Széchenyi Terv Plusz Építsük együtt Magyarországot!

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AUTONÓM RENDSZEREK
Nemzeti Laboratórium

BEYOND CONTROL. INTO AUTOMATED FUTURE.

NATIONAL LABORATORY FOR AUTONOMOUS SYSTEMS

PROFESSIONAL REPORT

The project was implemented with the support of the European Union, within the framework of RRF-2.3.1-2021 "Establishment and complex development of National Laboratories".

NEMZETI LABORATÓRIUM

HUN REN SZTAKI

MŰEGYETEM 1782

SZÉCHENYI EGYETEM UNIVERSITY OF GYŐR

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THE PROJECT

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Duration: 20th September 2021 to 28th February 2026

Members of consortium: HUN-REN Institute for Computer Science and Control (HUN-REN SZTAKI), Budapest University of Technology and Economics (BME) and Széchenyi István University (SZE)

Leading strategic partner: Automotive Proving Ground Zala Ltd. (ZalaZONE)

https://autonom.nemzetilabor.hu

FOREWORD

Dr. Gáspár Péter,
az ARNL projekt szakmai vezetője

Autonomous systems enable vehicles and robots to operate independently without human intervention, improving efficiency, safety, scalability, and reliability across a wide range of industries. At the same time, they are transforming our everyday lives by changing the way we work, travel and interact with technology. Self-driving vehicles help us avoid serious traffic accidents, while cooperative traffic management systems alleviate congestion in cities saturated with vehicles and mitigate the harmful effects of traffic jams on the environment, the economy, and quality of life. We use drones to collect data in hard-to-reach areas, supporting agriculture, nature conservation, and disaster response. Robots take over dangerous or monotonous tasks to protect human life, and our goal is to make everyday life easier by creating efficient and integrated transportation and delivery systems.
The staff researchers of the National Laboratory for Autonomous Systems strive to respond to the perhaps greatest and most complex challenges of our time through scientific research, development, and innovation. The collaboration between three institutions, each of which all of them has significant capacity on its own, created a new quality of research: over the past three years of the project, sustainable autonomous systems that can also be used in industry have been created by integrating the latest theoretical and practical results. Outdoor and indoor demonstrations conducted under the National Laboratory program have shown how the latest mathematical theories, new materials and technological solutions, as well as state-of-the-art computing and machine learning techniques, can be used to address the sustainability, flexibility, collaboration, and safety challenges facing ground and air transportation, mobile robotics, and manufacturing systems. This is not just a technological advance: it also contributes to increasing the social acceptance of autonomous solutions and ensuring that knowledge is not an abstract concept, but a lived experience.

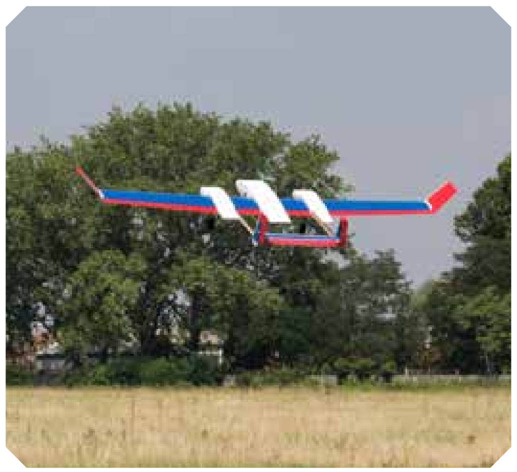
Dr. Péter Gáspár
Head of NLAS

AUTONOMUS SYSTEMS DO WATCH, DECIDE, PRODUCE, DRIVE, AND EVEN FLY

AREAS OF APPLICATION

Autonomous Road Vehicles

Development of experimental road vehicles with an emphasis on the component and the functional design, and with particular interest in the theoretical and design aspects of control related to the various levels of autonomy, geographical localization, road environment detection, safe and secure communication, cooperation among road vehicles and among vehicles of different kind, to robustness, real-time capability and demonstrability.



Autonomous Aerial Vehicles

Planning, execution and evaluation of UAV-based solutions to various highlevel aerial missions that need to be carried out in an autonomous fashion and need to ensure safe aerial manoeuvres, and thereby presume a harmonized operation of onboard sensors, multi-camera vision system, communication devices, and actuators.

Autonomous Robotics and Production Systems

Development and demonstration of cyber-physical production and logistics systems (CPPS, CPLS), both flexible and dedicated, that comprise autonomous components; with special emphasis on autonomous robotics, humanrobot symbiosis, cooperation, and teamwork, and by making use of the ‚digital twins' of the components.

EXECUTIVE SUMMARY

The National Laboratory for Autonomous Systems (NLAS) is a national center of excellence for research into autonomous systems. Our mission focuses on robotics, the control of autonomous ground and air vehicles, and their collaborative coordination. Thanks to the multidisciplinary collaboration and integration of artificial intelligence, control theory, robotics, and cybersecurity, we built a robust ecosystem that connects academia, the economy, and the government priorities set out in the János Neumann Program.

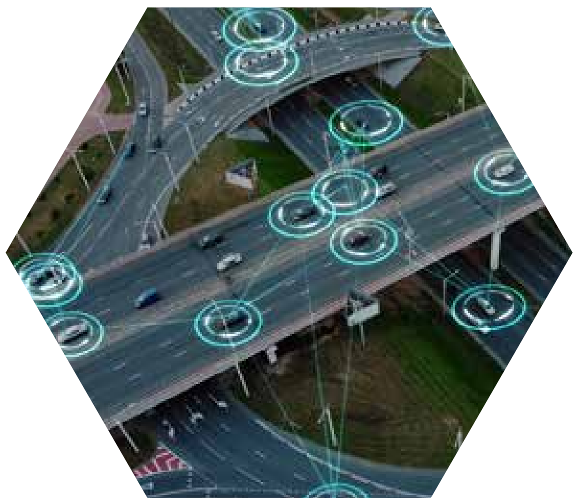
Our work promotes the green and digital transition, strengthens national technological sovereignty, and contributes to the global development of safe, efficient, and intelligent autonomous systems.

NLAS conducted theoretical and applied research in a number of several areas, resulting in innovations in vehicle control strategies, perception and localization, cooperative operation, and robotics.

Vehicle control strategies

A central idea in our research is the integration of data-driven machine learning and model-based robust control. This hybrid approach improves the adaptability and performance of systems, which we demonstrated through simulations and physical tests. Our new theoretical contributions are the following:

- Novel discrete-time system representation that enables the design of efficient, data-driven controls.
- Machine learning-based model augmentation that combines physical models and data-derived dynamics to create digital twins.
- Direct control design methods for unknown mechatronic systems with guaranteed reliability.
- Predictive control concepts based on twin models in physical simulators.
- Advances in accelerating deep learning for online identification and control, with noise-tolerant statistical guarantees.
- Further development of the so-called ultra-local model structure to improve adaptivity and handle instability, validated by autonomous path tracking experiments.



Environment perception and localization

We investigated the uncertainties of cameras, radars, and LiDAR sensors to improve filtering algorithms and perception reliability. The following innovations support robust and affordable autonomous navigation:

- Differentiable resampling schemes for training particle filters.
- Sensor fusion models that combine camera and radar data to improve accuracy.
- LiDAR-based object tracking and surface recognition algorithms, tested in both real and simulated conditions.
- Drone detection using LiDAR and neural network-based classification to reduce false positive detections.
- Low-cost, sensor fusion-based localization method that combines radar, camera, and inertial data. The outdoor navigation device that works without GPS or internet achieves 10-meter accuracy in most environments.
- Vision-based motion estimation and GPS-IMU fusion methods for detecting aircraft drift.

Autonomous vehicle control

Our research in the field of trajectory planning and adaptive vehicle control has resulted in several reinforcement learning (RL)-based methods:

- Deep Q-Network and DDPG agents for direct control and dynamic path planning.
- Meta-RL frameworks for online adaptation to changing environments.
- Hierarchical RL systems for emergency maneuvers, multi-agent RL systems for traffic and convoy control.

- We implemented AI-based and robust control systems on simulators and real test vehicles, and validated them exhaustively on the ZalaZONE automotive test track.
- The route optimization-based driver assistance application achieved significant energy savings with minimal increase in travel time.
- NLAS also played a pioneering role in the development of control algorithms for extreme driving conditions, such as drifting and high-speed cornering.
- We designed an ethical artificial intelligence-based control system for safe maneuvering in critical situations.

For aircraft, the laboratory has developed the following:

- Cargo-moving drones capable of autonomous pickup and placement from and onto moving platforms.
- An adaptive control method to support reliable, agile maneuvering of quadcopters even in uncertain, changing operating conditions.
- Control surface fault detection and aerial inspection solutions.

Cooperative vehicle control

The cooperation between ground and air vehicle systems is one of the central pillars of NLAS's research. Applications include:

- Object transport and logistics supported by optimization algorithms.
- Drone-supported reconnaissance for emergency and defense operations.
- Integrated air-ground image processing frameworks for 3D reconstruction.
- Neural network-based V2X simulation framework that allows large-scale networks to be accurately modeled with reduced computational requirements.
- Artificial intelligence-driven traffic control systems that run on industrial PLCs, enabling cost-effective implementation of smart cities.
- Game theory pedestrian models that ensure safe urban interactions.
- Predictive and robust control-based intelligent overtaking and driver assistance algorithms.
- Analysis of the subtle effects of speed limits on traffic safety and the environment.

