



dfki Deutsches
Forschungszentrum
für Künstliche
ai Intelligenz
*German Research
Center for Artificial
Intelligence*

Smart Wheelchair with Semi- and Fully Autonomous Navigation

Christian Mandel
Jan Janssen
Maria Angélica Lopez
Serge Autexier

Introduction

- **Smart Wheelchairs: State of the Art**
- **Trustable Robotic Navigation**
- **Project REXASI-Pro**
- **Research Question of this Work**

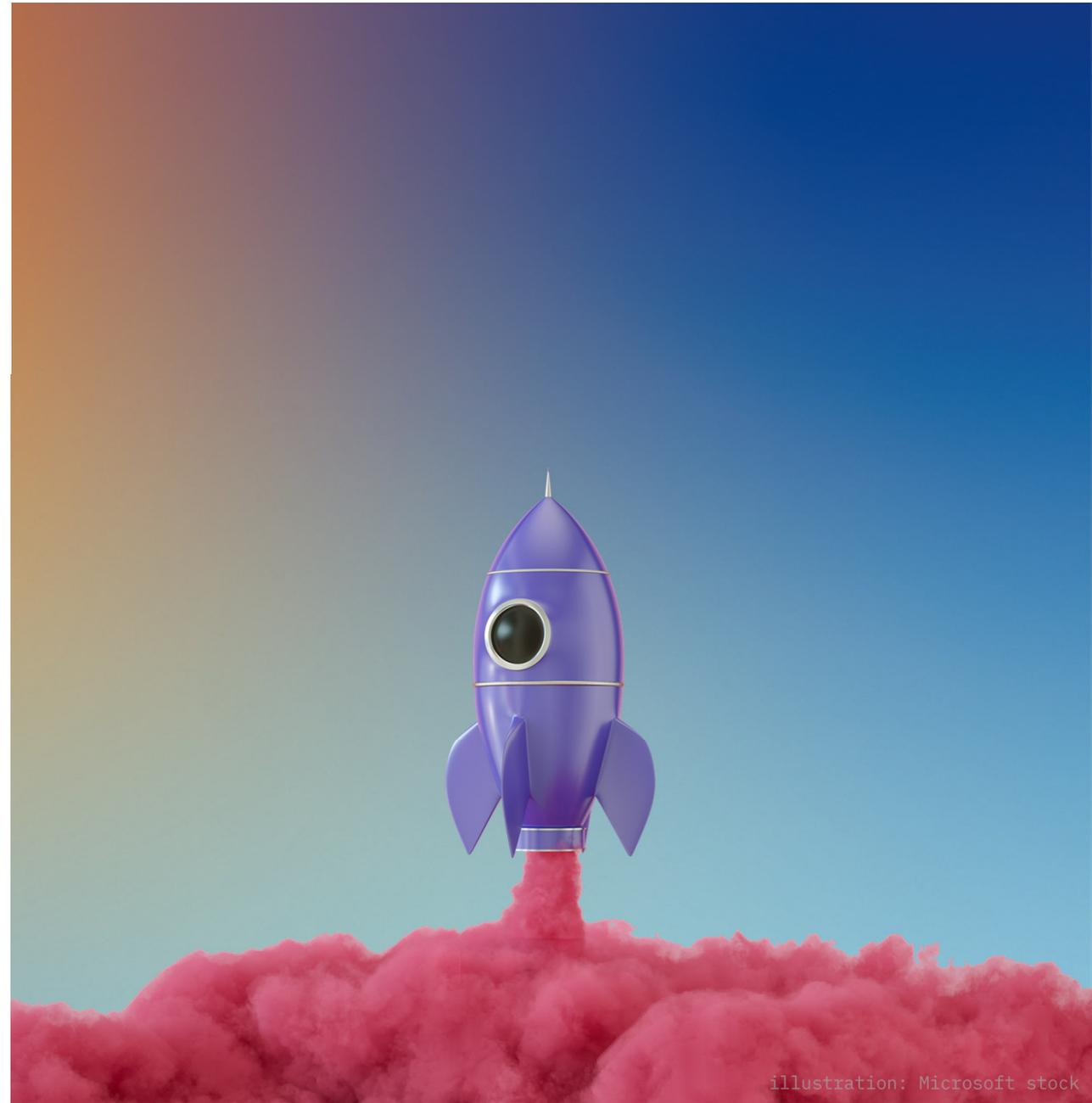


illustration: Microsoft stock

Smart Wheelchairs: State-of-the-Art

- Are developed in research and in industry
- Provide smart support in/for:
 - Compensation
 - Rehabilitation
 - Assessment and Training
- Use techniques such as:
 - User interfaces for special needs
 - Indoor and outdoor localization
 - (Semi-) autonomous navigation
 - Driving assistance systems
- **CoNav Chair** integrates Joystick input into MPC
- **iChair** integrates telemedicine sensors
- **iPW** with contributions from experts during design phase
- **WHILL autonomous wheelchair** developed by Panasonic and whill.inc and tested at several airports, e.g., Tokyo Haneda and Amsterdam Schiphol

Yifan Xu et al. 2025:
CoNav Chair (Shared Control)



Hou et al. 2024: An autonomous
wheelchair with IoT Health Monitoring



Zhang et al. 2021: Smart Wheelchair
design for operation in crowds



whill.inc/ca 2026: Smart wheelchair
operating at Schiphol airport, Ams.





- Work presented today is part of EU-funded project REXASI PRO (2022-2025)
- Overall goal of REXASI PRO: Design of trustable solutions for social robotic navigation
- Methods used in REXASI PRO:
 - DNN-based navigation vs. classical planning
 - Verification of functionality and safety
 - Orchestration of wheelchair, cameras and drones
 - Technical investigations and user study with 52 subjects



Daitek

**Consiglio Nazionale
delle Ricerche**

**dfki
ai**

**EURONET
CONSULTING**

**HOVERING
solutions**

**KING'S
College
LONDON**

spinóox.LABS

SIEMENS

Scuola universitaria professionale
della Svizzera italiana

SUPSI

**UNIVERSIDAD DE SEVILLA
U**

V-ReseArch

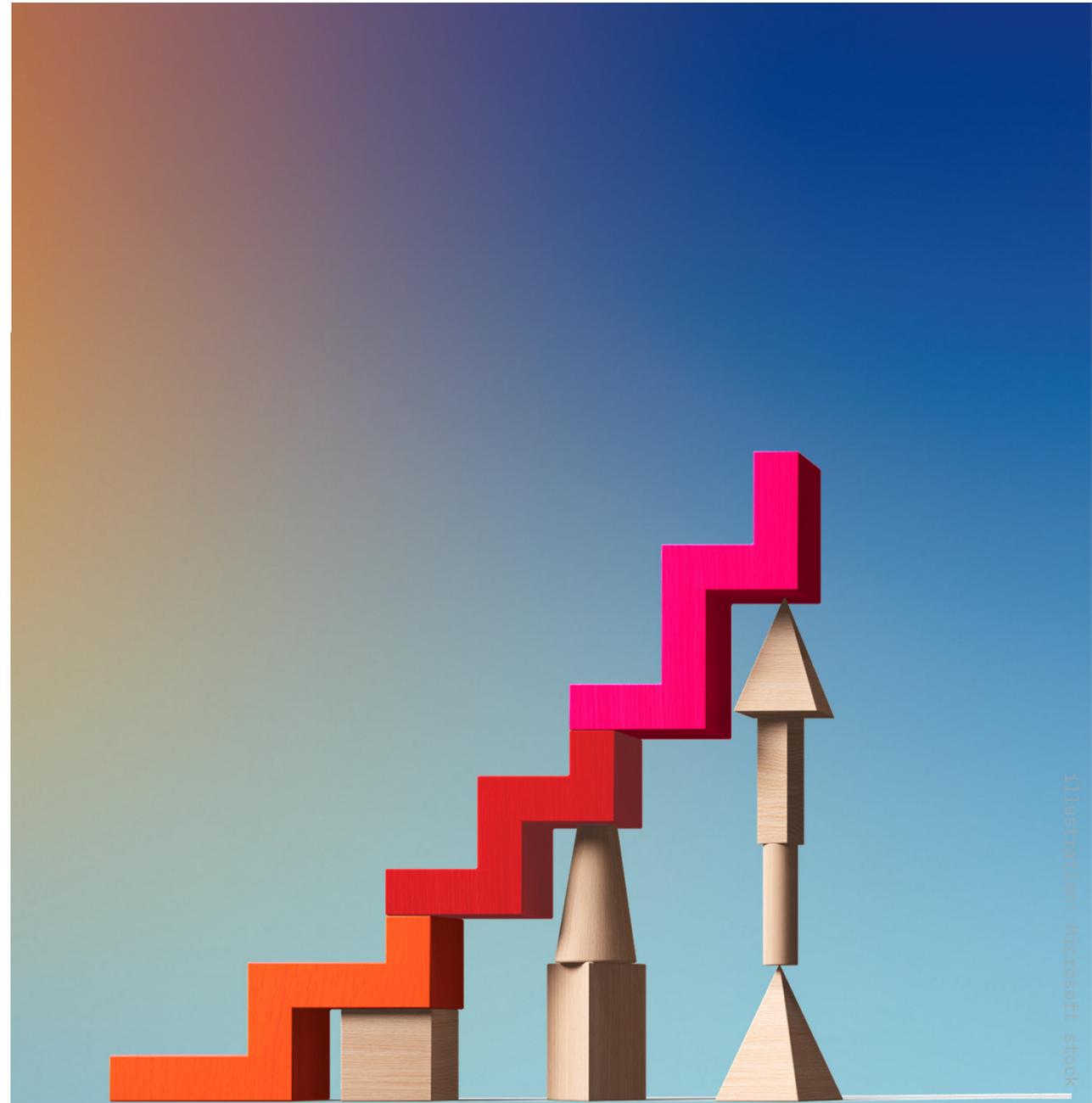
Research Question of this Work

Given the smart wheelchairs from project RexasiPro:

1. How do drivers and people in the surrounding area assess the overall system under fully autonomous and semi-manual driving conditions in busy indoor spaces?
2. What does the evaluation of the technical performance parameters show?

