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Editorial

Challenges in the Guidance, Navigation and Control of Autonomous and Transport Vehicles

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1. Introduction

In recent years, autonomous and transportation vehicles have been evolving towards more electric or hybrid electric systems, with new challenges arising in their guidance, navigation and control (GNC) systems. Some of these challenges are focused on allowing vehicles to operate more autonomously and efficiently but also more safely in challenging or increasingly congested city environments. Some of the challenges also involve anticipated requirements for collaborative GNC to allow new capabilities such as platooning or to benefit from the new mission capabilities that can be made possible through the coordination of different vehicle types. Some answers to these challenges have been developed in recent years, such as simultaneous localisation and mapping (SLAM) approaches [1]. Increasing levels of autonomy are also driving a need for advances in sensor fusion, trajectory optimisation and control, while new actuation and control technologies are giving rise to new control problems. These include torque vectoring [2], for which energy-optimised control allocation approaches have been developed but with little consideration of lateral motion control, for example. Another control challenge is the development of regenerative braking solutions for electric or hybrid vehicles in driving modes such as eco-approach [3] and autonomous lane management. Other challenges are associated with the new environments where some vehicles are increasingly required to evolve. These challenges must be addressed while meeting requirements regarding safety, efficiency and emissions for different types of autonomous or transportation vehicles, ranging from mobile robots to ground vehicles and aircraft. In the field of electric aviation, policies are shaping some of the priorities in the fields of GNC and vehicle autonomy. The Federal Aviation Authority (FAA) was recently (May 2024) authorised by the United States (US) House of Representatives to issue approvals for beyond visual line of sight (BVLOS) electric vertical take-off and landing (eVTOL) and drone operations, which will imply advances in their flight safety and autonomy. In Europe, the European Union has also adopted legislation on drones and eVTOLs, including air taxis, as part of a wider strategy towards reaching net-zero emissions by 2050. In the United Kingdom (UK), routine BVLOS drone operations by 2027 and fully autonomous eVTOL flights by 2030 are part of the UK Future of Flight Action Plan [4]. Many of the proposed innovative drone and eVTOL designs use hybrid aircraft configurations with new fault tolerance, aerodynamics and control challenges, combining the ability to cruise like a plane with VTOL capability. In car manufacturing, similar electrification trends are being observed, and the UK has, for example, mandated that zero-emission vehicles will represent 80% of all car manufacturers' sales by 2030 and 100% by 2035. The majority of road vehicles will also offer autonomy level 2+ (as defined by the Society of Automobile Engineers (SAE) International) or higher from 2030 [5], which will include new features such as lane-keeping assistance, safe distance maintenance, and automatic lane change manoeuvres. The proportion of vehicles with level 3 to level 5 autonomy will

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Citation: Horri, N.; Holderbaum, W.; Giulietti, F. Challenges in the Guidance, Navigation and Control of Autonomous and Transport Vehicles. *Appl. Sci.* **2024**, *14*, 6635. https://doi.org/10.3390/app14156635

Received: 16 July 2024
Accepted: 21 July 2024
Published: 30 July 2024

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also significantly increase compared to current levels. A direct implication is the need for higher-performance integrated sensor fusion using radar, Lidar and visual navigation technologies and higher-level computation performance, which also implies efficient GNC algorithm implementation. These trends are global; a fast-growing electric vehicle and eVTOL industry is also emerging in China, for example. Advances in vehicle autonomy also require the development of sense-and-avoid technologies and algorithms, the ability to autonomously handle constraints and recover from faults or sensor signal interruption, and an efficient combination of manned and automated control systems. Optimal and robust navigation and control systems are required to meet the performance challenges and energy requirements of the modern day. Increased levels of autonomy will also require advanced multimode navigation and control system architectures, including hierarchical mode-switching control strategies to handle challenges such as autonomous driving at junctions and roundabouts [6] and sensor fusion-based navigation algorithms in global navigation satellite system (GNSS) degraded environments [7]. Computationally efficient and optimal machine learning-based methods are also increasingly employed for autonomous vehicle path planning and following in urbanised or challenging environments or to deal with challenges linked to the vehicles themselves, as in the case of differential-drive ground vehicles [8]. When multiple vehicles are involved, some of the future GNC challenges will involve collaborative navigation and control problems, with accuracy, synchronicity and connectivity requirements, involving groups of similar (e.g., platooning with communication delays, as in [9]) or heterogenous vehicles to offer real-world solutions that other configurations cannot offer [10].

