Self-Driving Cars

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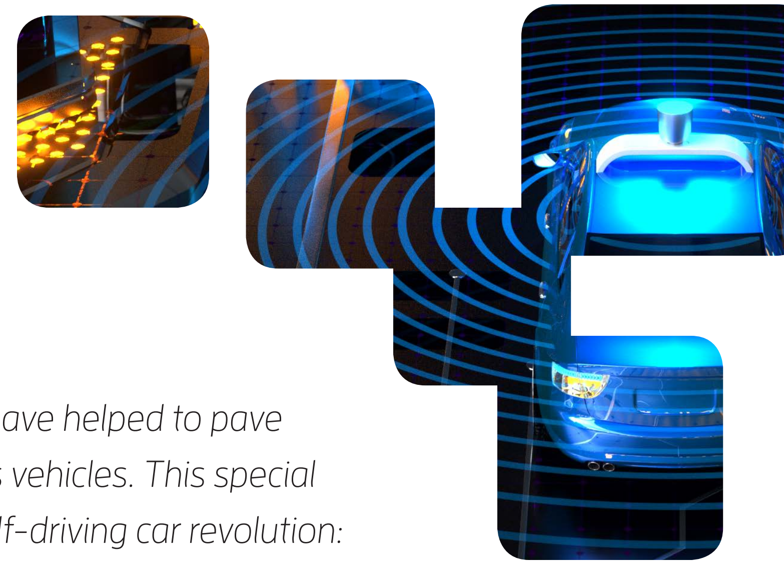


Many recent technological advances have helped to pave the way forward for fully autonomous vehicles. This special issue explores three aspects of the self-driving car revolution: a historical perspective with a focus on perception for autonomous vehicles, how government policy will impact self-driving cars technically and commercially, and how cloud-based infrastructure plays a role in the future.

Significant improvements in the last decade have greatly advanced self-driving car technology. These new capabilities will have profound global impacts that could markedly change society, not to mention the significant improvements they bring to the overall efficiency, convenience, and safety of our roadways and transportation systems. Addressing self-driving technology–related concerns is important, particularly given these broad potential impacts. Worldwide, 10 trillion automobile miles are driven each year, with complex and novel conditions generating millions of situations in which autonomous vehicles could fail. Yet there are many challenges that remain across all levels of system functionality.

To give readers some context for the work covered in this special issue, we have provided a summary of ongoing work in Asia, Europe, and the United States, as well as in academia.

SELF-DRIVING CARS IN ASIA AND INDIA

Several Asian countries including China, Japan, Korea, Singapore, and India are making significant contributions to the field. Although these countries are in various stages of adoption with respect to connected and autonomous vehicles, more effort is needed before these technologies can be reliably deployed on a large scale. Customizing and improving the existing automated driving technologies to traffic patterns and specific scenarios relevant to Asia remains a major focus of research in this region.

In addition to major Asian cities like Singapore, Shanghai, and Tokyo building deployment sites for testing and evaluating self-driving cars, significant activity in Asia-based corporations continues to expand. For example, Samsung in South Korea recently acquired US infotainment and audio company Harman, making it a Tier 1 company (Tier 1 companies supply parts to original equipment manufacturers [OEMs] like BMW). Analysts expect Samsung will now play a role in automotive telematics, infotainment, and driver-safety technology. In addition, Hyundai Motors is working with HDmaps to field self-driving cars in time for the 2018 Pyeongchang Winter Olympic Games. In Japan, automakers are working together to make self-driving cars a reality in time for the 2020 Tokyo Olympics.

In China, web services company Baidu is leading the way among Asian companies in bringing innovative deep-learning technologies to self-driving vehicles through its Project Apollo. Baidu's self-driving platform offers many capabilities including obstacle perception, route planning, cloud simulation, HD maps, and end-to-end deep learning. Whether this approach is adopted by a wider audience remains to be seen. The Chinese government has plans to encourage adoption of autonomous vehicles by 2025, particularly in the trucking industry. Several other OEMs, such as Didi Chuxing, NIO (formerly NextEv), Faraday Future, Geely through its ownership of Volvo, and Nvidia through its investments in JingChi are all in the race to reshape the transportation industry in China as well as the rest of the world.

Similarly, Tata and Mahindra in India are making progress in developing market-viable automated driving technologies that are relevant to local conditions. And, in Vietnam, FPT has set up a 1,000-person team to develop automated driving technology.