System Design

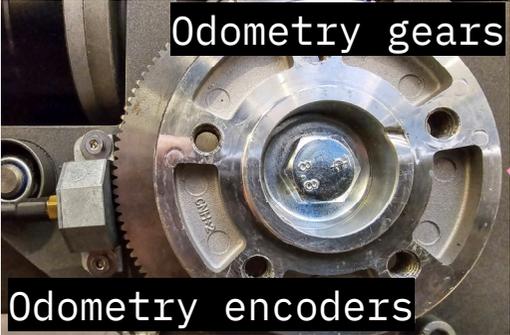
- Wheelchair Hardware
- 2D Driving Assistant (Baseline)
- 3D Driving Assistant (Extension)
- ROS2/NAV2-based Navigation Stack
- Human Machine Interface



Wheelchair Hardware



Right RGBD-Camera



Odometry gears

Odometry encoders



Front Lidar



Left RGBD-Camera

Emergency Stop



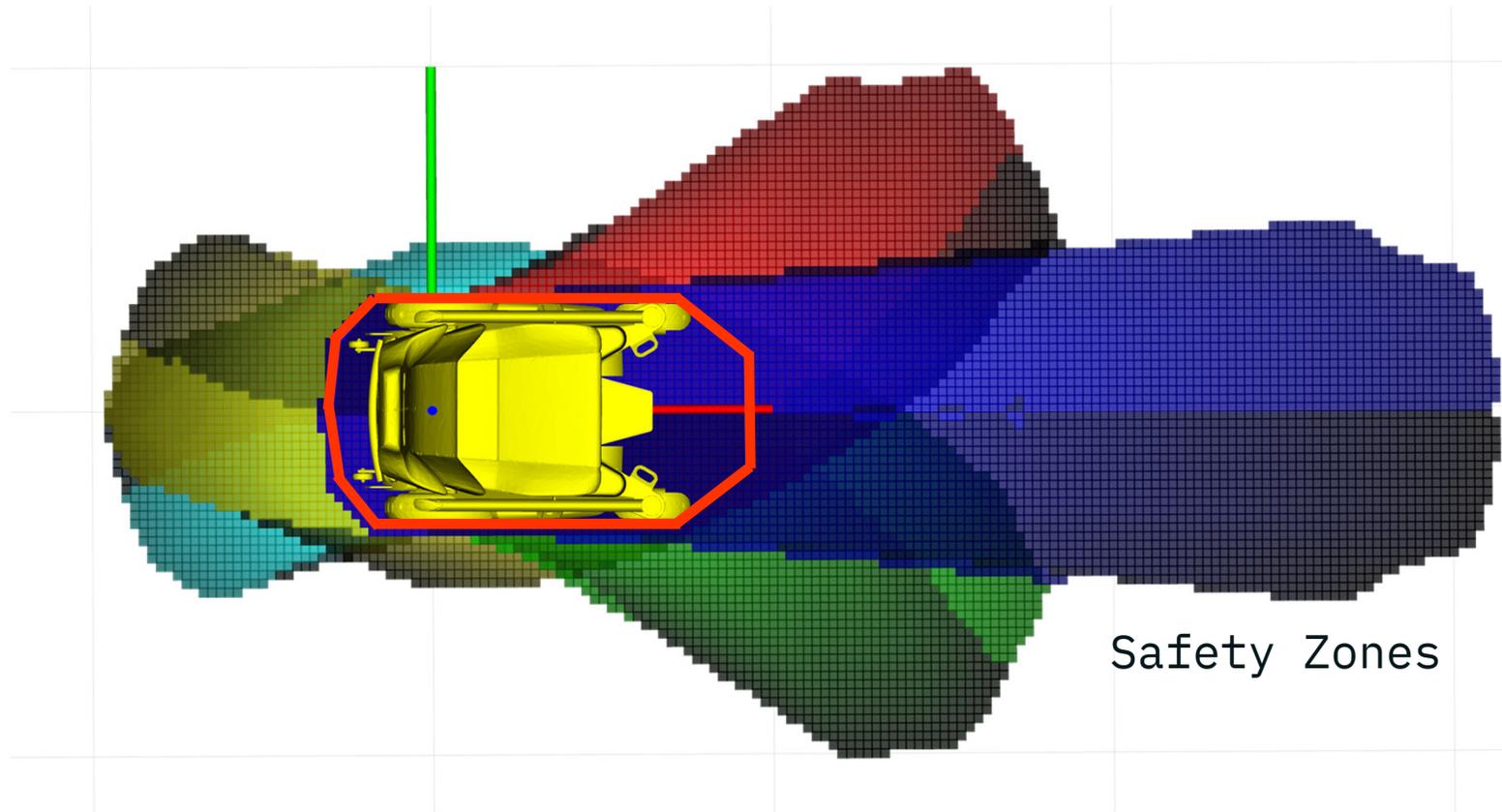
Jetson Orin NX 16GB



Rear Lidar

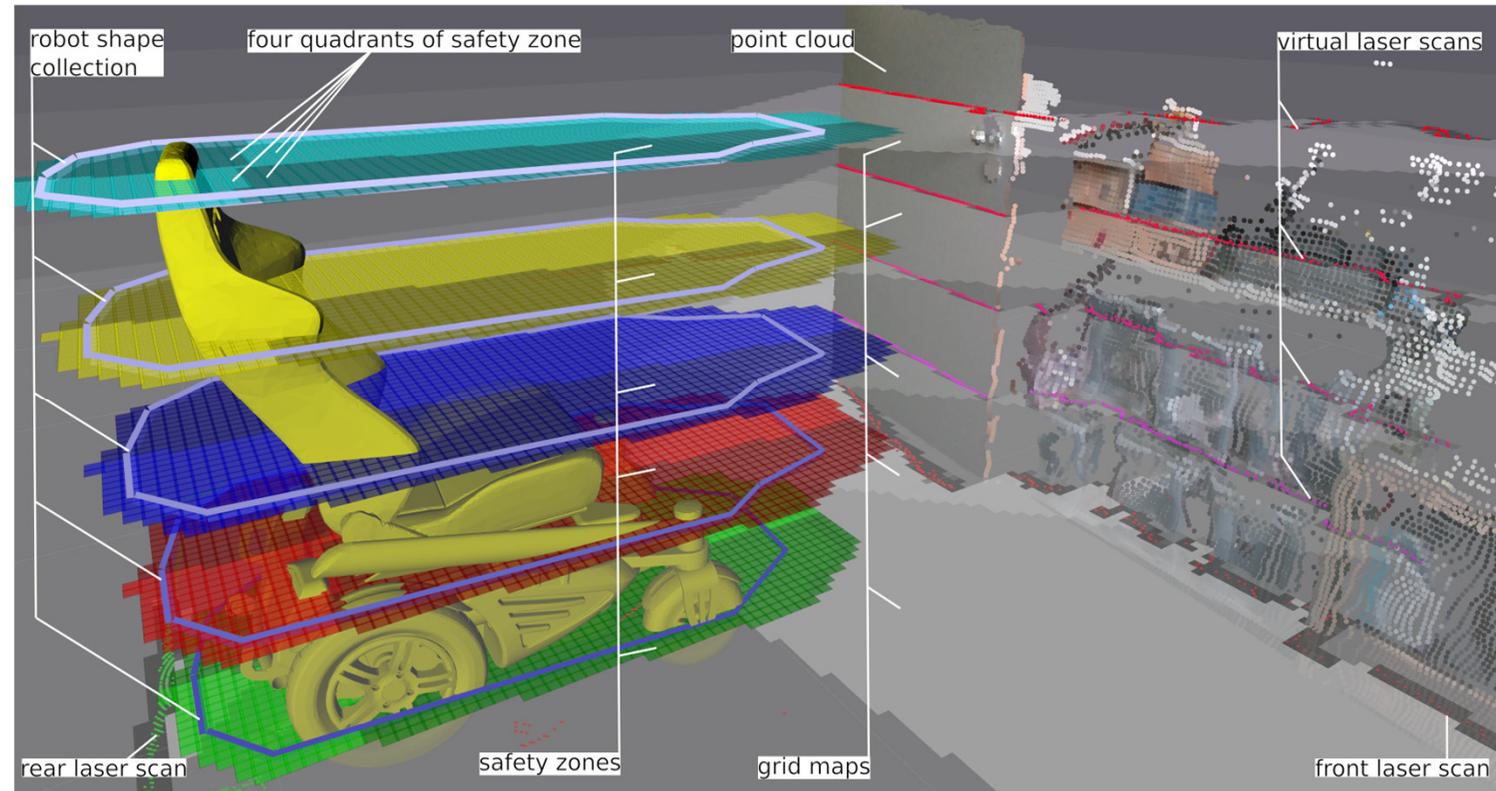
2D Driving Assistant (Baseline)