Robotic modeling and control

In the field of industrial automation, we developed digital twin-based robotic systems for object picking and placing, diagnostics, and assembly operations. Our main achievements include:

- TRL-9 level robotic measurement system for electronic testing, currently in use at five sites globally.
- Dynamic reconfiguration models for production lines, optimizing scheduling and resource allocation.
- Human-robot collaboration systems, including gesture control, attention level monitoring, and collision-avoidance cobots.
- Use of large language models (LLMs) to assist in production planning and scenario generation.
- Introduction of energy-optimized scheduling algorithms that combine linear programming with explainable artificial intelligence, helping to reduce manufacturing costs and emissions.
- Mobile construction robot prototype for automated placement and collection of traffic cones.
- Increasing the ghost-free viewing angle of head-up display (HUD) systems using images with different polarization for each viewing direction.

Infocommunications and cybersecurity

We created a methodological framework for assessing the resilience of V2X systems to cyber attacks. The key results are the following:

- Quantitative assessment of the impact of communication delays and packet loss on security.
- A large number of cyberattack simulation scenarios supporting artificial intelligence-based defense control.
- Radio control independent of all other systems for long-range human supervision.

We also developed battery diagnostic and predictive maintenance methods for electric and hybrid vehicles that identify early signs of aging through voltage deviation analysis.

Research platforms and infrastructure

NLAS has built advanced test environments to support research validation:

- An experimental vehicle platform that also demonstrates automated parking and smart city functions.

- An augmented reality testing framework that integrates real and virtual traffic environments.
- Indoor test arena (AIMotionLab) for drones and mobile robots, with a digital twin (AIMotionLab-Virtual) enabling hybrid real-virtual operation.

Further developments and practical innovations related to the platforms:

- Multi-drone navigation and path planning in dynamic environments.
- Hydrogen fuel cell drone models for emission-free long-range flight.
- Advanced GNSS station integrated into the European network for geodesy and atmospheric monitoring.
- HD map of ZalaZone Park for MATLAB users.
- Data management platform on the HUN-REN cloud for real-time processing, visualization, and secure storage.

Impact and utilization

The impact of NLAS extends to research, the economy, and society. In numbers:

- 497 publications, of which 130 appeared in Q1 journals and 67 are among the top 10% most cited.
- 10 domestic patents, 3 international patents, 3 trademark protections, and 1 design protection application.
- 3 spin-off companies with revenues of more than HUF 900 million.
- The laboratory's total revenue exceeds HUF 6.2 billion.
- Identification of 21 social and 11 environmental benefits, which are expected to reach 850,000 people by 2030 and represent a total value of HUF 177 billion.
- The number of media appearances exceeded 1,000 mentions, raising public awareness of autonomous technologies.

To promote understanding and trust in autonomous technology, NLAS organized public demonstrations and innovation competitions, and conducted surveys on attitudes toward driver assistance systems. The results showed limited public knowledge and caution regarding autonomous and shared mobility, emphasizing the need for further education and information.

THE OPERATION OF THE NATIONAL LABORATORY

MOTIVATION AND MISSION

The activities of the National Laboratory for Autonomous Systems are aligned with the focus areas defined in the János Neumann Program adopted in June 2023. The innovation strategy sets out that the government plans to focus its innovation investments on the areas of healthy living, green and digital transition, and safety.

The mission of NLAS is to conduct theoretical and application-oriented research related to the control and cooperative coordination of autonomous ground and air vehicles and mobile robots. This research is linked to several focus areas of the János Neumann Program.

Autonomous vehicles facilitate the digital transition, for example in warehousing, road and air freight transport, and above all in the area of human mobility.

They also indirectly contribute to the green transition of the economy through their positive impact on optimal transport organization and transport emissions.

Our research contributes to a drastic reduction in the number of accidents, which links our activities to the focal point of healthy living.

The objectives of several of our sub-projects are related to safety. Among these, the tasks solved by connecting ground and air vehicles, as well as research related to cyber security, stand out. The results of these research topics all increase the security of the digital transition and can also help to answer and solve national security issues.

We would also like to highlight research related to electromobility and increasing battery life, which directly contributes to the green transition of the economy.

Another direction of our research plan is autonomous manufacturing related to the digital transition. This area, linked to Industry 4.0 research, aims to digitize production and supply and addresses related theoretical and practical problems.

OUR MOST IMPORTANT RESULTS

The National Laboratory for Autonomous Systems carries out innovative work in the fields of self-driving ground and air vehicles, robotics, and cooperative control systems. As a leading domestic research center, our fundamental goal is to create and develop safe, sustainable, and intelligent autonomous systems.

Over the years, we involved a total of **335 researchers** and 53 technicians in the work of the National Laboratory, **34** of whom belong to the **D1** category of the Scientific Journal Rankings.

The National Laboratory published its scientific results in internationally renowned journals and presented them in person at conference presentations. **Of the 497 publications, 130** appeared in **Q1** journals, **39** in **Q2** journals, and **67** were among the **top 10% of the most cited** publications in their field.

Since its launch, NLAS has generated **HUF 715 million** in industrial revenue and **HUF 1,724 million** in domestic grant revenue. The acceptance rate of its applications submitted to international calls for proposals is 32%, which translates into **HUF 2,848 million** in grant support. Spin-off companies have generated **HUF 921 million** in revenue to date. Taking into account the realistic revenue expected from additional contracts and tenders, the laboratory has generated a total of **HUF 9,032 million** in revenue.

As a result of the project, we have submitted **10 domestic patents, 3 trademarks, 4 international patents, and 1 design patent** so far. The National Laboratory supported the establishment of **3 spin-off** companies.

The researchers and developers of the National Laboratory are actively involved **in university education** (BME Autonomous Vehicle Control MSc) and the training of future researchers, thereby contributing to talent development management and increasing the number of domestic researchers. We involved **114 BSc** students, **74 MSc** students, and **68 PhD** students/junior young researchers in the research and development tasks of the NLAS program, who wrote **183** theses for the **Conference of Scientific Students' Associations.**

NLAS has achieved numerous results in terms of both social (21) and environmental (11) benefits, the impact of which confirms the legitimacy of the National Laboratory. In the period up to 2030, we estimate that more than **850,000 people** will benefit **from the social benefits,** with a total value of more than **HUF 177 billion.** The estimated total value of the positive **environmental impacts** is more than **HUF 27 billion,** and the expected **number of people affected** is more than **15 million.**

Our results were published approximately **450** times in social media, and the number of traditional press appearances exceeds **650.**

NATIONAL LABORATORY FOR AUTONOMOUS SYSTEMS

INNOVATION & IMPACT

Digital & autonomous systems

Green transitions

Security & resilience

Industry 4.0

Vehicle and drone control	Perception and localization	Cooperative systems (V2X, UAV-UGV)	Robotics and smart manufacturing	Cybersecurity and predictive maintenance

497 publications

013 patents

003 spin-off companies

Total revenue of HUF **6,2 billion**

850 000 beneficiaries by 2030

ZalaZONE test track	AIMotionLab & AIMotion-Lab-virtual	AR/VR vehicle simulator	GNSS station	HUN-REN data cloud

Highlighted effects

Safer transportations

Industrial digitalization

Skilled workforce development

SOCIAL AND ENVIRONMENTAL IMPACTS

In order to promote understanding and trust in autonomous technology, we organized public demonstrations and innovation competitions, and conducted surveys on attitudes toward driver assistance systems. The results showed limited public knowledge and caution regarding autonomous and shared mobility, highlighting the need for education and information.

As part of the project, we conducted a questionnaire survey to examine attitudes towards advanced driver assistance systems (ADAS). Respondents were not particularly open to car-sharing services (e.g., robotaxis), preferring to use their own vehicles. The research also clearly showed that (Hungarian) society currently lacks sufficient knowledge about the driver assistance systems available on the market, which significantly hinders their acceptance and use, as well as the future penetration of autonomous technology.

This is very unfortunate, given that the estimated social benefit generated by the National Laboratory for Autonomous Systems within the framework of the project is more than HUF 177 billion by 2030, with more than 850,000 people expected to benefit from it. For this reason, we held several demonstration days to showcase the social benefits of autonomous systems and raise awareness of the opportunities they offer, where both professionals and the general public could learn about our results.

These include the Lexus experimental vehicle, UAV support for vehicles using special warning lights, junction optimization for route planners based on human preferences, the AIMotionLab test environment, testing of networked vehicles, improving their cybersecurity, and organizing the Smart Manufacturing Festival.

Let's illustrate with a calculation example how important it would be to widely deploy autonomous systems as soon as possible.

- Based on a 2004 PhD dissertation in economics, let the value of a human life—as far as it can be quantified—be HUF 400 million.
- Last year, there were 19,862 accidents involving personal injury in Hungary, of which 497 were fatal and 4,721 resulted in serious injury.
- 90% of the fatal accidents could be prevented by autonomous vehicle control.
- With our developments in monitoring driver fatigue, we could eliminate 0.5% of the possibility of human error.

