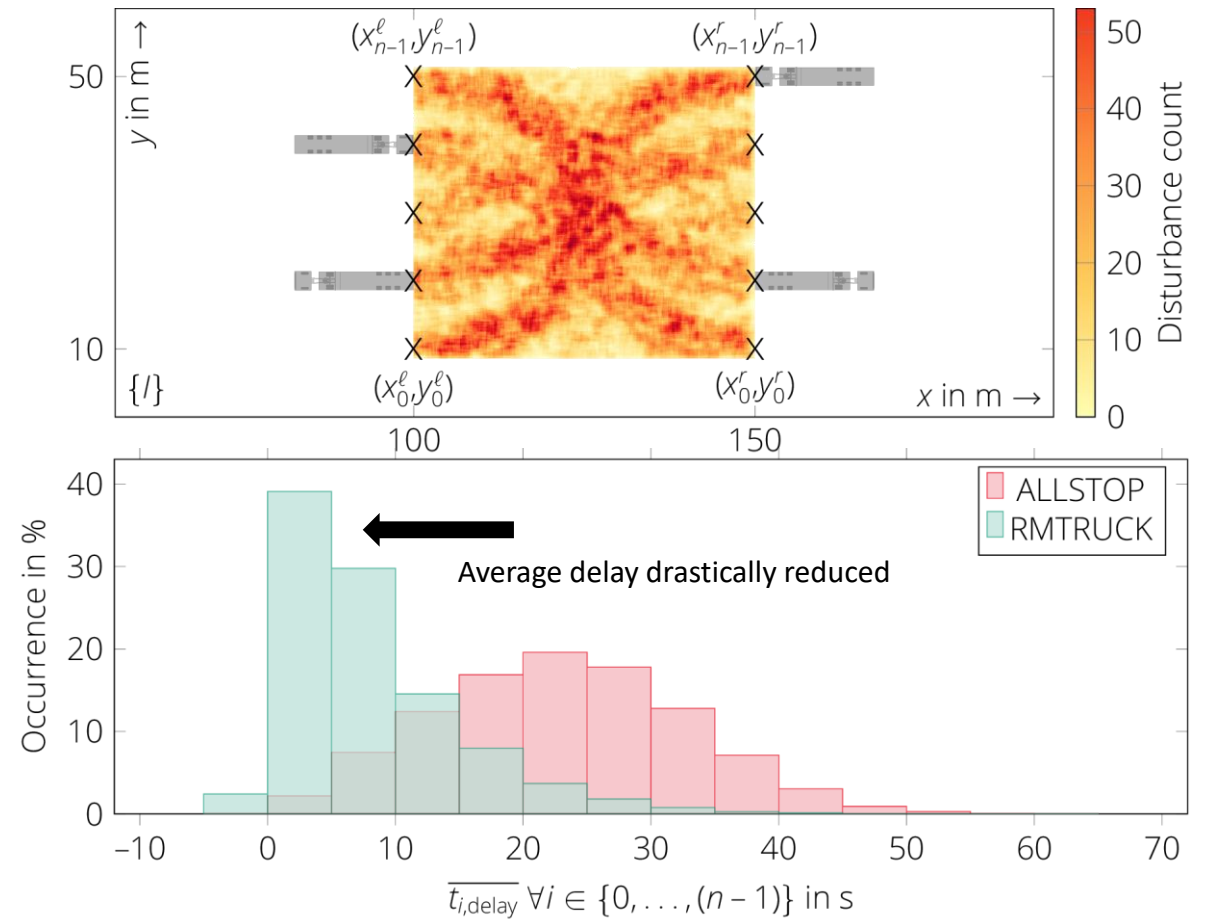
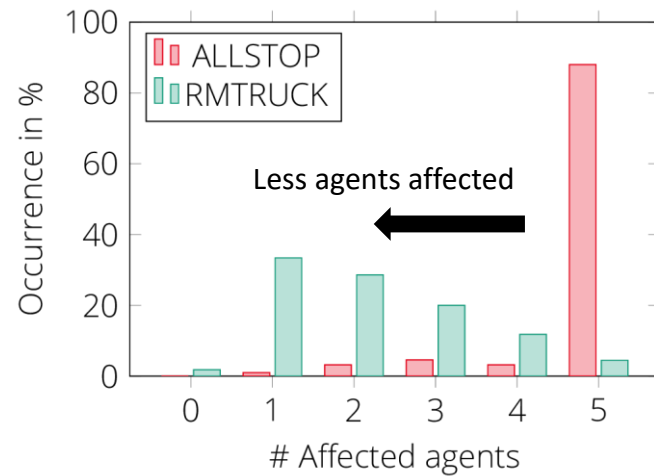