- **Purpose:** Safeguard driving commands (human & computer)
- **Approach:** realtime collision checks with safety zones over obstacle maps
- **Tool:** Safety zones determined by:
 - Kinematic wheelchair properties
 - Bounding shapes
 - Current velocities
 - Current driving command
 - Modeled velocity uncertainty
- **Avoidance strategy:**
 - Obstacle in bright area → steer towards dark region
 - If not possible → stop in time



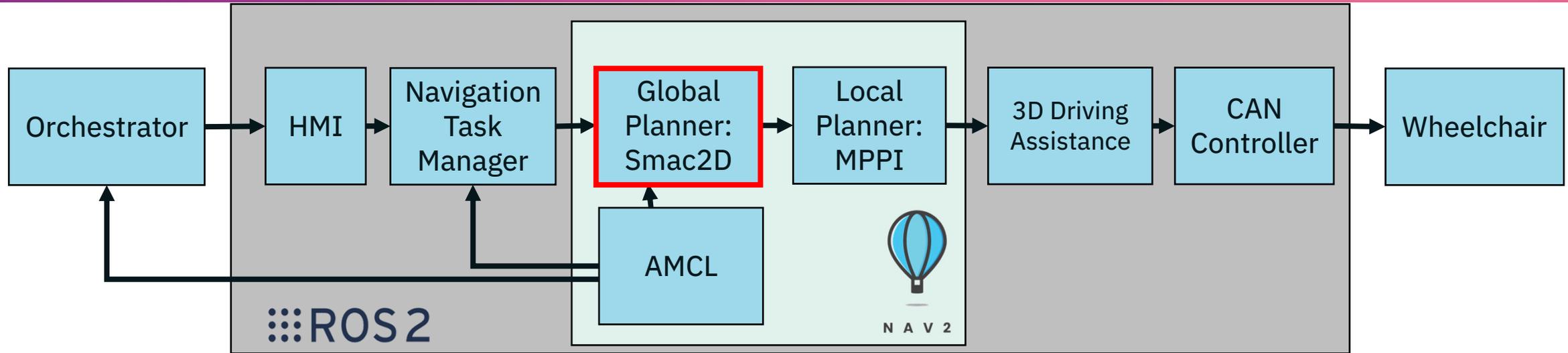
3D Driving Assistant (Extension)

- **General idea:** Stack robot shapes and safety zones along height-axis of wheelchair
- **Keep** grid map from LiDAR data
- **Add** representations:
 - virtual scans and maps describing flattened point cloud volumes
 - traversability map describing holes in the ground
- **Algorithmic approach:**
 - Incrementally check safety zones against maps for collisions
 - Combine obstacles of each safety zone and calculate avoidance direction as in 2D

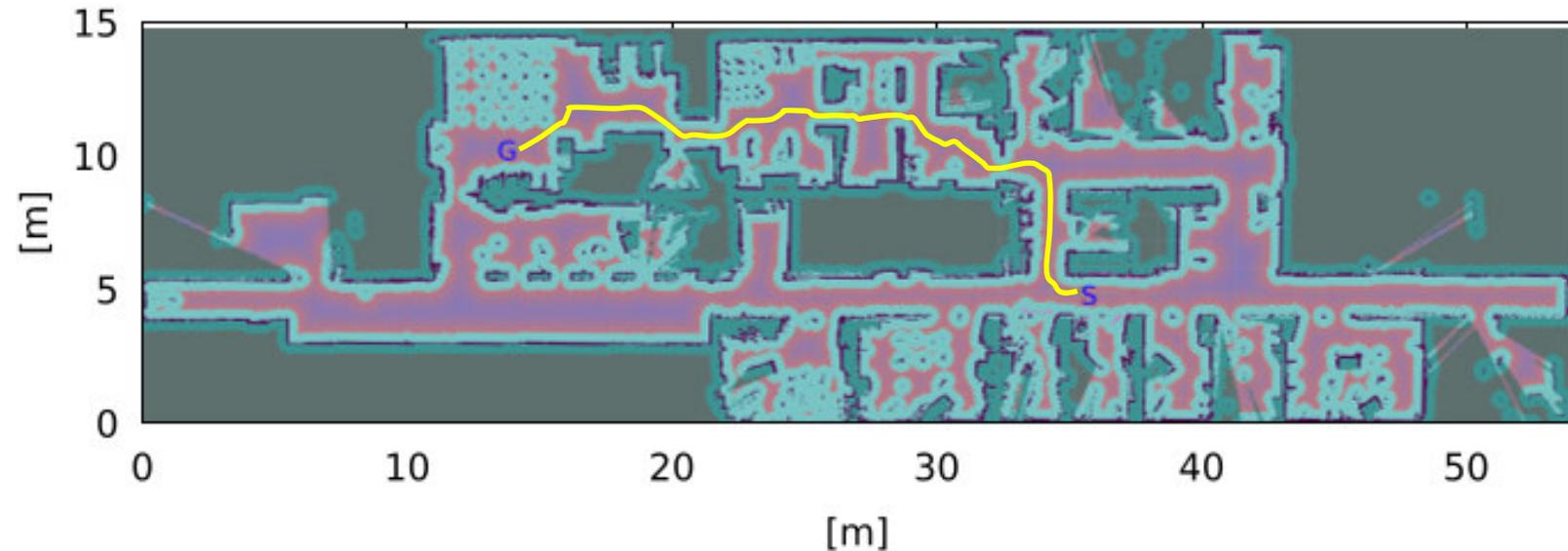


3DDA Percepts and State Representations

ROS2/NAV2-based Navigation Stack (I)

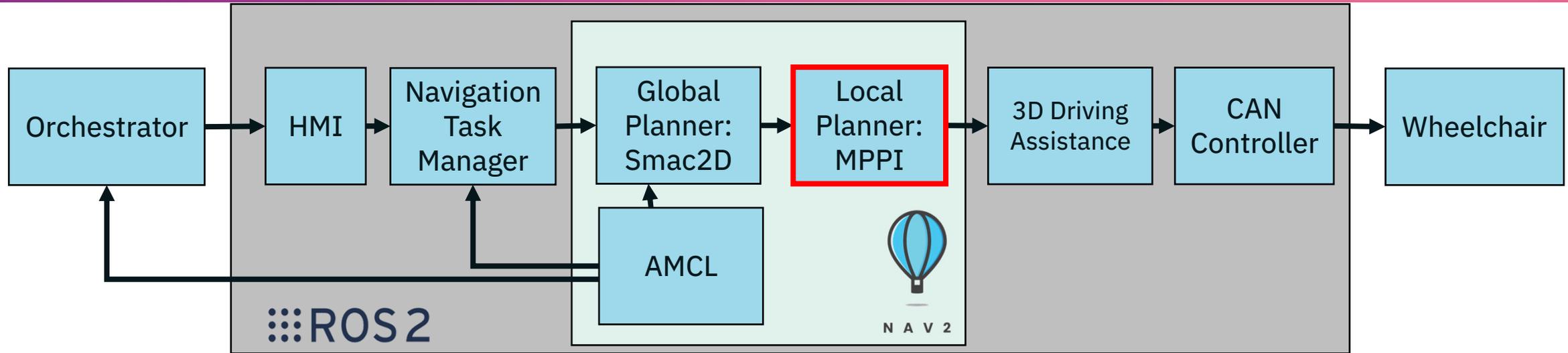


- Global path planning on occupancy grids and costmaps
- Cost-aware holonomic A* algorithm
- Uses orientation θ during planning
- Solution can be smoothed before being executed

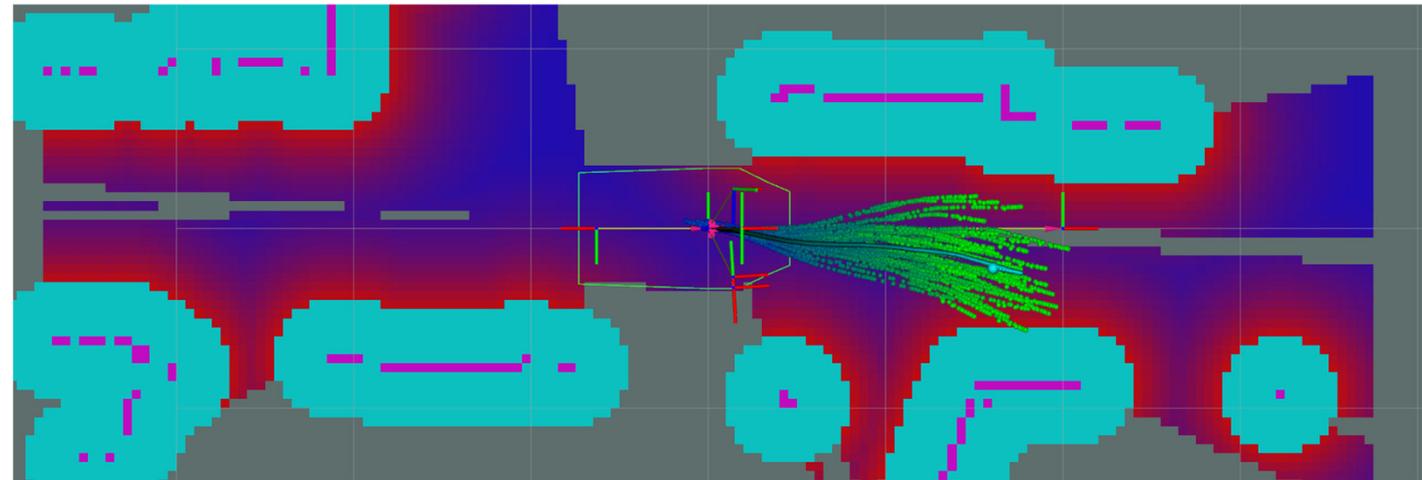


Global Path Planned in SLAM-Map

ROS2/NAV2-based Navigation Stack (II)