Taking all this into account, the following estimate can be made:

HUF 400 million × 497 × 0.9 × 0.005 =
= HUF 895 million / year

In other words, putting our research on driver fatigue monitoring into practice could save two lives a year, generating a social benefit of 900 million HUF. The technology is available, it just needs to be used.

The researchers and developers at the National Laboratory are actively involved in university education and the training of future researchers, thereby contributing to talent development management and increasing the number of domestic researchers. They hold science popularization and career orientation lectures for high school students and organize competitions, while university students are given the opportunity to participate in research and development activities and competitions. In addition to mentoring research conducted at Scientific Students' Associations, they also undertake the announcement and mentoring of BSc/MSc thesis topics.

The application of artificial intelligence methods in autonomous systems is spectacularly demonstrated by our solutions developed for autonomous vehicle racing, with which we successfully competed in international competitions.

In addition to disseminating the results, with the aim of actively increasing the social acceptance of autonomous systems, we developed a control system capable of handling critical situations and implementing ethical maneuvering. The system evaluates the traffic situation in a qualitative and quantitative manner within a control planning structure and plans movements for the autonomous vehicle that are predictable by human participants.

The environmental benefits generated by NLAS are also significant: their estimated value by 2030 is more than HUF 27 billion, and the expected number of people affected is more than 15 million. This figure may seem excessive, but while safe and energy-efficient vehicle traffic advisory systems, machine learning-based control of networked traffic light intersections, modular bus driver monitoring systems, or even the monitoring of driver fatigue affect those directly involved in transport, the production of atmospheric delay data for the European Meteorological Services Network based on GNSS measurements, or the safety of the power supply system for electric vehicles, have an indirect impact on almost the entire society.

As a calculation example, let us consider the control of networked traffic light intersections.

- Based on simulations, this method can achieve an approx. 10% reduction in CO^2 emissions.
- CO^2 emissions from transport in Budapest amount to 1,794,906 tons of CO^2 per year.
- The algorithm can achieve a 5% increase in efficiency, which translates to 89,745 tons of CO^2 per year.
- 1 ton of CO^2 quota equals to approx. EUR 100.

Based on these figures, the environmental benefit is:
EUR 100 × 89,745 =
EUR 8,974,500 / year =
= approx. HUF 3,500 million / year.

We used similar approximate calculations to estimate the environmental impact of the National Laboratory's other activities.

ORGANIZATIONAL STRUCTURE, OPERATION, AND PARTNERS

NLAS is free from the constraints of strict corporate protocols and can cost-effectively address RDI problems that are too risky for companies and investors. Within NLAS and its partner institutions, an extremely wide range of scientific and engineering expertise is immediately available at an international level of quality, in a business structure that is favorable to companies. The consortium has better opportunities to access significant support and financial resources.

The National Laboratory for Autonomous Systems comprises three institutions with excellent research capacities and research teams, which, in addition to their research and development achievements, also perform outstandingly in the field of training the next generation.

SZÁMÍTÁSTECHNIKAI ÉS AUTOMATIZÁLÁSI KUTATÓINTÉZET

The HUN-REN Institute for Computer Science and Control is a member of the HUN-REN research network and the country's oldest and most successful IT research institute.

BUDAPESTI MŰSZAKI ÉS GAZDASÁGTUDOMÁNYI EGYETEM

The Budapest University of Technology and Economics is the most prestigious technical university in Central Europe and Hungary, and, founded in 1782, it is the world's first technical university.

SZÉCHENYI ISTVÁN EGYETEM

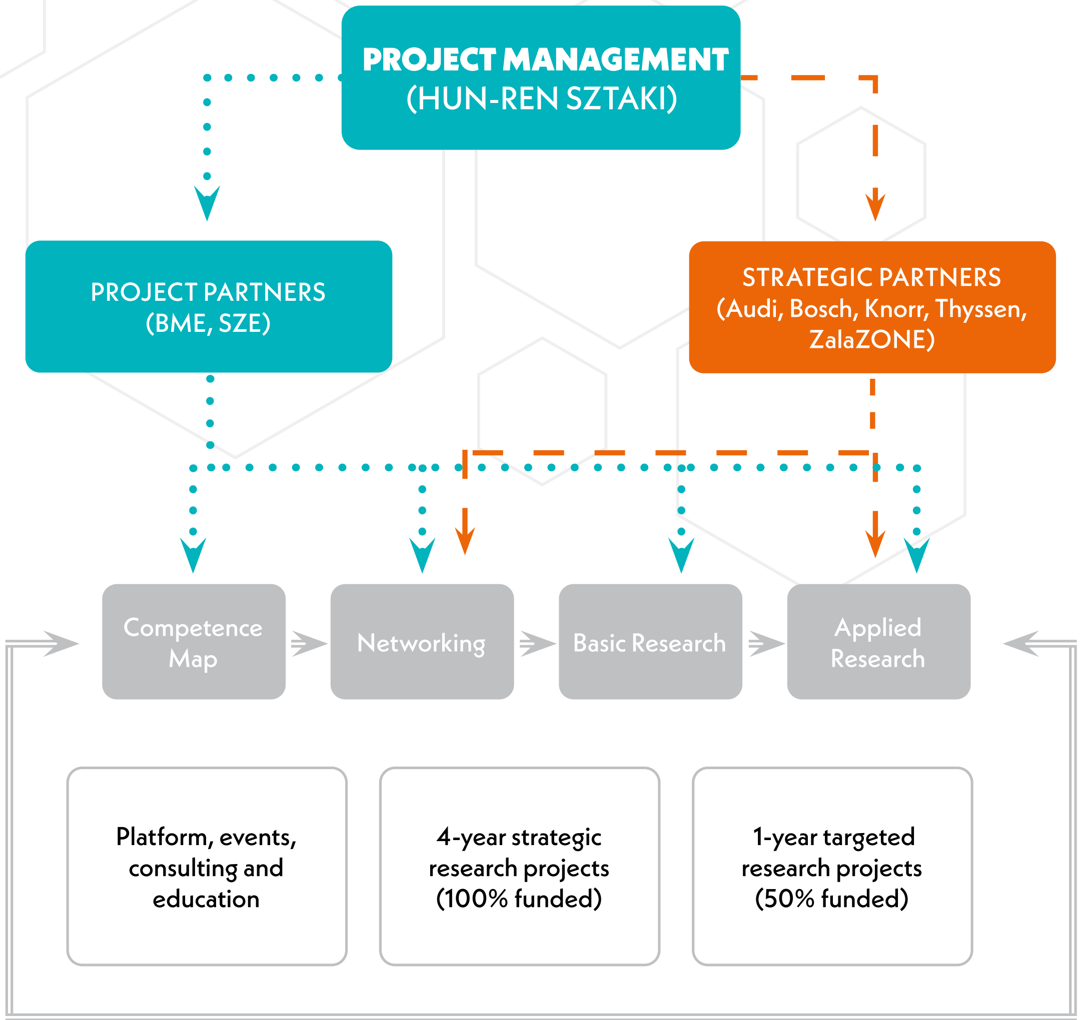
Széchenyi István University is a prestigious, dynamically developing technical university in Győr, the legal successor of the Technical College founded in 1968, which was granted university status in 2002.

Since its inception, the founding members of the National Laboratory have assessed domestic institutions and companies that are actively involved in or apply the results of research related to autonomous systems. This has resulted in the creation of a network organized around the laboratory, through which participants can exchange information on funding opportunities, state-of-the-art scientific and industrial developments, and best practices.

There is a significant gap between the activities carried out in the research institute, university, and industrial sectors in the field of autonomous systems. Representatives of all three areas can be found among the organizations brought together by the National Laboratory. The laboratory's main tasks are to coordinate RDI activities across sectors, eliminate fragmentation, transfer knowledge, channel disciplines that are lacking in Hungary, and create a kind of cooperation platform to make research more efficient.

The fundamental goal of NLAS is to put fundamental research results to practical use, increase the innovative performance of businesses, and strengthen cooperation between participants in the RDI ecosystem. The catalysts of this process are the founding institutions, which conducted multidisciplinary research by integrating and further developing their core competencies and identified gaps, and published their results in relevant international forums.

Due to their academic nature, the consortium partners of the National Laboratory did not participate directly in product development, but market information was channeled into the laboratory's operations through the advisory role of strategic industrial partners.



NLAS has an extensive network of contacts and cooperates extensively with international research centers and universities. Its members participate in a number of influential international organizations.

We also have industrial partnerships in all areas of research, which we are constantly expanding by seeking new partners and participating in tenders and project collaborations.