RMTRUCK

Benchmarking Results

Idealized simulation

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



Die Fraunhofer-Gesellschaft

Auf einen Blick

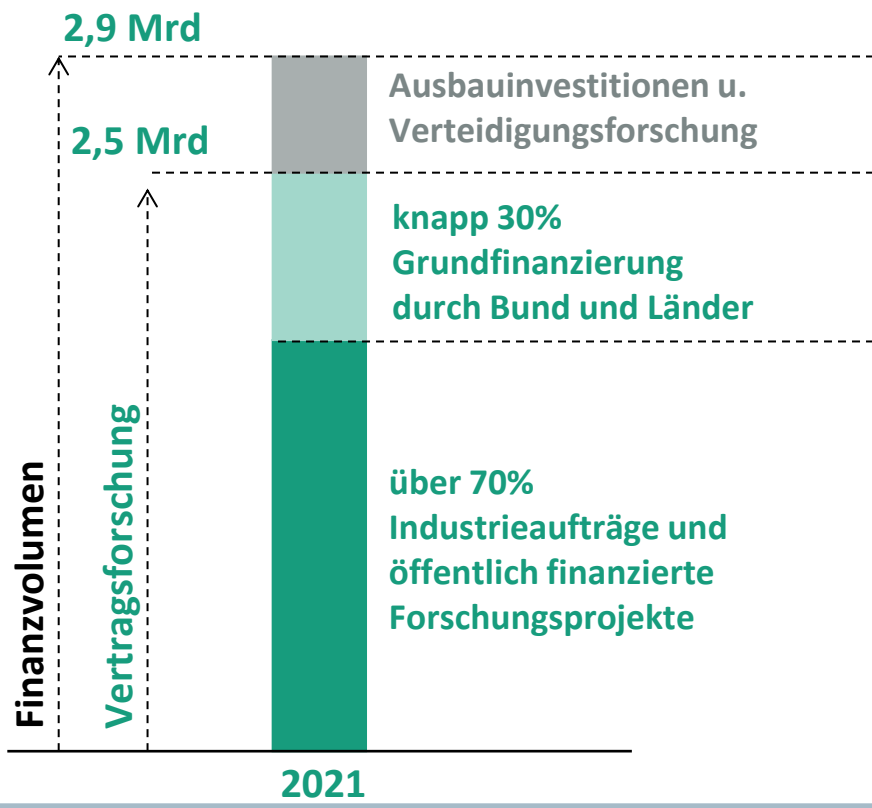
Anwendungsorientierte Forschung mit Fokus auf zukunftsrelevante Schlüsseltechnologien sowie auf die Verwertung der Ergebnisse in Wirtschaft und Industrie. Wegweiser und Impulsgeber für innovative Entwicklungen.



~31 000 Mitarbeiterinnen
und Mitarbeiter



76 Institute und
Forschungseinrichtungen



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

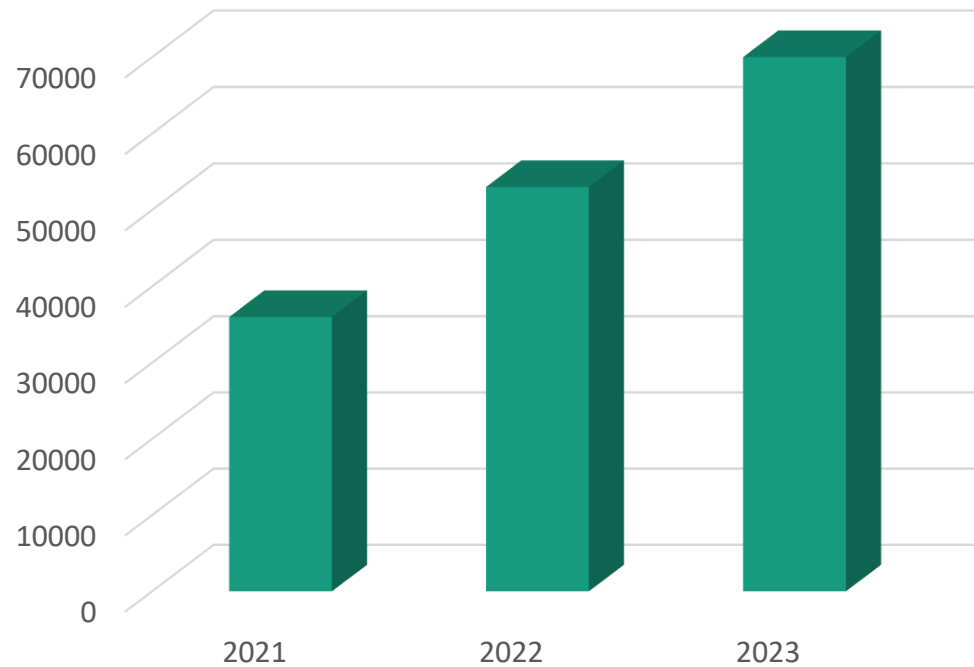
- Antriebstechnik, Mehrachslenkung und Spurführung
- autonomes Fahren und kooperative Fahrmanöver
- Feldrobotik und mobile Arbeitsmaschinen