Intel, which can now claim to be a Tier 2 automotive supplier with its acquisition of collision-avoidance system purveyor Mobileye, is making significant progress in Asia through its development of deep-learning capabilities. The company is putting together integrated heterogeneous platforms with multicore processors, field-programmable gate arrays (FPGAs), and chips that are much needed for automated driving.

Singapore, with its high population density, small physical area, and high adherence to traffic regulations, has proved to be an ideal environment for adopting driverless cars. nuTonomy (recently acquired by Delphi) and Drive.ai are using Singapore as a base to develop technologies impacting mobility, and nuTonomy has begun work on self-driving taxi services.

In many countries in the region, such as India, Thailand, Indonesia, and Vietnam, the transportation systems and the experience of driving are challenged by the lack of a regulatory environment, sound infrastructure, adherence to traffic laws, and safe driving practices. The presence of heterogeneous classes of on-road vehicles, the irregular compliance to traffic rules, close proximity of surrounding vehicles especially in highly congested areas, unstructured road conditions and traversal patterns, unexpected scenarios, unpredictable driving habits, and poor signage all need to be tackled with novel technologies. Often traffic chaos overburdens the lanes—four lanes of vehicles form and try to use two physical lanes—reducing the safety envelopes around vehicles to a few centimeters. Existing autonomous vehicle technology can only serve as a baseline upon which custom and affordable solutions will need to be further developed. Accident rates in such countries are high, with nearly 150,000 deaths every year in India alone—that is almost 400 every day. Thus, Asian countries' governments are very focused on reducing the accident rates, as well as on promoting initiatives for reducing pollution caused by cars clogging the roads.

Beyond the latest wave of automated driver-safety solutions, such as blind-spot warnings, lane-departure warnings, lane-change assistance, and adaptive cruise control, successful adoption and viability of autonomous vehicles in Asian countries will require much more work in other areas. Because safety rules are often violated in these regions, autonomous vehicles with current technologies would freeze or not function properly. Systems deployed in these environments will need to be more aggressive and take more risks while learning to sense and interpret social cues, become context-aware, and understand driver intent as they are scaled to negotiate a plethora of scenarios. Inclement weather presents another challenge for autonomous vehicles in these regions, particularly given that the generally poor road infrastructure also warrants the need for better detection of hazards such as potholes, especially if recommended speeds have to be maintained.

In India, which is one of the larger markets, a gradual adoption of autonomous technologies is expected, with initial deployments and expansion in farming and mining applications. Indian OEM Mahindra is working toward providing autonomous capabilities to its farm equipment, exploiting the structured environments and regular driving patterns. There is also the expectation that government initiatives to reduce pollution rates by reducing automobile congestion in the narrow lanes would also help leapfrog to electric vehicles, thereby easing the transition to autonomous vehicles. Of course, the cost of an autonomy sensor suite must come down, because the current lowest price for LiDAR is equivalent to the price of two entry-level cars, and, for a fraction of that, many Indian car owners can afford to pay a chauffeur to drive them around.

Several of the campaigns across Asia are looking to leverage open source or curated software, lower research costs, establish strict regulations, employ a minimalistic sensor suite, and exploit learning from simulations to reduce accidents, make traffic flow smoothly, decrease pollution, and improve safety and reliability to customers, especially as we move toward complete autonomy.

AUTONOMOUS VEHICLES IN EUROPE

On the European front, several significant autonomous vehicle research efforts have been underway since the 1980s which laid the foundations of autonomous vehicle technology. In particular, the Eureka PROMETHEUS Project (Programme for a European Traffic of Highest Efficiency and Unprecedented Safety [1987–1995]), funded by the European Commission, provided support for the development of many groundbreaking technologies that would eventually lead to the driver-assistance systems we know today. Aimed at improving road traffic safety, the project attracted many European car manufacturers that became participants and developed the early prototypes of these

components and approaches. The most ambitious of the program's funded projects was the development of the first fully autonomous passenger road vehicle. Many of the resulting technological approaches (such as the 4D approach, recursive estimation, and clothoid modeling of road curvature) set the standard for the suite of driver-assistance systems we use in modern vehicles. The 4D approach also inspired the NIST 4D/RCS reference architecture for unmanned vehicle systems. It is worth noting that in this special issue, author Ernst D. Dickmanns, the architect of this 4D approach, describes the historic development and significance of this concept throughout the past few decades. Among other prizes, he was awarded the IEEE ITS Lifetime Achievement Award in 2016 for his contributions to autonomous vehicles.