KEY PARTNER COMPANIES AND ORGANIZATIONS

KEY UNIVERSITY AND RESEARCH INSTITUTE PARTNERS

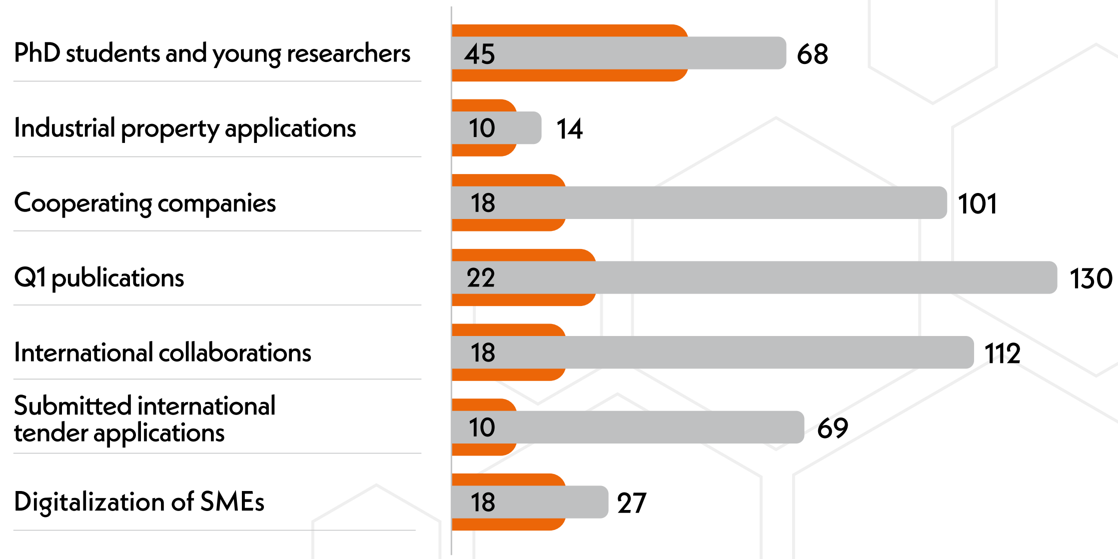
CONTRIBUTION TO THE DIGITALIZATION OF BUSINESSES

COMPANY	CONTENT/SCOPE OF COOPERATION
aHead Photonics Kft.	Wide-angle head-up display
Albacomp Elektronikai Kft.	Joint workshops
D3 Seeron Kft.	LiDAR camera sensor fusion
DriveByCloud Kft.	Innovative services based on real-time twin models
Hepenix Kft.	Development of flexible human-robot manufacturing technology based on artificial intelligence through the synchronized in-situ operation of digital twins and real cells. Provision of an industrially relevant test environment at TRL6 level. Joint SME focus and TÉT (Science and Technology) tenders.
Inventure Automotive Kft.	Development of a CAN data recording unit
Ivy Technology Kft.	Robotic automation of electronic circuit measurement
Közlekedés tervező Iroda Kft.	Digitization of traffic measurement data
Lillyneir Kft.	Model-based determination of accident risk levels
Microsec Kft.	Digital authentication in road transport
MM-Vill Kft.	Joint HE cascade tender
MouldTech Systems Kft.	Mechanical installation of test car HMI unit
NCT Kft.	Digital twin model of autonomous NC machine tool
Prolan Irányítástechnikai Zrt.	Train driver support application
QTICS Automotive Zrt.	Automotive testing in a fully digital environment
SDR Technologies Kft.	Artificial intelligence-controlled robot
Theco Kft.	Creation of shared workspaces
Willisits Mérnökiroda Kft.	Digital timing system for go-kart track

PERFORMANCE INDICATORS

FULFILLMENT OF MANDATORY COMMITMENTS

Target value and current value



SCIENTIFIC IMPACT

	2020	2021	2022	2023	2024	2025	Total
Number of publications since the Laboratory was established (pcs)	4	88	95	91	95	124	**497**
Of which the number of Q2 publications (pcs)	2	10	8	10	0	9	**39**
Of which the number of Q1 publications (pcs)	1	23	22	28	20	36	**130**
Of which the number of scientific publications that are among the top 10% most cited worldwide (pcs)	0	4	16	14	15	18	**67**

RESEARCH RESULTS

VEHICLE CONTROL STRATEGIES

One of the central elements of our research is the integration of data-driven machine learning and model-based robust control. This hybrid approach improves the adaptability and performance of systems, which we demonstrated both through simulations and physical tests.

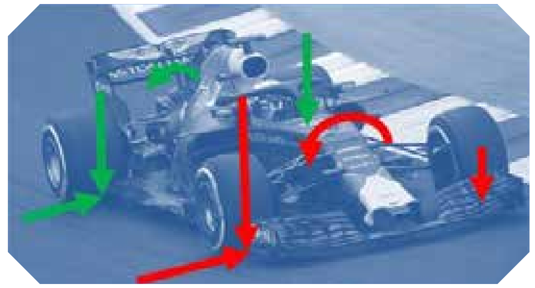
We proposed a new data-driven, discrete-time system representation that supports analysis and design tasks. We specified a condition under which a given trajectory set generates an actual system representation and also presented an exhaustive parameterization of these representations. We have achieved new results in realization theory in increasing the efficiency of data-based control design methods, which are suitable for running deep learning identification methods in real time.

Based on large data sets containing vehicle dynamics measurements, we identified locally valid linear models, among which we determine the current operating point using decision trees. Based on the resulting model set, an LPV (Linear Parameter Varying) structure can be built, which allows the application of robust control design methods. These methods are capable of cooperating with non-traditional control, regardless of its structure, if the conditions of stability, performance, and convergence are met.

The result of the research is autonomous vehicle control that ensures safe and energy-efficient participation in traffic. We developed artificial intelligence-based and robust control methods in a joint optimization task to achieve efficient operation. We analyzed the designed control in a vehicle dynamics and traffic simulator, on an indoor mobile vehicle, and on an outdoor real test vehicle.

The integration of data-driven machine learning methods and model-based robust control methods plays an important role, which we achieve either through direct cooperation or by using a supervisor. The integrated application of these methods can significantly improve the quality characteristics of the control, and the behavior of the completed system can be directly influenced by parameterizing the cost function. We demonstrated the effectiveness of the method through the lateral control task of autonomous vehicles in a simulation environment and validated it on a variable geometry chassis test bench.

We developed a fault-based version of the ultra-local model, which we used for ultra-local MFC-based observer and controller design. This new structure is capable of handling instability problems while retaining the advantages of adaptivity. We successfully applied the proposed method to the trajectory-following control design of autonomous vehicles, which we implemented and validated in real-world conditions.



We developed machine learning-based model augmentation methods that are capable of automatically creating a digital model of a given physical system by combining existing engineering and physical knowledge, basic models used in industry, and dynamic relationships that can be reconstructed from the data. The resulting digital twin models can be used to analyze the dynamic behavior of the system and to design control algorithms.

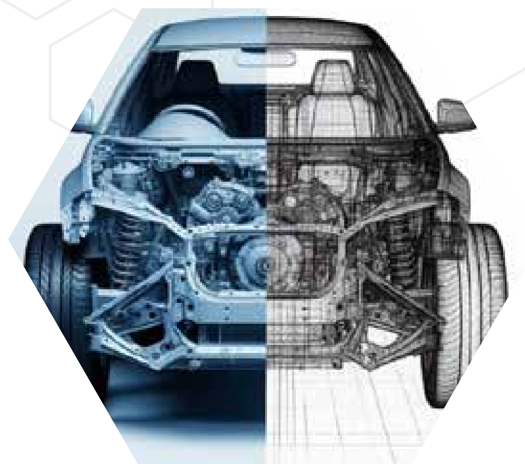
We developed procedures that are capable of directly designing controllers for unknown mechatronic systems based on time or frequency data, with mathematically guaranteed operational reliability. Our research results make it possible to eliminate costly and expertise-intensive modeling, automate controller design, and ensure the recursive adaptability of controllers, adapting to dynamic changes.

The goal of modeling complex mechanical systems is to understand the dynamics of motion. Analyzing responses to changes in influencing parameters allows for a better understanding of performance limits and can provide data for design and control.

We developed a predictive control concept in which the calculation of the actual control signal is performed directly using a twin model compiled in a physical (multi-body) simulator, instead of a model derived from physical relationships in the form of differential equations.

It has long been common practice in the mechatronics industry to design controllers directly for the frequency response function measured on a given device, omitting analytical modeling. Through deep learning of so-called Koopman operator models, we have achieved groundbreaking theoretical and practical results in this field at an international level.

We also developed methods that enabled us to significantly accelerate deep learning processes in data-driven modeling and control, enabling online solutions. Our method provides statistical guarantees for model learning in the presence of noisy measurements and disturbances.



ENVIRONMENTAL PERCEPTION AND LOCALIZATION

To improve filtering algorithms and perception reliability, we studied the uncertainties of cameras, radars, LiDARs, and other automotive sensors. The following innovations support robust and affordable autonomous navigation.

We simulated the measurement uncertainties (false signals, measurement noise) of cameras, radars, and other automotive sensors and compared the real-time performance of different filtering algorithms. We developed a differentiable resampling scheme for gradient-based training of particle filters.

In the developed semi-automatic ground-truth generation process, we used mono-camera and radar data to annotate moving objects as accurately as possible. Based on real-world scenarios, we created an object-level simulation model that realistically reproduces radar and camera measurements.

During real vehicle experiments, object detection and tracking, as well as the examination of dynamically changing environments, were carried out in simulated and real environments. In addition, we developed a road surface deviation detection algorithm. We examined in detail the measurement data of non-periodic scanning LiDAR sensors for object detection and segmentation tasks. We researched and developed robust solutions for separating foreground and background in static surveillance systems.