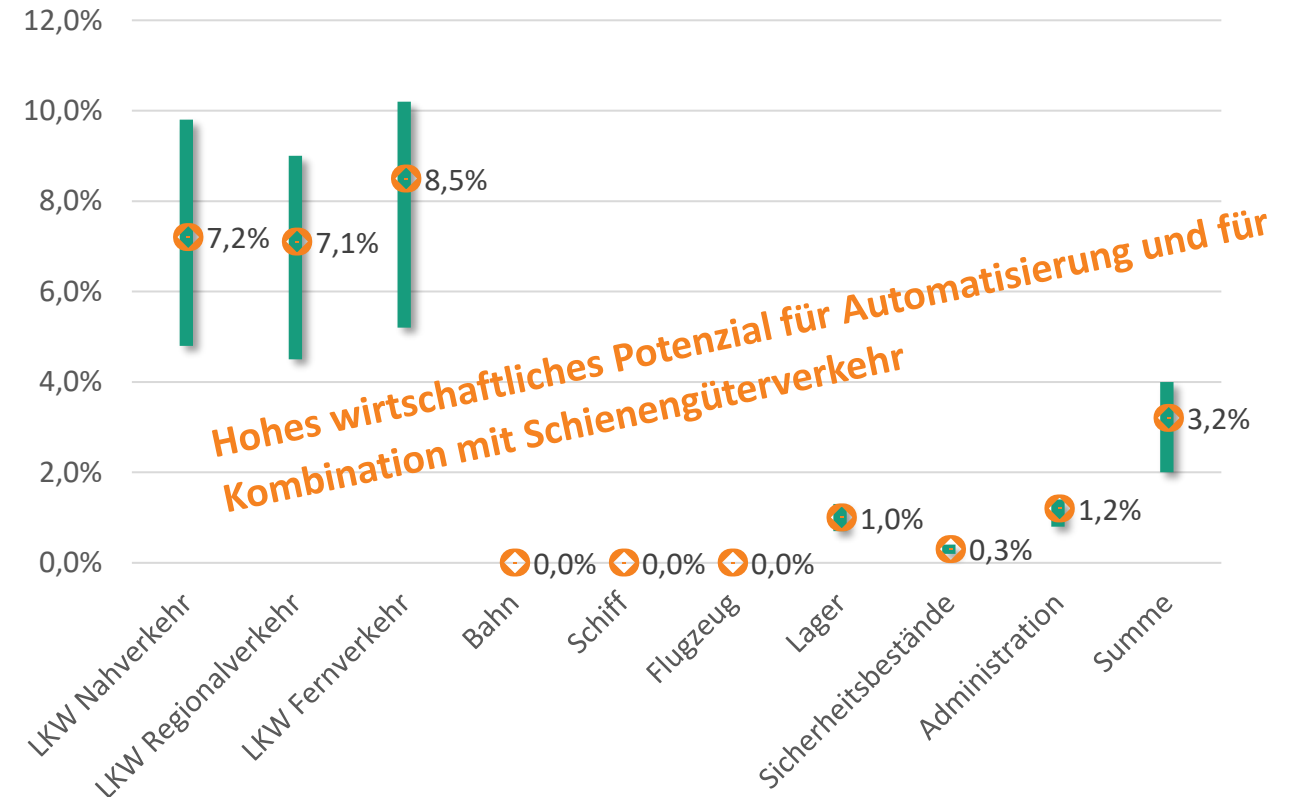
Automatisierung von LKW

Motivation: Fachkräftemangel

Fahrer*innenmangel in Deutschland^[1]