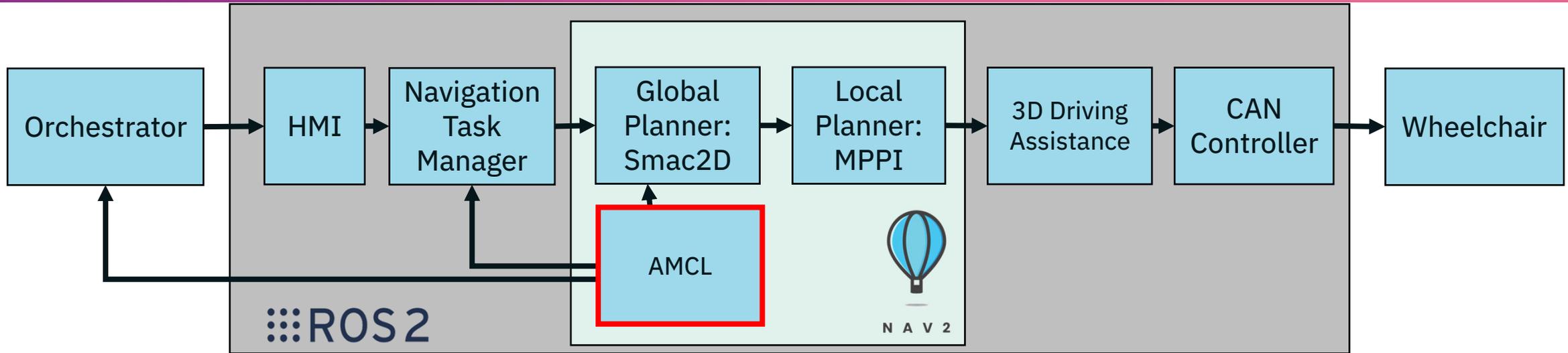


- Trajectory rollout (we use 375 up to 1.68s)
- Model predictive control
- Obstacle avoidance on cost grids
- From simple to complex collision checks
- Critics (the core of MPPI) w.r.t. goal, obstacles, path alignment, ...



MPPI Trajectory Bundle

ROS2/NAV2-based Navigation Stack (III)



- Probabilistic robot localization
- Particle filter-based approach
- Motion model prediction
- Sensor model update
- Adaptive resampling
- Global localization & recovery



AMCL Particle Set

Human Machine Interface

- Primarily based on natural spoken language
 - **STT** relies on “*Whisper*”, i.e., a transformer-based encoder-decoder model
 - **NLU** relies on “*Rasa*”, i.e., a natural language understanding module to be trained on intents and sentences used in the application domain
 - **TTS** relies on “*OpenTTS*”
- To connect HMI’s input and output options, keypress-based *Streamdeck Mini* has been integrated
- Key functionalities:
 - Start/stop manual driving (with & without 3DDA)
 - Activation of autonomous navigation
 - Selection of target node
 - Stopping of wheelchair
 - Start/stop recording of system data
 - Shutdown/restart of wheelchair (ROS2) stack
 - User voice profile creation & user recognition (relies on open-source **PyTorch-toolkit** “*speechbrain*”)



Headset



StreamDeck Mini Key-Interface

Experimental Evaluation

- **Recruitment**
- **Experiment Phases**
 - **Introduction & Training**
 - **Investigation**
- **Analysis**
 - **Driven Trajectories**
 - **Interventions of 3D Driving Assistance**
 - **Runtime Performance**
 - **User Experience Questionnaire**
 - **Godspeed Questionnaire**



illustration: Microsoft stock

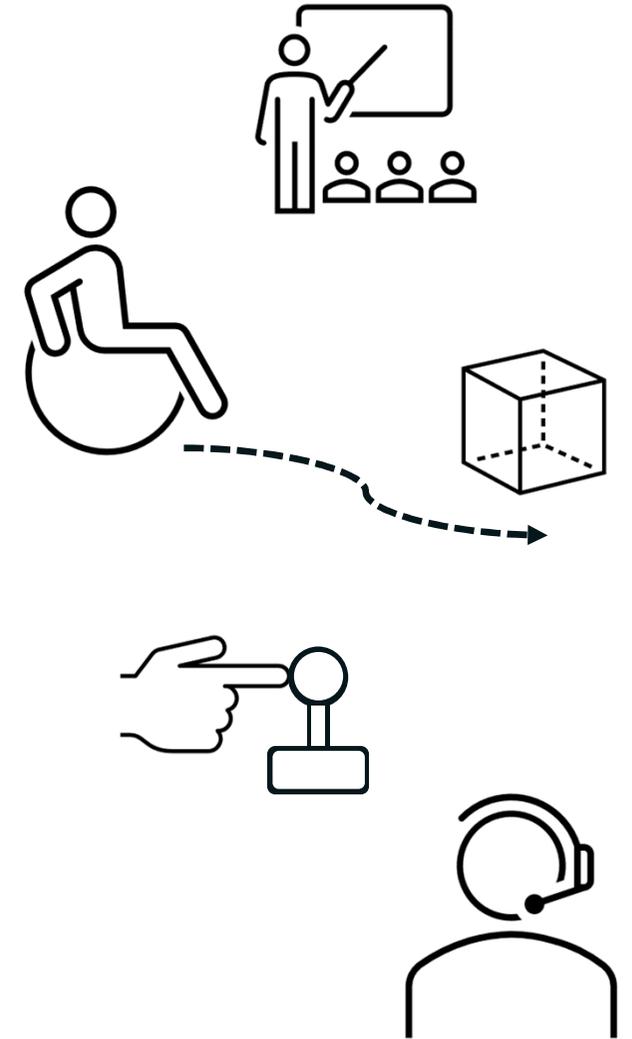
Recruitment

- Participants were recruited by project partners in Genoa, Italy, in collaboration with local stakeholders.
- Recruitment was supported and supervised by neuro-rehabilitation experts from the NeMO Clinical Center (Arenzano/Genoa).
- Familiarity with robotics (all subjects):
 - $\mu = 3.23, \sigma^2 = 1.24$ (5-point Likert)
 - Indicates moderate prior exposure to robotic systems
- Familiarity with wheelchairs (drivers only):
 - $\mu = 2.69, \sigma^2 = 2.23$ (5-point Likert)
 - Reflects heterogeneous experience levels among drivers
- Ethical compliance:
 - All participants provided informed consent prior to the study, covering: objectives, planned activities and relevant safety information

role	age	female male
Wheelchair driver	18-25	- 1
Wheelchair driver	26-40	5 5
Wheelchair driver	41-50	1 2
Wheelchair driver	51-60	- 2
		$\Sigma = 16$
Crowd	18-25	5 8
Crowd	26-40	8 15
Crowd	41-50	- -
Crowd	51-60	- -
		$\Sigma = 36$

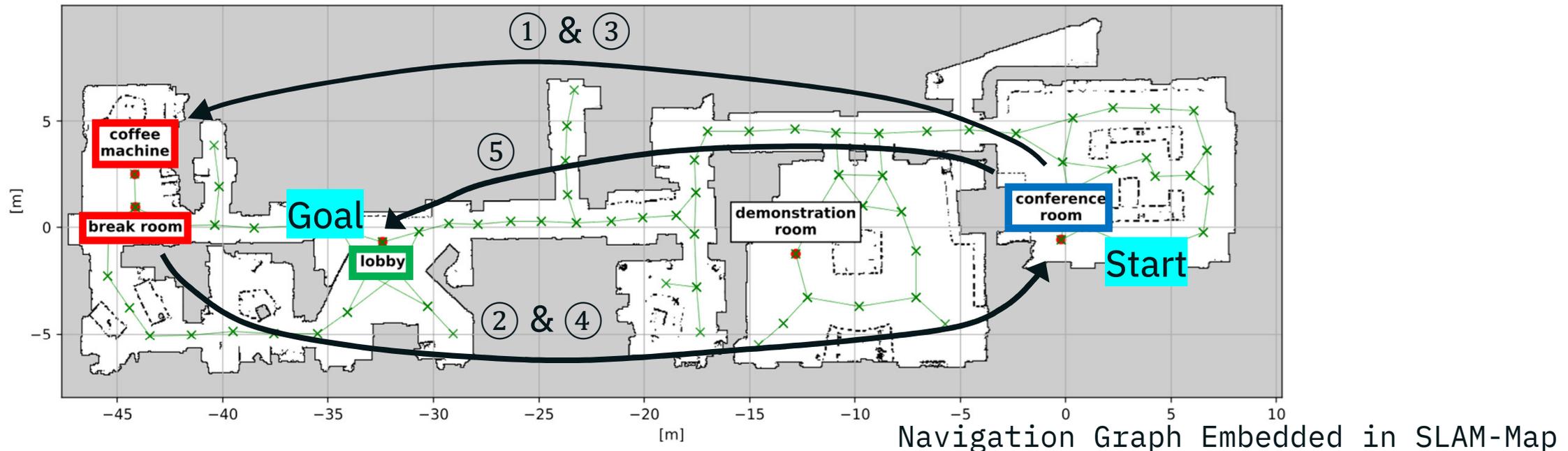
Introductory & Training Phase

- Goal: enable participants to
 - operate semi-autonomous driving mode
 - select destinations on map by using voice commands
- Brief introduction to wheelchair, sensors and capabilities
- Train use of semi-autonomous driving mode with Joystick and 3DDA by:
 - Drive simple loops within a predefined area
 - Introduce basic cardboard-box as static obstacles
- Train use of fully autonomous navigation by:
 - Activate drive-mode on the StreamDeck keypad
 - Verbally specify named destination from navigation graph on screen
 - Confirm selected target on the StreamDeck keypad
 - Use a deflected joystick as a *deadman switch* to allow participants to interrupt navigation at any time