To support the movement of high-speed maneuvering aircraft, we developed a method for detecting, recognizing, and tracking drones against a dynamic background using LiDAR with a rosette scanning pattern, based on sparse point cloud data.

In addition, we designed and developed an algorithm that integrates a classification network with a semantic segmentation network, which can effectively filter out false detections caused by birds and other flying objects.

As a result of sensor fusion research, we developed a new camera-radar fusion solution with improved numerical complexity, together with a sensor simulation and ground-truth generation algorithm. We developed a neural network using Bayesian inference to implement a sensor fusion-based localization method.

To achieve fully autonomous driving, we developed an accurate, robust, and universally available positioning function. To solve this problem, we proposed a method based on the fusion of available sensors. The algorithm that estimates the localization and other states of vehicles (e.g., orientation, longitudinal and lateral velocity) uses signals from cost-effective sensors and applies efficient sensor fusion.

We developed an outdoor navigation device that is capable of real-time tracking and map display of vehicle position without GPS or internet. The algorithm relies on a combination of a Kalman filter and a hidden Markov model to calculate the most probable route, which is determined based on the vehicle's movement data and the Open Street Map road network. Tests have proven the solution to be functional.

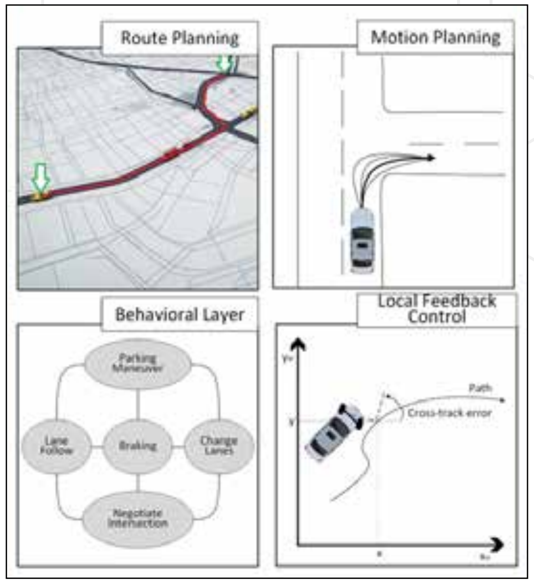
We developed monocular vehicle detection and vehicle body shape estimation using cameras installed in the infrastructure. We further improved the consistency and reliability of detection using time series-based processing.

For aerial vehicles, we developed a method that uses image data to determine whether the camera performed only rotational or also translational motion, and whether it sees points of a flat or a 3D surface. By separating the cases, the specific image processing method can be selected and the camera's motion parameters can be extracted with high accuracy. We determined the motion parameters using optical flow-based angular velocity estimation, providing increasingly accurate linear solutions to the originally nonlinear computational task. In further research, we investigated the effect of GPS drift on state estimation using GPS-IMU fusion and provided a method for camera image-based drift detection.

AUTONOMOUS VEHICLE CONTROL

Our research in the field of trajectory planning and adaptive vehicle control has resulted in a number of reinforcement learning-based methods. We implemented artificial intelligence-based and robust control systems on both simulators and real test vehicles, and validated them exhaustively on the ZalaZONE automotive test track.

One of the key issues in autonomous driving is planning a trajectory that allows the vehicle to travel safely and efficiently, avoid obstacles, and respond in real time to a constantly changing environment.



We developed several methods: the Deep Q-Network-based method gives steering commands directly based on the vehicle's angle errors and trajectory tracking errors; a method combined with a DDPG agent provides feasibility-based trajectory planning; the RL-based route planner creates dynamically feasible trajectories in critical situations; the Twin Delayed DDPG-based method is capable of avoiding moving objects through continuous re-planning; and the online adaptation solution applies a meta-RL framework for rapidly and unpredictably changing environments.

We developed a hierarchical reinforcement learning system that can plan and execute emergency evasive maneuvers. The single-step RL agent plans the trajectory, while the model predictive controller executes the intervention.

We developed multi-agent-based reinforcement learning systems for controlling traffic light intersections, variable speed limit signs on highways, and vehicle convoys.

We developed autonomous vehicle control by integrating artificial intelligence and robust control techniques, which is enables safe and energy-efficient driving in urban traffic environments. We integrated the planned vehicle control into a vehicle dynamics and traffic simulator, an indoor mobile vehicle, and an outdoor real-world test vehicle. To evaluate and demonstrate the results we conducted extensive testing at the ZalaZONE test track, analyzed interactions with pedestrians, and verified performance in real traffic using an augmented reality solution.

We achieved groundbreaking results in motion control and motion planning for vehicles at the limit of traction. We developed several algorithms that enable vehicles to operate safely and

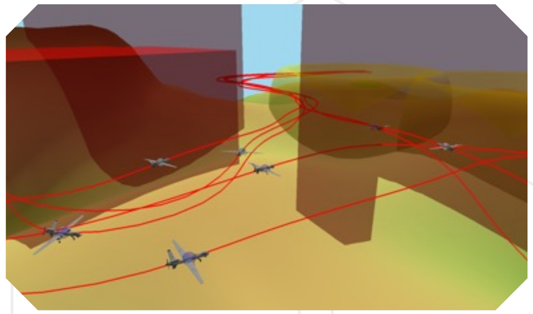
stably in extreme driving conditions, such as drifting or sudden changes of direction, when the rear tires are already saturated and stability is difficult to maintain. Some of the solutions are based on reinforcement learning, while others use nonlinear optimization.

Using reinforcement learning and mathematical optimization, we proposed a speed control that enables energy- and time-efficient, economical driving. Based on theoretical research results and supported by simulation and road testing, we developed a vehicle-type-independent practical application. A prototype version of a mobile application has been completed.

The solution takes into account terrain conditions, speed limit signs, and speed conditions determined by vehicles on the road. We analyzed the developed method under real conditions and achieved energy savings of 5-10%, while travel time increased by only 1-3%.

We developed efficient trajectory planning methods to support the navigation of large numbers of drones in highly fragmented environments containing both moving and stationary obstacles. The methods are suitable for the efficient management of danger zones and support rapid re-planning, enabling quick adaptation to changes in the environment.

In our research on autonomous drones, we have achieved valuable results in the areas of navigation and perception. For systems based on indoor quadcopters, we supplemented the MAPF (Multi-Agent Pathfinding) method with new features that take into account the uncertainties of the flight environment and effectively handle danger zones. To support navigation in dynamically changing environments, we developed a correction method that results in a continuous



trajectory, and we introduced multi-level planning solutions based on high-resolution occupancy matrices that are capable of handling danger zones in 3D space.

We developed a method based on motion primitives for drones and fixed-wing aircraft navigating in outdoor environments. By developing the new procedure, we greatly reduced the complexity of the graph search that forms the basis of trajectory planning and partially parallelized the algorithm, thereby significantly reducing planning time. This allows the method to handle a large number of drones.

We developed a predictive method for efficient load handling with quadcopters. Using a hook mounted on a rod, the quadcopter is capable of lifting objects completely autonomously, even from a moving platform, and placing them even on a moving vehicle with high precision. The advantage of this method is that it does not require a complex gripping mechanism (e.g., robotic arm, electromagnet), so it can be widely used and easily integrated into quadcopters of different types and physical properties.

The algorithm continuously optimizes the drone's trajectory during task execution, taking into account model uncertainties and adapting to external disturbances, thus ensuring reliable operation. We implemented the method on our in-house designed Bumblebee drone, which operates at the AIMotionLab.

We developed an adaptive control method to support the reliable and agile maneuvering of quadcopters even under uncertain and changing operating conditions. During the process, we supplemented the physical model of the quadcopter with a learning component (Gaussian process), which we tune during flight based on operational data and adapt to the behavior of the real drone. We developed geometric trajectory-following control for the resulting augmented model structure and provided mathematical guarantees for the reliable operation of the resulting system.

In terms of practical applications, we conducted successful research into the identification of stuck control surface faults and developed and demonstrated an aerial inspection solution for the detection of unknown ground objects.

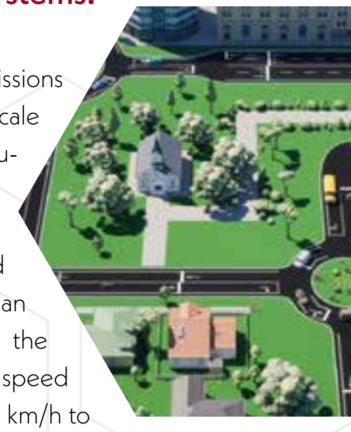
COOPERATIVE VEHICLE CONTROL

Cooperation between ground and air vehicle systems is one of the central pillars of research at the National Laboratory for Autonomous Systems.

Cooperative and coordinated control is a key element in the effective operation of autonomous systems. By researching the possibilities for cooperation between ground and air vehicles, we ensure a high level of autonomy for solving complex tasks that require artificial intelligence. The potential offered by cooperation is particularly important in supporting autonomous ground transportation, planning defense operations, preparing infrastructure investments, increasing agricultural efficiency, and geoinformatics.