The Special Issue that led to this book captures the diversity of the research, hot topics and latest advances in GNC systems for a good range of transport and autonomous vehicles. It brings together some of the theoretical developments, as well as simulation-based and experiment-based studies in the field. This editorial aims to encourage the reader to explore these publications and to appreciate the commonalities between the main emerging GNC research priorities for a diverse range of transport and autonomous vehicles.

2. Growing Research Areas in Vehicle Navigation and Control

From this Special Issue on the GNC of autonomous and transport vehicles and from global policy trends, it is possible to identify areas for which research and development interest is growing in vehicle navigation and control, driven by the needs of the industry and by policy decisions in the field of future transport.

The articles collected in this book cover air, ground and sea vehicles over the time horizon from 2022 to 2024. The current trends identified in these articles indicate that navigation challenges in cities or challenging environments represent the leading research direction, followed by trajectory optimisation and control challenges. The navigation and trajectory optimisation challenges are mostly focused on sensor fusion, collaborative localisation or navigation in challenging or urbanised environments. Control challenges are often associated with new actuation and control system technologies.

Sensor fusion and sensing for specific environments are the focus of a number of contributions. Contribution 1 introduces a machine learning algorithm that consists of a new version of the light gradient boosting machine (GBM) regression algorithm. This algorithm displays improvements as compared to a random forest algorithm, through faster training and more accurate prediction of the vehicle's position during a global navigation satellite system (GNSS) outage, by using the inertial navigation system (INS) in a GNSS/INS implementation. In Contribution 4, multiple positioning systems including GNSS, simultaneous localisation and mapping (SLAM) and INS are used, and error residuals are used for fault detection and correction in an autonomous vehicle. In Contribution 13, issues with poor GNSS signal quality are also handled for application to forestry vehicles. To deal with a similar problem, Contribution 12 uses computer vision based on a YOLOv4 image detection architecture and an nVidia Jetson AX Xavier device with the ability to handle image quality issues and detect landmarks in the Arctic region. Another computer vision-based approach is proposed in Contribution 21, using Kalman filtering with dynamically adjusted measurement noise to allow for precise navigation using multiple tags in environments where GNSS signals are not available. Apart from environment perception issues using sensors, the importance of scene understanding is also emphasised in Contribution 16 for autonomous robot navigation in unstructured environments. Multimodal data fusion is another challenge and is the focus of Contribution 17, wherein a generative adversarial network (GAN) model framework to fuse different types of images and data is proposed for autonomous vehicles.

Connected autonomous vehicles are at the centre of several contributions to this Special Issue. In Contribution 3, the focus is on the secure platooning of multiple vehicle convoys against denial-of-service jamming attacks that exploit the fact that such convoys rely on wireless communications. To overcome this cybersecurity challenge, a behaviour-based approach is used where sensor inputs are fed to a behaviour manager that is used to arbitrate between possible actions. The behaviour manager leverages layered costmaps with Vector Field Histogram (VFH) path planning. In Contribution 11, the focus is on energy efficiency. In Contribution 7, the focus is on the specific problem of cooperative control at roundabouts through the optimisation of merge-in flows under vehicle safety constraints. The cost function being optimised accounts for the waiting time and the number of vehicles at the roundabout, with improved queue lengths and safety. Collaborative networks of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) are another emerging hot topic. Contribution 5 tackles the cooperative localisation problem in a UAV–UGV vehicle network in three dimensions. In Contribution 6, a UAV–UGV multicast cluster-based routing approach is used to increase the communication throughput and reduce delays in landmine detection and message dissemination between different vehicles. Cluster maintenance algorithms are used to incorporate motion (speed, direction) information and update the record (group) of vehicles in the cluster.