Investigation Phase

- Conduct experiments with two identical wheelchair systems
- Study began with subject seated in wheelchair at **conference room**, then:
 - ① autonomous navigation → **coffee machine / break room** (no crowd)
 - ② joystick driving (+3DDA) → **conference room** (no crowd)
 - ③ autonomous navigation → **coffee machine / break room** (crowd accompanies wheelchair)
 - ④ autonomous navigation → **conference room** (stationary crowd at lobby)
 - ⑤ autonomous navigation → **lobby** (crowd coming towards wheelchair)



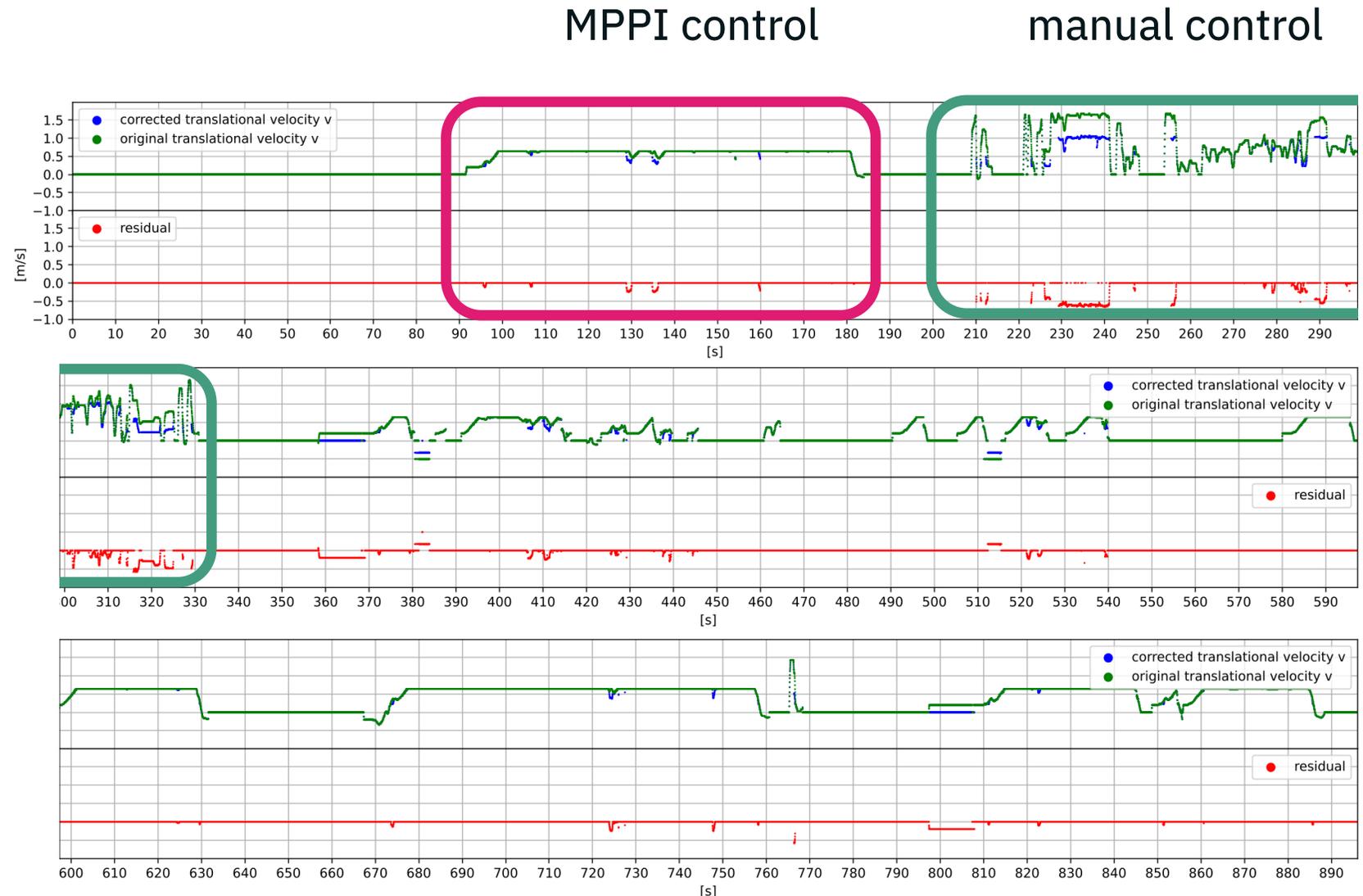
Analysis: Driven Trajectories

- **Observed:** Trajectories concentrate in narrow corridors
 - **Implication:** Obstacle avoidance effectively prevented from collisions with static obstacles
- **Observed:** Some complex evasive maneuvers at critical points
 - **Implication:** The system performed collision avoidance with dynamic obstacles when required



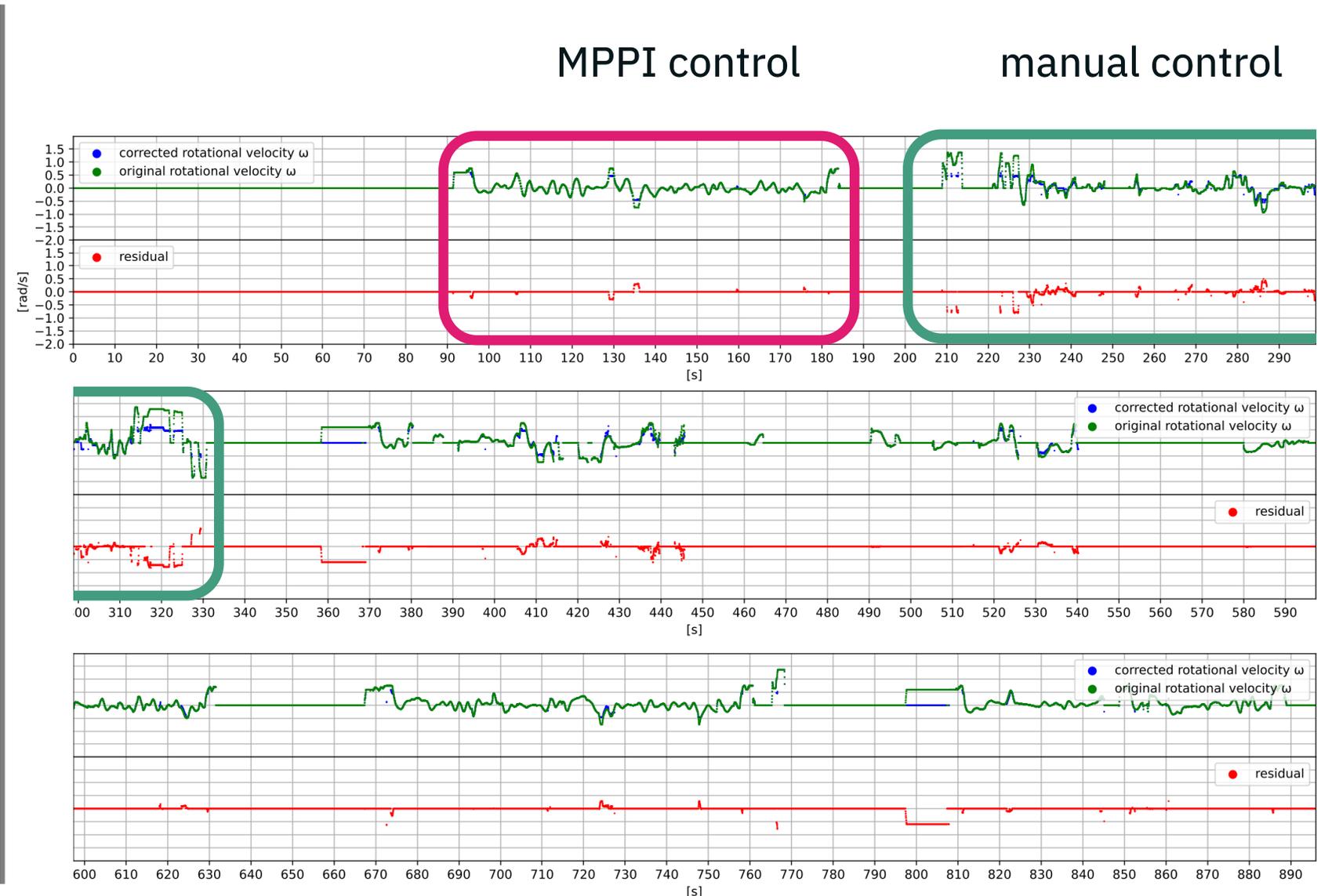
Analysis: Interventions of 3D Driving Assistant (v)

- Clearly distinguishable system behavior between manual and algorithmic control
- MPPI is well configured so that the 3DDA rarely needs to intervene.
- In manual control, this case shows a frequent change in the commanded translational speed.