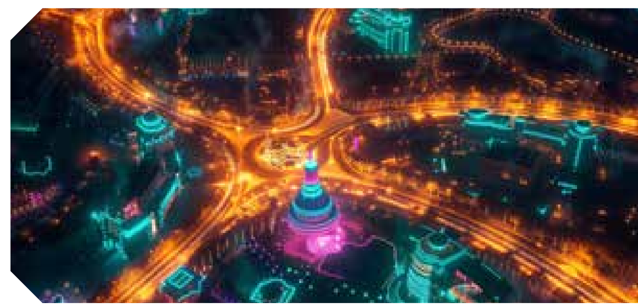
We developed new safe control procedures for handling interactions with human participants in transportation (e.g., pedestrians, passengers) in an urban test environment. We formalized a game-theoretical pedestrian model describing interactions with pedestrians crossing the road and tested it based on real measurements.

We used potential field-based situation assessment, graph route planning, neural network trajectory planning, and robust control techniques to ensure the safe execution of overtaking maneuvers. Using artificial intelligence, we developed a solution to actively support drivers by incorporating information from blind road sections into vehicle control.



We also examined the emissions of road vehicles on large-scale traffic networks using simulation and HBEFA (Handbook Emission Factors for Road Transport) based emission models. In urban networks, we examined the impact of reducing the speed limit within cities (from 50 km/h to 30 km/h) on emissions. Although reducing speed clearly has a positive effect on traffic safety, this is not always the case when it comes to emissions. Based on the study, in urban areas characterized by short road sections and many intersections, where traffic is also low (e.g., suburbs), the effect of slowing down is positive, but on busy road sections it is rather negative.

In the close cooperation of unmanned vehicles (the use of so-called companion drones), real-time information sharing, effective machine perception, and fast and robust optimal motion planning are of fundamental importance. When using multiple drones, it is possible to take advantage of sensor redundancy by allowing them to check



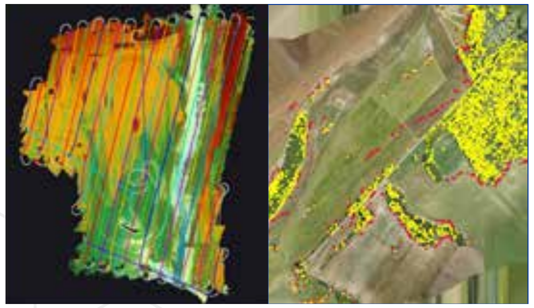
each other's position – and even orientation – optically, and to provide external assistance to each other in the event of a navigation problem.

We developed the concept of a reconnaissance forerunner drone for emergency response units working in urban environments. The camera drone flies in front of the road vehicle to support the rescue unit, making areas hidden from the driver's view visible and alerting the driver to various hazards.

We implemented ground-air vehicle cooperation for the efficient transport of objects and support for manufacturing and logistics processes. We developed an optimization procedure for process analysis and efficiency improvement of the autonomous vehicle network that enables this cooperation, and demonstrated its operability in a real-life situation at the ZalaZONE Automotive Test Track.

We developed and demonstrated a cooperative

chain for loose cooperation between unmanned aerial and ground vehicles. We integrated the processing of images received from ground and aerial perspectives into a common framework. The role of the aerial vehicle (UAV) is to take aerial photographs, patrol, and conduct reconnaissance. We proposed ground vehicle route planning procedures to complete the incomplete reconstruction detected in the images. The ground vehicle (UGV) performs the inspection and analysis of



points of interest (POI) that are not visible from the air and are obscured.

We provided a scalable, practical solution for object recognition tasks based on the cooperation of unmanned aerial and ground vehicles, supported by artificial intelligence methods.

Comprehensive testing and validation of vehicle-to-everything (V2X)-based solutions is too computationally intensive for current microscopic simulation systems and cannot be performed in real time. We have proposed a new, innovative, mesoscopic V2X simulation approach for comprehensive testing of vehicle communication, which uses a neural network-based function approximator to estimate the number and transmission frequency of messages sent. The method replaces microscopic traffic nodes even on an urban scale with an accuracy of up to 10% deviation from the original simulation. The entire control process can be implemented on a standard industrial programmable logic controller (PLC) with low computational requirements.

With the help of the flexible software, we have launched new developments in cooperation with an industrial partner to implement traffic-dependent signal control, building on V2X communication. The primary result of our artificial intelligence-based intelligent traffic control development is the successful technological demonstration of a traffic control system using reinforcement learning.

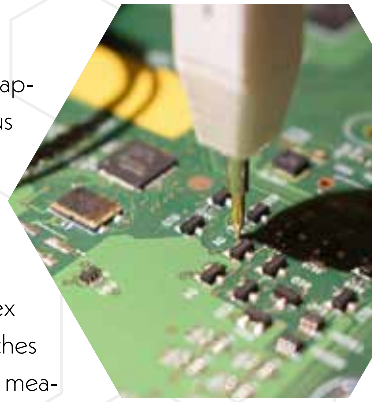
ROBOTIC MODELING AND CONTROL

In the field of industrial automation, NLAS developed digital twin-based robotic systems to support object picking and placing, diagnostic and assembly operations, the implementation of which was successfully brought to TRL-9 level in one case.

We provided a generalized solution for real-time planning of the sequence of manufacturing and assembly operations performed by autonomous robots. We developed an autonomous, digital twin-based robotic pick-and-place system with a general design workflow that ensures that the physical implementation and digital twin model of a given manufacturing system match each other with a given tolerance during execution.

For the robotized electronic measurement and diagnostics of faulty printed circuit components we combined visual servo-based active feedback, feature-based measurement point training, and homography-based localization with autonomous data collection. We implemented a TRL-9 level autonomous robotic measurement system for the mass testing of electronic products. In cooperation with an industrial partner, our solution is in operation at 5 sites on 3 continents.

Based on industrial motivation, we developed a mathematical programming model and an efficient solving algorithm that enables the dynamic (re)configuration and scheduling of production lines.



To support the industrial application of autonomous robotic cells, we have introduced a new, extended technology plan format that allows the creation of complex diagnostic profiles. Branches can be coded based on measurement results, and diagnostic exploration can be focused, which reduces measurement time and increases production efficiency. The robotic measurement system was developed with database-driven information and knowledge sharing, enabling the sharing of measurement technologies between sites.

We developed a new method for assigning and scheduling tasks for a fleet of autonomous robots (ARVs) designed to serve production, using state-of-the-art tools for manufacturing system simulation, data analytics, and machine learning. We designed the components of a small fleet of transport vehicles consisting of autonomous units, supported their domestic production, and integrated them into the HUN-REN SZTAKI SmartFactory cyber-physical manufacturing and logistics system. The experimental application of the method was successful at a world-leading semiconductor manufacturing company: they were able to reduce the number of ARVs serving production while significantly improving production output.

We developed and demonstrated a technology that can be used in remanufacturing for autonomous robotic tasks, and in an industrial research collaboration we developed a digital twin model of a machine used in battery manufacturing. We analyzed the root causes of process disturbances and errors and, with the help of digital twins, determined the requirements and cybersecurity expectations for the solution.

Our goal was to identify combinations of resources that would ensure the most efficient production for given products, manufacturing process plans, and volumes. We also used large language models (LLMs) to support the generation of design scenarios and their corresponding inputs, moreover, we linked an energy state model to the process.

To minimize manufacturing costs and energy demands, in order to reduce the industry's exposure to changes in energy prices, we developed an efficient and exact solution by combining mixed-integer linear programming techniques and unique heuristics, which provides explainable optimization to support decision-making and has an intuitive, graphical user interface.

We developed a joint human-robot assembly cell and introduced a new technological design format that can be used in industrial practice. The developed cell controls the robot and sends instructions to the operator, checks the assembly based on camera images, provides gesture control, and follows the correct assembly sequence.

The innovative application of interactive technologies helps the operator avoid collisions during various assembly tasks, which is a novel approach in cobot-based manufacturing and assembly. The operator can see the cobot's movements in advance, and a signal following a virtual collision warns them to avoid a real collision.

To support the collaboration between autonomous robots and humans, we developed and implemented a procedure for monitoring human attention levels in a robotic cell workstation environment.

We created a mobile construction robot prototype that is capable of autonomously placing traffic cones on the ZalaZONE Automotive Test Track with human instructions and remote supervision. The result of the project is the TRL 5 level implementation of the prototype test track service robot. We developed, tuned, and tested a complex control system for the robot platform's trajectory-tracking and positioning tasks.

We have completed the assembly of the hardware required for manipulating the traffic cones, the construction of the machine vision-based solution required for localization, the construction of the GNSS-RTK-based navigation system, the development of low-level control, mission management and high-level control, and the graphical user interface.

INFOCOMMUNICATIONS

NLAS created a methodological framework for assessing the resilience of V2X systems against cyberattacks, and we also further developed battery diagnostic and predictive maintenance methods for electric and hybrid vehicles.

We developed a comprehensive methodological framework for assessing the resilience of V2X-based vehicle functions against cyber attacks. Based on numerous real-world and simulation tests, we have succeeded in quantifying the impact of communication characteristics (e.g., delay, packet loss) on vehicle safety, as well as the consequences of DoS attacks. We successfully applied our solutions to the analysis of authentication systems and the statistical evaluation of the behavior of autonomous systems. We developed a new method for analyzing the relationship between vehicle safety and V2X-based cyber attacks.