Control challenges are also presented in this book to address emerging challenges with advances in power, actuation and control technologies. Contribution 8 is focused on the use of nonlinear programming to optimise hybrid electric vehicle (HEV) power distributions. Contribution 15 focuses on torque vectoring strategies for hybrid vehicles with in-wheel rear motors and presents a comparison of different optimal and sliding-mode control strategies. In Contribution 10, a fuzzy logic rule-based approach is used to determine the torque of the powertrain system and manage regenerative braking and eco-approach, using a conventional pure pursuit lateral controller and realistic powertrain models. In Contribution 19, a new actuator that uses shape-memory alloys is used for idle air control, with PID control to manage actuation stroke delays.

Path planning and trajectory optimisation issues are also covered in this book. In Contribution 14, an improved hybrid A* graph-based global path planning algorithm is used for a nonholonomic mobile robot using a robot operating system (ROS) implementation and model predictive control (MPC) for local path planning to avoid obstacles, with reduced path lengths and search times as compared to A* + DWA (dynamic window approach). A new path planning algorithm is also proposed in Contribution 18, using an improved bidirectional search Gaussian (BSG) A* algorithm for differential-drive mobile robots, with reduced path lengths and search times as compared to D* lite (dynamic A*), the genetic algorithm (GA) and ant colony optimisation (ACO). Machine learning is another research trend in this field, particularly for increasingly autonomous vehicles. Reinforcement learning is used in Contribution 20 for the dynamic trajectory optimisation of a self-driving vehicle.

Other areas that are less strongly present in this Special Issue but where research will be essential include the handling of connectivity constraints in vehicle trajectory optimisation and control problems, particularly the ones requiring communication between vehicles, as in the case of unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV) collaboration, but more generally in the case of vehicles navigating within sensed environments and obtaining information from a ground sensor network using advances from the Internet of Things (IoT). The human–machine aspects of interfacing human operator input with automation remain important, and Contribution 2 of this Special Issue illustrates an example of the effect of onboard training in simulated maritime environments on the navigation performance of autonomous surface vessels. Contribution 9 focuses on scenario designs for advanced driver assistance systems (ADASs) and autonomous driving systems (ADSs) applied to longitudinal motion using MPC-based driver models. To construct the models, human drivers' characteristics were derived using a large driving database. Future systems are expected to allow both humans and machines to learn from each other, even though increasingly autonomous systems are also expected to operate with reduced human operator input.

3. Conclusions

This book presents a collection of articles spanning the diversity of GNC with applications to different types of autonomous or transport vehicles. Many of the foreseen challenges lie in the development of robust and fault-tolerant navigation systems allowing the vehicles to operate in challenging environments, including GNSS-denied or degraded environments, urbanised environments, and environments that are difficult to access due to severe weather or other conditions. To address these challenges, sensor fusion methods and systems will be needed to advance emerging capabilities, such as the ability to sense and avoid obstacles. Other challenges are linked to system complexity and connectivity issues when multiple vehicles are required to operate in the same environment and collaborate to perform missions. Control challenges are emerging from the new power systems and control technologies that are being developed, given the increased reliance of autonomous and transport vehicles on electric power to meet emissions and energy efficiency requirements. Trajectory optimisation is also becoming increasingly challenging, with an increased reliance on artificial intelligence and machine learning approaches, even though there is still a need to further develop the robustness and performance of mainstream optimisation techniques for new vehicle types and their applications.

Acknowledgments: The authors of this book would like to thank all contributors to the Special Issue https://www.mdpi.com/journal/applsci/special_issues/Autonomous_Transport_Vehicles, (URL accessed on 15 July 2024) without whom this book would not have been possible.

Conflicts of Interest: The authors declare no conflicts of interest.

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