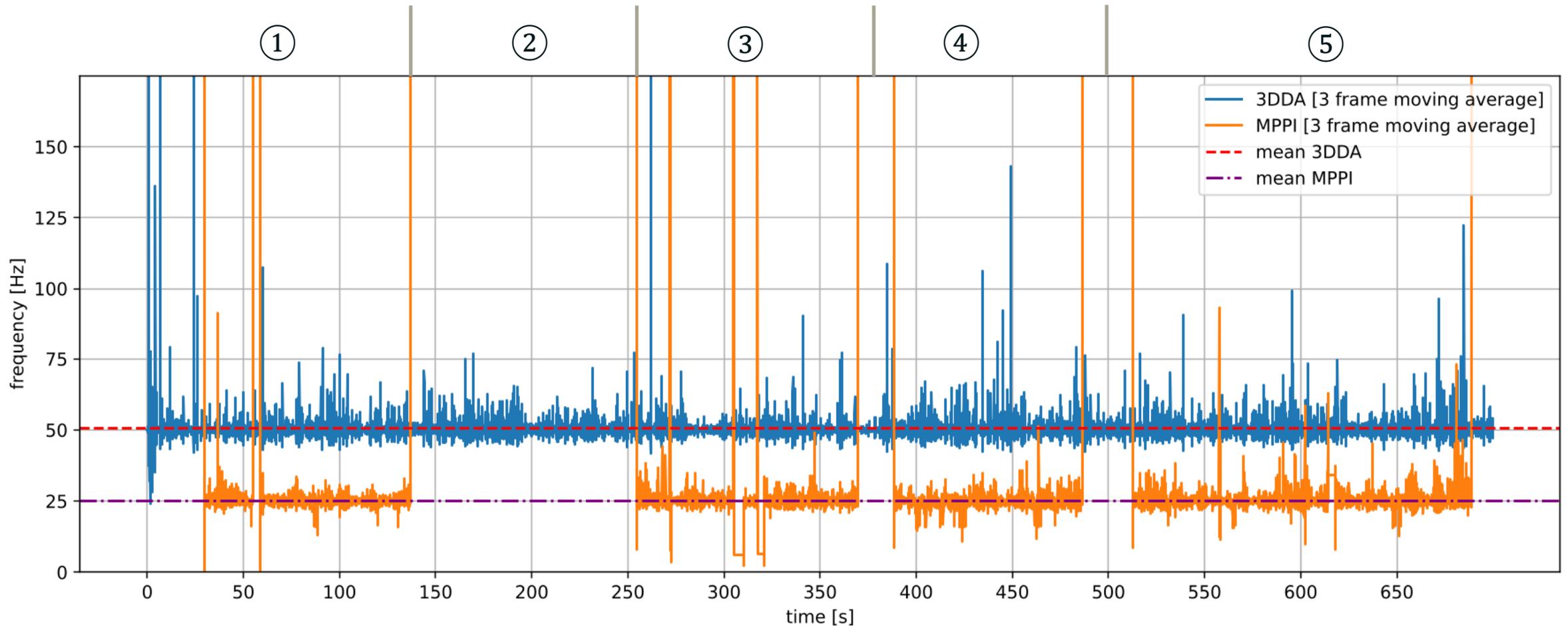
Analysis: Interventions of 3D Driving Assistant (ω)

- Distinguishable system behavior between manual and algorithmic control
- MPPI is well configured so that the 3DDA needs less interventions



Analysis: Runtime Performance

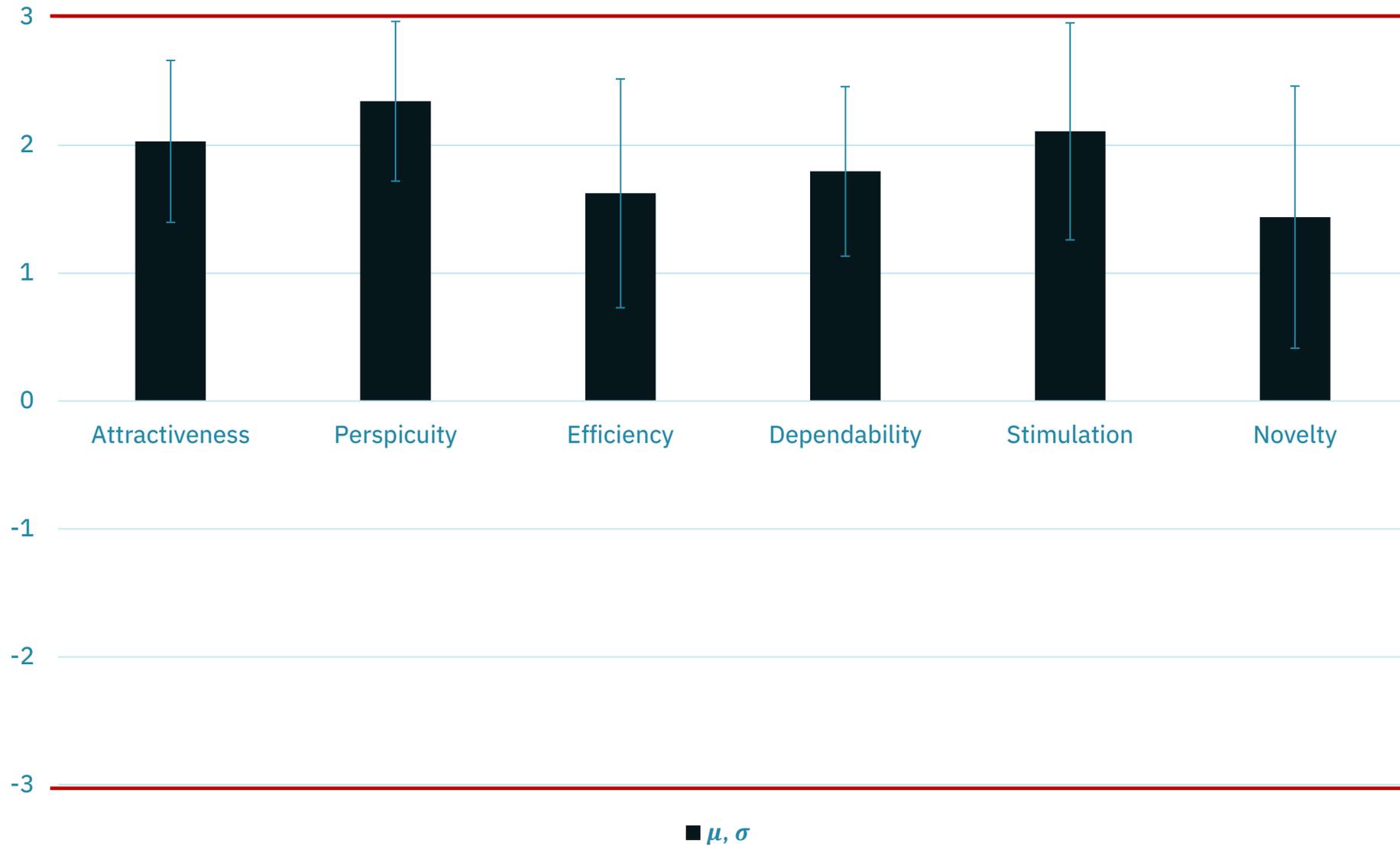
- Target frequencies of MPPI (25Hz) and 3DDA (50Hz) are consistently achieved on Jetson Orin NX 16GB with proper configuration



Analysis: User Experience Questionnaire I

#	Quality from	-3	-2	-1	0	1	2	3	Quality to	UEQ-Scale	μ	σ^2	#	Quality from	-3	-2	-1	0	1	2	3	Quality to	UEQ-Scale	μ	σ^2
1	annoying	0	0	0	0	0	0	0	enjoyable	Attractiveness	2.2	0.4	14	unlikeable	0	0	0	0	0	0	0	pleasing	Attractiveness	1.8	1.1
2	not understandable	0	0	0	0	0	0	0	understandable	Perspiciuity	2.5	0.5	15	usual	0	0	0	0	0	0	0	leading edge	Novelty	1.0	1.9
3	creative	0	0	0	0	0	0	0	dull	Novelty	1.4	2.3	16	unpleasant	0	0	0	0	0	0	0	pleasant	Attractiveness	2.1	0.7
4	easy to learn	0	0	0	0	0	0	0	difficult to learn	Perspiciuity	2.5	0.5	17	secure	0	0	0	0	0	0	0	not secure	Dependability	2.4	0.5
5	valuable	0	0	0	0	0	0	0	inferior	Stimulation	2.4	0.7	18	motivating	0	0	0	0	0	0	0	demotivating	Stimulation	2.1	1.0
6	boring	0	0	0	0	0	0	0	exciting	Stimulation	1.6	1.6	19	meets expectations	0	0	0	0	0	0	0	does not meet expectations	Dependability	1.8	1.2
7	not interesting	0	0	0	0	0	0	0	interesting	Stimulation	2.4	1.2	20	inefficient	0	0	0	0	0	0	0	efficient	Efficiency	2.0	0.8
8	unpredictable	0	0	0	0	0	0	0	predictable	Dependability	1.2	1.1	21	clear	0	0	0	0	0	0	0	confusing	Perspiciuity	2.4	0.4
9	fast	0	0	0	0	0	0	0	slow	Efficiency	0.5	1.9	22	impractical	0	0	0	0	0	0	0	practical	Efficiency	2.0	1.6
10	inventive	0	0	0	0	0	0	0	conventional	Novelty	1.4	2.8	23	organized	0	0	0	0	0	0	0	cluttered	Efficiency	2.0	0.8
11	obstructive	0	0	0	0	0	0	0	supportive	Dependability	1.8	1.5	24	attractive	0	0	0	0	0	0	0	unattractive	Attractiveness	1.8	1.9
12	good	0	0	0	0	0	0	0	bad	Attractiveness	2.4	0.8	25	friendly	0	0	0	0	0	0	0	unfriendly	Attractiveness	1.9	1.1
13	complicated	0	0	0	0	0	0	0	easy	Perspiciuity	2.0	0.7	26	conservative	0	0	0	0	0	0	0	innovative	Novelty	2.0	0.8