After government funding for self-driving vehicle technologies dried up in the late 1990s, further development in this area was conducted with less public participation and less media coverage. However, in 2005 autonomous driving was back in the public spotlight when German car manufacturer Volkswagen collaborated with Stanford University, and their vehicle (named "Stanley") became the winner of the 2005 US DARPA Grand Challenge, beating the assumed front-runner vehicle by Carnegie Mellon University. Since then we have seen a lot of growth in development of driver-assistance technology by many car manufacturers across the world and particularly in Europe, and much of this technology is available in our cars today.

In 2017, German lawmakers set the legal framework for allowing self-driving vehicles on public roads (as long as a human driver is at the controls, to take over in critical situations), helping to realize this technology by providing clear legislation and legal responsibilities for its use. Work continues on these technologies such that it is expected that by 2020 a vehicle of Level 5 autonomy (fully autonomous) could be delivered. However, we still need to address the legal framework for situations in which vehicles have no human driver, no steering wheel, and no pedals.

SELF-DRIVING VEHICLES IN THE US

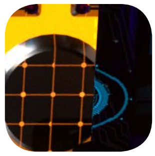
In the US, the technology for self-driving cars—not to mention the business, policy, legal, ethical, and regulatory challenges—have received enormous attention in the popular media. Not a day goes by without additional coverage, new information, and predictions of lasting changes in the US transportation and transit systems. The business models of automotive manufacturers operating in the US are in flux. Autonomous vehicles have the potential to remake not only the automotive industry, but transportation services and infrastructure requirements for cities as well.

In the US, Level 2 systems (that is, partial automation in which humans are still responsible) are available from a number of automotive manufacturers. For example, Cadillac's Super-Cruise on the CT6 model enables lane following with adaptive cruise control, while monitoring the driver's eye movements to determine vigilance.

Level 3 systems (conditional automation with some human involvement) are still under development. For example, the Audi 8 aims to be one of the first production cars to offer initial capability at less than 40 mph within the next year. Commercial autonomous ride-sharing services could be the enabler that helps build out the technology while limiting complexity and avoiding cost constraints. For example, Cruise, Waymo, Uber, and Lyft are all planning service rollouts in the next year or so in limited "geo-fenced" regions.

A huge influx of interest and funding are supporting advances in self-driving systems. Waymo has spent over $1.1 billion so far to develop its own internal capability, with particularly large investments in simulation and mapping, as well as real-world driving, training, and testing. Many suppliers of sensing and perception systems are pursuing lower-cost alternatives. A number of companies are developing LiDAR systems that can function in much smaller, more easily produced packages, even on a chip (for example, Strobe, Valeo, and Velodyne). The rapid development of higher-quality sensing in the optical, radar, and LiDAR domains has helped funnel data to a variety of deep-learning systems to recognize objects with improved detection accuracy and fewer false-positives. In today's systems, processing throughput is predominantly determined by front-end perception capability, which has received much attention from non-automotive companies, including Intel (through its acquisition of Mobileye) and Nvidia.

In the US, most technology developers agree that more advanced decision-making capability is needed to enable functionality in the difficult "corner cases." Exactly how this can be accomplished is still an open question: a next generation of data-driven deep-learning methods, top-down knowledge–driven



reasoning, and everything in between. Another challenge is the means to prove a system is safe; there is interest in a variety of possible solutions, ranging from formal methods to accelerated testing in simulation to driving lots of miles. The path to fully autonomous vehicles will depend greatly on the future developments in the areas of improved decision-making and demostrating safety.

ACADEMIA'S CONTRIBUTION

As in most scientific and technological breakthroughs, academic researchers have played and continue to play a major role in contributing innovative and novel ideas, proof-of-concept systems, and a continuous pool of talented engineers and entrepreneurs in advancing the technology that makes autonomous driving and highly automated vehicles a reality. These contributions come from multiple engineering and computational science disciplines. Given the nature of these vehicles, intelligent systems orientation and real-world experimental programs have found a special niche in advancing the field of autonomous driving—not only in academic research groups but also, more recently, in industry.

Self-driving and highly automated vehicles must navigate smoothly and avoid obstacles, while accurately *understanding* the highly complex semantic interpretation of scene and dynamic activities. For achieving such goals, further developments in perception, 3D scene understanding, and policy planning are needed. Designing fully autonomous robotic vehicles that can drive on roads typically does not require models of drivers and how they interact with vehicles. In contrast, the design of intelligent driver-assistance systems, especially those that activate controls of the car to prevent accidents, requires an accurate understanding of human behavior as well as modeling of human–vehicle interactions, driver activities while behind the wheel, and predictable human intent.