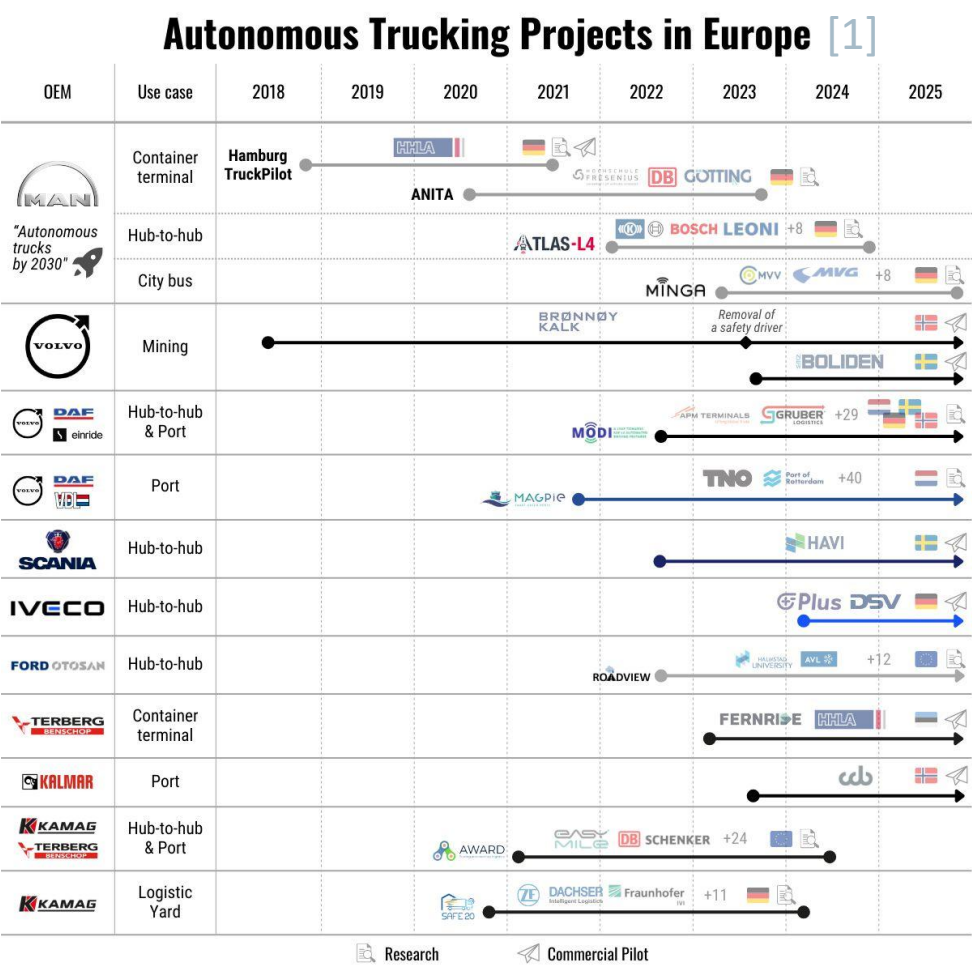
Kostensteigerungen im Bereich Logistik 2022^[1]



[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?



- Zahlreiche Aktivitäten namhafter Hersteller



- 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



Realisierung:

Straße:
Yard/Depot:

Zukunft
seit 2019

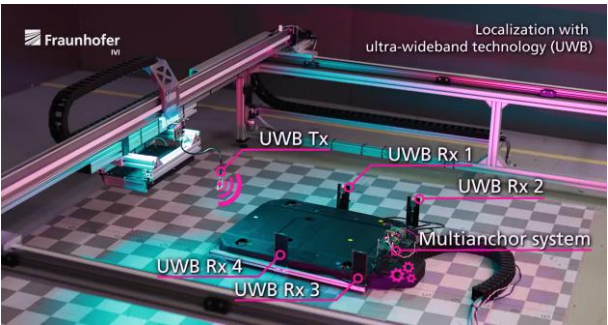
Aktuelle Forschung:

Präzise Rückwärtsfahrregelung, Lokale
Bahnplanung zur Hindernisvermeidung

Projekte:

AutoTruck, SAFE20, MAGPIE, COGNAC,
Feldschwarm

Positionieren



bis 2027

Hochgenaue Positionierung mit
Kameras und UWB

Eigenforschung

Nachladen



Bis 300 kW (Fahrzeug): 2024
> 1000 kW (Labor): 2023

> 1000 kW (Fahrzeug): bis 2027

GUW+, MEGA-LADEN, COGNAC