Analysis: User Experience Questionnaire II

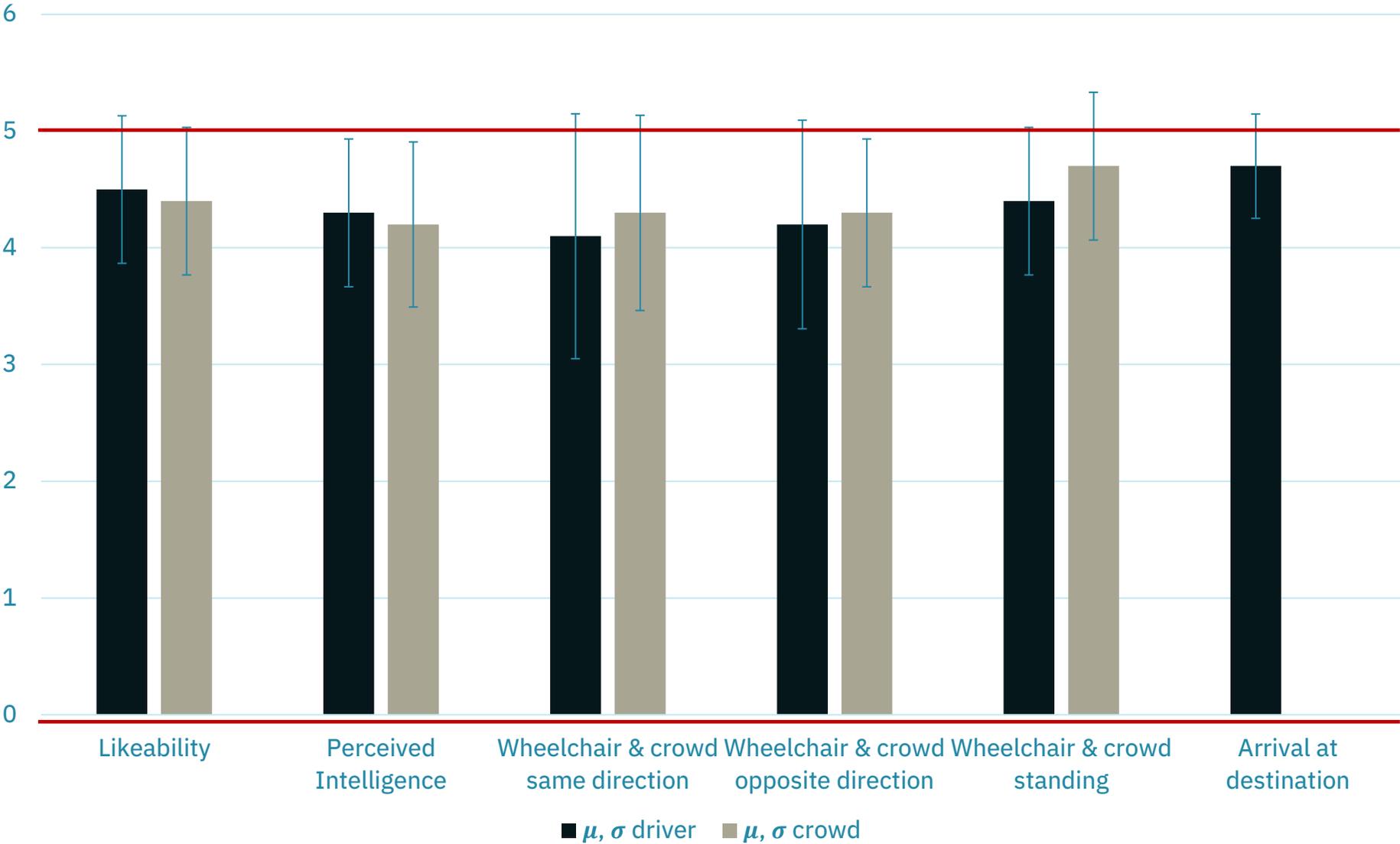


Distributions of UEQ-Scales

Analysis: Godspeed Questionnaire I

#	Quality from	1	2	3	4	5	Quality to	Godspeed-Scale	driver		crowd		#	Quality from	1	2	3	4	5	Quality to	driver		crowd	
									μ	σ^2	μ	σ^2									μ	σ^2	μ	σ^2
1	Dislike	0	0	0	0	0	Like	Likeability	4.8	0.2	4.6	0.4												
2	Unfriendly	0	0	0	0	0	Friendly	Likeability	4.6	0.3	4.3	0.4	11	Very Poorly	0	0	0	0	0	Very Well	4.1	1.1	4.3	0.7
3	Unkind	0	0	0	0	0	Kind	Likeability	4.4	0.9	4.3	0.4												
4	Unpleasant	0	0	0	0	0	Pleasant	Likeability	4.4	0.3	4.3	0.6	12	Very Poorly	0	0	0	0	0	Very Well	4.2	0.8	4.3	0.4
5	Awful	0	0	0	0	0	Nice	Likeability	4.6	0.3	4.5	0.4												
6	Incompetent	0	0	0	0	0	Competent	Perceived Intelligence	4.3	0.3	4.3	0.4	13	Very Poorly	0	0	0	0	0	Very Well	4.4	0.4	4.7	0.4
7	Ignorant	0	0	0	0	0	Knowledgeable	Perceived Intelligence	4.1	0.9	4.3	0.6												
8	Irresponsible	0	0	0	0	0	Responsible	Perceived Intelligence	4.6	0.3	4.3	0.6	14	Never	0	0	0	0	0	Always	4.7	0.2		
9	Unintelligent	0	0	0	0	0	Intelligent	Perceived Intelligence	4.5	0.4	4.1	0.6												
10	Foolish	0	0	0	0	0	Sensible	Perceived Intelligence	4.4	0.4	4.3	0.5												

Analysis: Godspeed Questionnaire II



Distributions of Godspeed-Scales & add. Questions

Conclusions

- **Assessment**
 - **User Experience (RQ1)**
 - **Technical Performance (RQ2)**
- **Future Works**

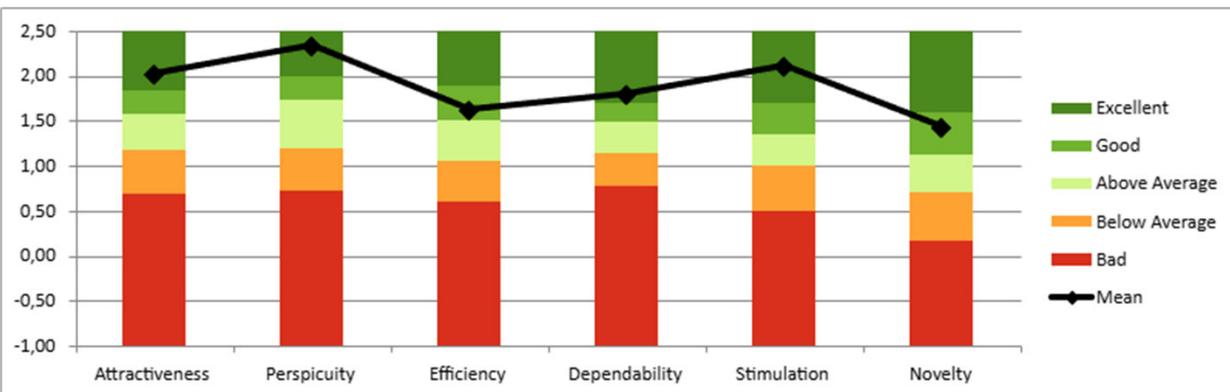


illustration: ChatGPT 5.2

Assessment (RQ1): User Experience

Pro

- UEQ: across all dimensions the system received a **very positive evaluation** ($\mu > 0.8$)^[1]
- UEQ: Compared to benchmark dataset of 21k participants in 468 studies:^[2]
 - *Attractiveness, Perspicuity, Dependability* and *Stimulation* ranked in top 10%
 - *Efficiency* and *Novelty* ranked in top 25%



Con

- UEQ: Some participants described wheelchair movement as being generally **too slow**
- UEQ: Some participants described robotic solution as being **outdated**, which may have affected their overall impression of the system
- Godspeed: Some participants felt being **impeded** by crowd walking same direction

[1] Laugwitz, B. et al. (2008). Construction and evaluation of a user experience questionnaire. In: Holzinger, A. (Ed.): USAB 2008, LNCS 5298, pp. 63-76.