In our research on cybersecurity protection for transportation systems, we generated 48 million scenarios, including 5 million accident situations, enabling the training of control strategies that ensure safe operation even in environments with limited information.

We implemented independent radio control, which is capable of intervening in the platform's basic functions and providing human control even from a distance of several kilometers. To this end, we designed an artificial neural network capable of providing reliable estimates of the position of the apex of traffic cones in the camera's field of view without spatial information.

We developed a cell-level battery diagnostic methodology that can be integrated into and applied to various types of electric and hybrid vehicles. The method is based on examining the deviation of cell voltages from the average under different operating conditions.

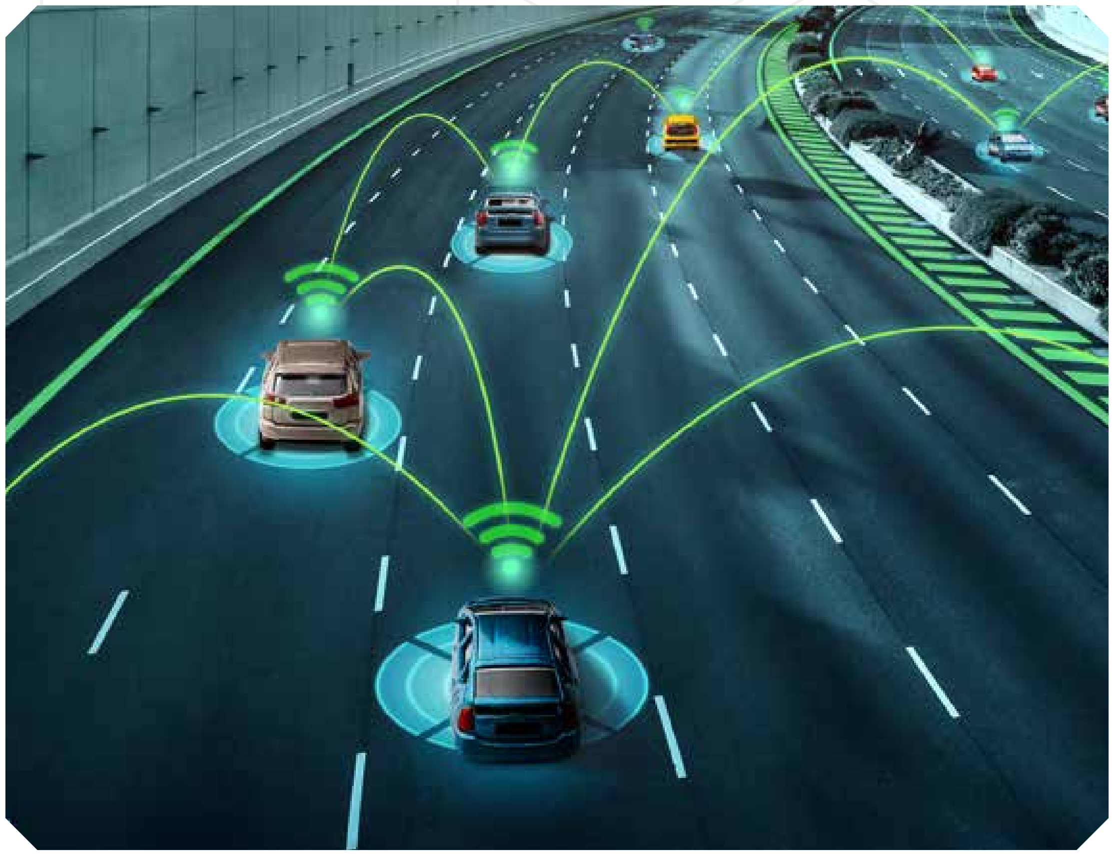
A significant part of the measurements were was performed on various modules of the ZalaZONE test track. We have proven that sections involving sudden acceleration and regenerative braking generate the greatest voltage variation between cells, which is suitable for rapid condition assessment.

We developed a method for monitoring the main units of the vehicle, thereby preventing potential failures and enabling predictive maintenance. With sufficient amount of data, we can identify malfunctions using machine learning algorithms. Based on the general methodology, we developed detailed procedures for predicting brake system wear and failure for industrial purposes.

In order to increase the social acceptance of autonomous systems, we developed a control system that is capable of handling critical situations and performs ethical maneuvers, which also assesses the traffic situation and plans movements for the autonomous vehicle that are predictable by human participants.

We also held demonstration events to showcase the social benefits of autonomous systems and raise awareness of their potential. We organized innovation competitions for high school and university students. To demonstrate the methods of artificial intelligence in a spectacular way, we developed solutions for autonomous vehicle racing with which we successfully participated in international competitions.

As part of the project, we conducted a questionnaire survey to examine people's attitudes towards driver assistance systems. The research clearly showed that society currently lacks sufficient knowledge even about the available driver assistance systems, which is why we made it an important goal to appear in various forums and disseminate information in a popular form.



RESEARCH INFRASTRUCTURE AND PLATFORMS

Using the most advanced technologies available on the market, NLAS built advanced test environments that accommodate outdoor and indoor, ground and aerial vehicles, and mobile robots to support the validation of research results.

We built an experimental vehicle platform that is suitable for testing, validating and demonstrating research and development methods and algorithms in a closed test track environment. The solution is suitable for analyzing the design, control and environmental perception research functions implemented in the individual software layers of the highly automated vehicle.

The modular framework and simulation environment provide an excellent basis for the research and development of more complex decision-making models using artificial intelligence.

The system includes the necessary environmental sensors, vehicle dynamics measurement systems and industrial computers. We also developed a SIL (Software-in-the-Loop) system that enables laboratory testing of algorithms, as well as a VIL (Vehicle-in-the-Loop) system for creating a virtual testing environment.

As a result of the development, the vehicle is capable of demonstrating several impressive self-driving functions. Using the automated parking assistant, it can navigate and park itself in a parking lot. Using a smartphone application, the car starts and navigates safely back to its owner. In the Smart City section of the ZalaZONE test track, the vehicle is capable of driving legally on the urban road network and reacting to environmental elements (e.g., signs, obstacles).

The demonstrations achieved a significant social impact thanks to the modern and attractive technology, which was mainly manifested in career orientation and the promotion of the master's degree program in automotive development and research engineering.

We developed an augmented reality-based framework for the analysis, development and testing of autonomous vehicle control methods. We supplement the real vehicle environment with virtual elements such as intersections, roundabouts, lanes, other vehicles, pedestrians, traffic signs, and even trees and fields that correspond with the real image. In this environment, the movement of a given vehicle can be examined in the context of the entire traffic situation, and cooperative vehicle control can also be analyzed.

We developed a method for increasing the ghost-free viewing angle of head-up display (HUD) systems. We experimentally verified that the entire surface of the windshield can be made suitable for displaying color images using a polarizing filter with point-by-point variable polarization, which is proposed to increase the ghost-free viewing angle of HUD systems using a reflective thin film.

With the development of augmented reality functions, we developed an experimental system for viewpoint-dependent testing in a user environment simulating urban free driving conditions. During the development, we completed the camera-based eye-tracking system, the collision warning and pedestrian detection functions, and began the ergonomic optimization of the displayed information.

We created an indoor demonstration and test environment, the so-called AIMotionLab, where trajectory planning and control algorithms developed for solving cooperative robotics tasks can be tested and validated on real systems.

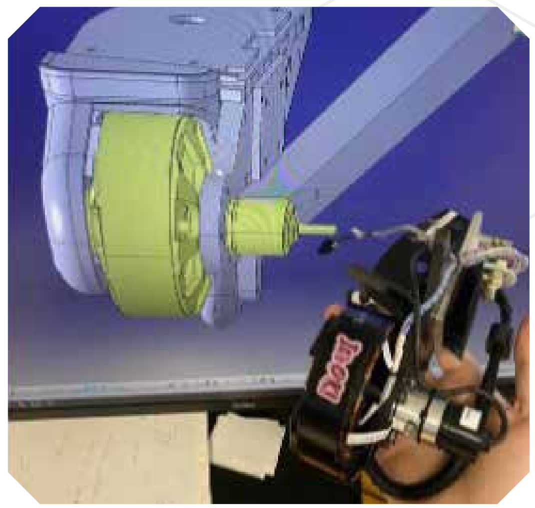
We designed and built a unique indoor drone (Bumblebee) to ensure full control of the experiments conducted in the AIMotionLab drone arena. In addition, we can conduct experiments with F1TENTH cars, and the integration of additional robots is easy thanks to the developed interfaces.

In addition to the real environment, we created a digital twin model of the test environment in the MuJoCo advanced physics simulator – this is AIMotionLab-Virtual, which contains twin models of all drones. We designed the two systems to be able to work together, creating an extended virtual reality in which real and virtual drones can be operated in a shared space.

Research and development was carried out to build industrial-grade, rapidly iterative drone technology capabilities with a focus on demonstration purposes. We designed, developed and tested a unique autopilot, an autonomous on-board control system (HW + SW) for ground, aerial and water vehicles.

We also developed unique actuators contributing to an industrial project and created a unique autopilot for fixed-wing drones using an advanced HIL framework and MATLAB/Simulink-based automatic code generation.