In a relatively short span of about three decades, a handful of vehicle prototypes that passed a "self-driving" test in carefully orchestrated demonstrations in fewer than a dozen labs have so far given rise to technology to support highly automated driving and advanced driver-assistance systems in millions of vehicles currently on the road. Highly reliable and accurate sensing, digital mapping, embedded systems, powerful computing, machine perception, sensor fusion, machine learning, path planning, and control have been crucial in making these technological advances.

It is the noteworthy and sustained contributions of academic institutions in both the US and Europe that have proved critical: for example, technological advances in the areas of distributed dynamic controls, computer vision, and machine learning from the University of California, Berkeley; intelligent robotic systems, machine vision, and experimental AI from Carnegie Mellon University; simultaneous localization and mapping (SLAM) and robotics at Stanford and the University of Michigan; and human-centered intelligent vehicles and vision systems from the University of California, San Diego, have clearly moved the research and development of these technologies to the market in a big way. These advances offer a glimpse of how key ideas from academic labs have played a foundational role in what is rapidly becoming one of the most far-reaching technological and societal revolutions since the advent of the transistor.

However, there remain many important issues in need of deeper examination so that the safety, reliability, and robustness of these highly complex systems can be assured. Moving toward vehicles with higher autonomy opens new research avenues in the areas of learning, modeling, active control, perception of dynamic events, and novel architectures for distributed cognitive systems. Furthermore, these challenges must be addressed safely and within very tight time constraints to avoid collisions or unstable operation. Globally, many academic institutions, in partnership with industry and government agencies, are now committed and seriously engaged in the field. Interested readers can follow IEEE publications such as *IEEE Transactions on Intelligent Vehicles*, *IEEE Transactions on Vehicular Technologies*, *IEEE Transactions on Robotics and Automation*, and *IEEE Transactions on Intelligent Transportation Systems* for important and exciting new developments in the field. For a current technical overview of autonomous vehicles, see the new book *Creating Autonomous Vehicle Systems*.[1] We are confident that any limitations of the current breed of autonomous vehicles will be successfully resolved to withstand the real-world test of time.

IN THIS ISSUE

We received many high-quality submissions for consideration, and after rigorous assessment by dedicated reviewers, we selected three articles that represent the arc of research and development in self-driving vehicles.

In "Developing the Sense of Vision for Autonomous Road Vehicles at

UniBwM," pioneer Ernst D. Dickmanns describes efforts under the European PROMETHEUS Project, which began in 1987 to lead the charge in developing real-time vision capabilities for autonomous vehicles. He traces the development of technologies, including the 4D approach to dynamic real-time vision that used an internal 3D representation in space and time suitable for driving vehicles at highway speeds. By the end of 1994, the systems were capable of a variety of highway driving, including lane-following and autonomous lane changes.

In "Current US Federal Policy Framework for Self-Driving Vehicles: Opportunities and Challenges," Mina J. Hanna and Shawn C. Kimmel offer an in-depth view of the US federal government's current policies and trends in five major issue areas: privacy, cybersecurity, safety regulation, energy and the environment, and ethical issues. These authors give a summary of many of the key impacts self-driving vehicles will have, as well as the principal motivators driving both technology development and government investment in this area. They also discuss the many challenges and opportunities for autonomous vehicle technology developers.

In "A Unified Cloud Platform for Autonomous Driving," Shaoshan Liu, Jie Tang, Chao Wang, Quan Wang, and Jean-Luc Gaudiot describe the features and implementation of a future autonomous driving cloud, an essential part of the autonomous driving technology stack. This unified infrastructure provides distributed computing and distributed storage capabilities, as well as heterogeneous computing for autonomous vehicles. Using this infrastructure, the authors describe how to implement several essential autonomous driving services, including data storage, simulation, high-definition (HD) map generation, and deep-learning model training, all built on a heterogeneous computing layer.

We hope you enjoy this special issue. We thank the authors, reviewers, and *Computer*'s editor in chief and staff for their hard work and assistance in preparing this special issue. Self-driving cars are the future, and we're almost there!

REFERENCE

1. S. Liu et al., *Creating Autonomous Vehicle Systems*, Morgan Claypool Publishers, 2017.

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