[2] Schrepp et al. (2017). Construction of a benchmark for the User Experience Questionnaire (UEQ). International Journal of Interactive Multimedia and Artificial Intelligence, Vol. 4, No. 4, pp. 40-44.

Assessment (RQ2): Technical Readiness & Limitations

Pro

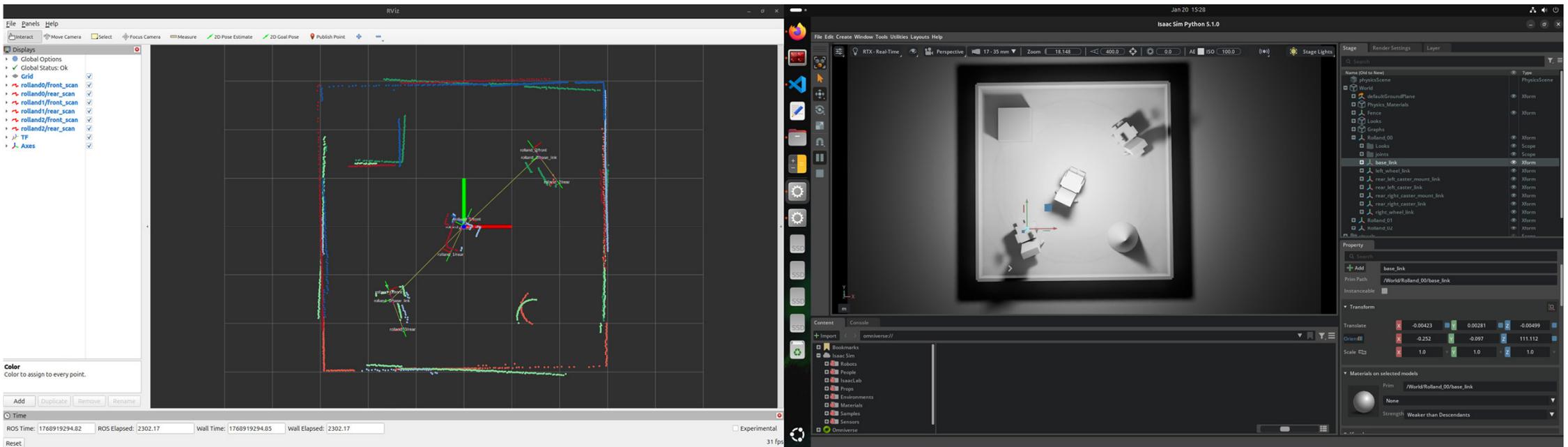
- Medium-sized **compute hardware sufficient** for 3D Driving Assistant, global and local path planning, and spoken natural language UI
- Experimental evaluation demonstrates **reliable collision avoidance** with both static and dynamic obstacles under manual and autonomous control.
- ROS2/NAV2 combined with a carefully tuned MPPI controller provides a **robust and deployable foundation** for indoor autonomous wheelchair navigation.

Con

- The current system does not yet include **semantic human tracking**; therefore, people and static obstacles are handled equivalently, limiting socially-aware navigation behavior.
- Consumer-grade **RGB-D sensors** show limitations under strong direct sunlight, motivating multi-modal outdoor perception strategies.
- For outdoor usage, hole-in-the-ground detection and **traversable area classification** needs a more integrated approach

Future Works

- Replace MPPI-based local navigation with a Deep Neural Network (DNN)
 - **Goal:** Enable more socially appropriate interaction with people in the environment
 - **Problem:** A first imitation-learning attempt trained on ~35 hours of real-world data did not achieve the stability required for prolonged real-world deployment
 - **Proposed approach:** Use multi-robot reinforcement learning to increase data diversity and robustness



Multi-robot reinforcement learning in Isaac Sim / Lab



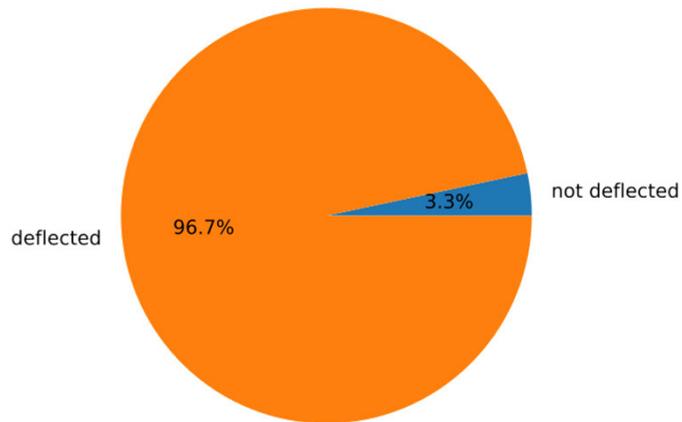
dfki
ai
Deutsches
Forschungszentrum
für Künstliche
Intelligenz
*German Research
Center for Artificial
Intelligence*

**Thank You for
Your Attention**

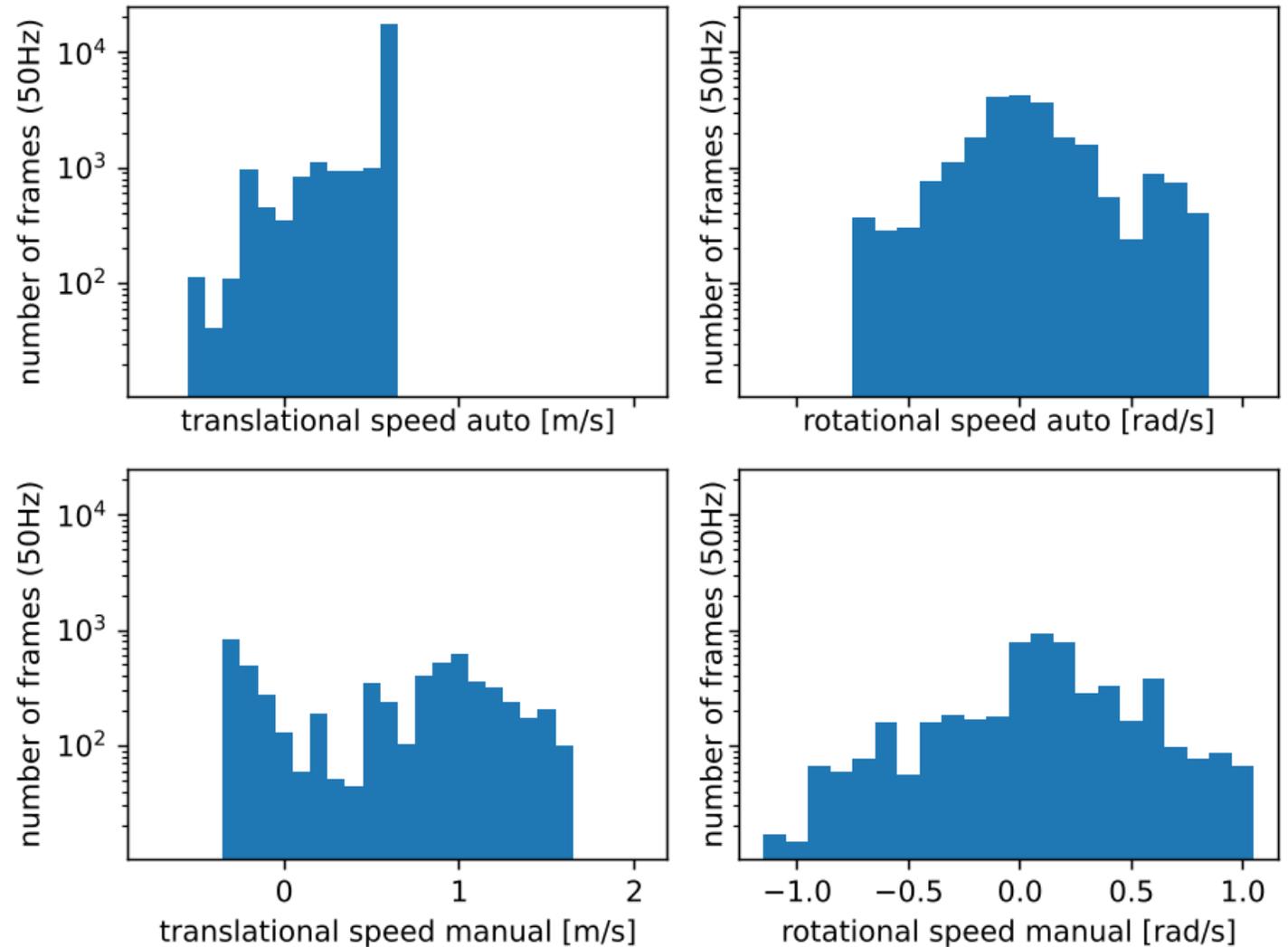
Christian Mandel, Jan Janssen, Maria Angélica Lopez, Serge Autexier

Appendix I: Commanded Velocities & Trust in Autonomy

- Narrow band of commanded translational and rotational velocities in automatic mode → due to MPPI configuration
- Ratio of dead man switch deflection during automatic mode reflects participants' trust in system



Dead Man Switch Deflection (Autonomous Mode)



Velocity Histograms