In cooperation with an industrial partner, we fine-tuned the VTR Hornet on-board control system for „tail-sitter" drones with vertical take-off and landing (VTOL) capabilities, which are radically different from traditional drones. The main goal of the development was to support the analysis



of flight tests and to investigate the application of fault detection methods during real flight tests.

The actuator developed in-house has achieved a breakthrough in the field of active flutter suppression during flight. Based on laboratory and flight experiments, the system is capable of accurate position tracking and stable operation even in the critical frequency range, which is unique in the world.

Hydrogen fuel cell propulsion could be a key breakthrough in drone technology, as it enables long flight times and emission-free operation. The research is directly aligned with the European green transition objectives and sustainable air mobility trends. During the research, we studied

the dynamics of the fuel cell: we created a mathematical model that takes into account the effects of load, temperature, and flight profile. This model is the basis for fuel-optimal route planning algorithms that aim to minimize hydrogen consumption and maximize flight range.

We implemented a complex data management system that ensures the management of large-scale and heterogeneous research data on the HUN-REN Cloud infrastructure. The platform aims to support the entire data lifecycle: from data collection from indoor and outdoor sensor networks, through real-time pre-processing and transformation of data streams, to long-term storage, visualization and analysis.

The key to data management is the use of dynamically scalable, containerized services and virtual machines, which ensure the reliable operation and scalability of the system. The environment created not only enables the secure and efficient management of data, but also provides decision support and, if necessary, active intervention based on these data.

We have built a permanent GNSS station at the ZalaZONE automotive test track and integrated it into the European Permanent Station Network, so that others can also freely use the station's data, for example, to maintain a geodetic reference system and monitor plate tectonic processes. In addition, we also use the measurement results for environmental remote sensing applications (e.g., atmospheric humidity, ionosphere status).

Based on data from mobile mapping, we created MathWorks® RoadRunner models of the surveyed track elements of ZalaZONE Park. During the course of our work, we developed several model sets that are suitable for the accurate and realistic modeling of domestic roads and their surroundings, and also enable development and testing in a dynamic urban environment. The models, developed in cooperation with Mathworks® development engineers, are now available to MATLAB users.

TALENT MANAGEMENT

The National Laboratory for Autonomous Systems treated talent development as a key strategic priority throughout the entire duration of the project, recognizing that the long-term competitiveness of domestic autonomous technologies primarily depends on well-trained and motivated young professionals. During the project, students were able to engage in real research and development tasks at an early stage, gaining insight into state-of-the-art methods in autonomous vehicles, robotic systems, artificial intelligence–based control, and sensor fusion. Mentored research activities and participation in project-based tasks provided opportunities for participants not only to acquire theoretical knowledge, but also to develop project-based thinking, teamwork skills, and an innovation-oriented mindset.

Events organized by the National Laboratory for Autonomous Systems, as well as those implemented with its support and with the active involvement of its researchers and developers, served not only to transfer scientific knowledge but also to actively encourage students toward technical, engineering, and research careers. These activities directly contributed to talent development in the field of autonomous systems, motivating young people and fostering the integration of emerging talents into the national innovation ecosystem.

In order to strengthen talent development, the National Laboratory for Autonomous Systems participated in the following key career-orientation, science communication, and talent development events:

- The closing event of the REFORMula Challenge Innovation Competition, co-organized by ARNL,

was held on 30–31 May 2025 in Mátraháza, with the participation of nearly 50 secondary school students. This event played a significant role in enabling young participants to actively test their creative problem-solving skills through engineering tasks based on autonomous systems.

• ARNL researchers and developers took part in the "Girls' Day" event at BME, where young participants interested in vehicle engineering and the laboratory's autonomous vehicle platform were able to explore the field through hands-on activities. This represented an especially important step toward promoting gender equality in innovation-driven career paths.

• In April 2025, ARNL researchers delivered a lecture titled "Artificial Intelligence and Autonomous Vehicles" during a career-orientation day at the Pécs Reformed College Secondary School, where they presented the laboratory's work to secondary school students, inspiring them toward technical and research-oriented career paths.

As a result of the talent development program, the number of young researchers and engineers with expertise in the field increased significantly, with several participants continuing their diploma projects, doctoral research, or subsequent professional careers in close connection with the laboratory. The project thus delivered not only scientific and technological results, but also contributed in a sustainable manner to the development of a strong, future-oriented professional community that will support the long-term advancement of autonomous systems in Hungary.

VISION AND RESEARCH DIRECTIONS

Building on the strengths of the National Laboratory for Autonomous Systems and the results presented in this technical report, and combining them with state-of-the-art international trends, we identified four specific, utilizable future research directions. A brief description of these directions outlines what we plan to research, why the topic is relevant to NLAS, how we approach the problem, what the indicators of success are, and who the potential partners are.

Vehicle control and identification

We aim to further develop the results achieved by combining data-driven and model-based control, the real-time model adaptation for autonomous ground and air vehicles using online reinforcement learning, improving stability and performance in the presence of varying dynamic effects (load, tire wear, wind, etc.). The approach bridges the gap between nonlinear dynamic modeling and linear control design.

We develop online identification procedures (sensor → feature extraction → incremental operator update) and integrate them into the Model Predictive Control (MPC) / supervisory control structure in the NLAS digital twin system, finally validating the results in a Hardware-in-the-Loop environment (laboratory, road and air test vehicles). By using safety control loops, this approach provides statistical guarantees even in noisy environments. Our goal is to achieve 30-50% faster model adaptation in the event of dynamic disturbances, while maintaining the same level of tracking error.

With these results, in addition to collaborating with control theory research groups at renowned foreign universities and research institutes, we can play a role in solving scientific tasks arising in automotive OEMs.

Sensor fusion in the case of incomplete data

Building on NLAS's successful sensor fusion work, we plan to create robust sensing methods that can handle sparse and incomplete scans, disturbances and false detections, as well as hostile signals – all of which are critical for high-speed positioning, ground and air trajectory motion and vehicle tracking, and AV safety.

We plan to conduct research in the areas of differentiable particle and graph filters, training end-to-end fusion networks with synthetic + real radar/camera/LiDAR data, and integrating Bayesian uncertainty estimates into the design process. Our goal is to improve detection/tracking accuracy for sparse data, reduce the impact of latency, and ensure robustness in the event of occlusion/false measurements.

The actively researched topic and NLAS's internationally unique access to the ZalaZONE test track offer us an outstanding opportunity to increase our international visibility and position NLAS as a global „Open Science" contributor. This requires the publication of a public dataset via the HUN-REN Cloud (including environmental and weather metadata) and the development of benchmark machine learning models and evaluation scripts.

The results could be useful for both sensor manufacturers and automotive suppliers, and cooperation with foreign research laboratories working on computer perception and vision will help us become more internationally embedded.

Control and safety of cooperative systems

Our primary goal is to integrate cooperative, reliable, and safe ground and air vehicles into traditional transportation, safety, and sustainability solutions. This approach increases traffic efficiency and safety while significantly reducing the impact of human error.

A further objective is to extend the neural network-based mesoscopic V2X communication simulator of NLAS to support the analysis of resilience to cyber attacks (DoS, spoofing, message loss), and to create a real-time, city-level testing platform for AI-based traffic management and security assessment.

International organizations (e.g., EU CCAM, ETSI ITS-G5) are focusing on „cybersecurity-by-design," and NLAS, with the help of the ZalaZONE infrastructure, can play a leading role in providing a scalable, machine learning-based test environment.

We want the simulator to run in quasi-real time on an urban scale, and traffic control can be considered reliable if the reduction in safety is less than 5% under moderate attack intensity.

To boost our international positioning, we plan to organize conferences on control theory and the automotive industry, and actively participate in the CCAM consortium alongside Horizon Europe. The above topics related to cooperative systems also open new doors for us towards the automotive OEM sector.

Safe human-robot interaction

According to the latest studies, the main obstacle to the spread of autonomous systems is the low level of social acceptance (lack of trust). Therefore, we plan to expand our research on human-robot collaboration (e.g., ethical maneuvering, pedestrian interaction, robotized manufacturing) in the direction of socially acceptable, explainable decision modules and human-centered interfaces (Head-Up Display, Augmented Reality).

Our goal is to combine game-theoretical pedestrian models tested in user studies, intention-based inference, and interpretable decision summaries (HUD/AR), integrate them into ZalaZONE urban scenarios, and measure behavioral changes. We want to achieve an improvement in trust/acceptance measured in a sociologically and psychologically relevant way, with reduced emergency interventions. Our partners could be urban transport authorities and international research groups dealing with human factors.

As a promising and strategically coherent extension of this area, we plan to launch a „humanoid interaction and control" program focusing on the control, perception, and simulation of humanoid and quadrupedal robots using artificial intelligence, integrated into the AIMotionLab digital twin system, with a focus on safe human-robot collaboration.

Our vision is that NLAS will eventually position itself as a key player in European humanoid initiatives – without having to manufacture hardware (complete robots).

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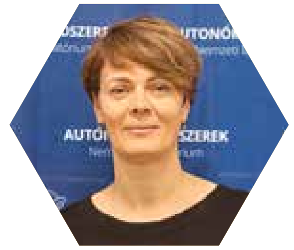

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