Autonomous vehicles: from paradigms to technology

Silviu Ionita
University of Pitesti, Romania
Department of Electronics, Computers and Electrical Engineering
e-mail: silviu.ionita@upit.ro

Abstract. Mobility is a basic necessity of contemporary society and it is a key factor in global economic development. The basic requirements for the transport of people and goods are: safety and duration of travel, but also a number of additional criteria are very important: energy saving, pollution, passenger comfort.

Due to advances in hardware and software, automation has penetrated massively in transport systems both on infrastructure and on vehicles, but man is still the key element in vehicle driving. However, the classic concept of ‘human-in-the-loop’ in terms of ‘hands on’ in driving the cars is competing aside from the self-driving startups working towards so-called ‘Level 4 autonomy’, which is defined as "a self-driving system that does not requires human intervention in most scenarios".

In this paper, a conceptual synthesis of the autonomous vehicle issue is made in connection with the artificial intelligence paradigm. It presents a classification of the tasks that take place during the driving of the vehicle and its modeling from the perspective of traditional control engineering and artificial intelligence. The issue of autonomous vehicle management is addressed on three levels: navigation, movement in traffic, respectively effective maneuver and vehicle dynamics control. Each level is then described in terms of specific tasks, such as: route selection, planning and reconfiguration, recognition of traffic signs and reaction to signaling and traffic events, as well as control of effective speed, distance and direction. The approach will lead to a better understanding of the way technology is moving when talking about autonomous cars, smart/intelligent cars or intelligent transport systems. Keywords: self-driving vehicle, artificial intelligence, deep learning, intelligent transport systems.

1. Introduction

Fundamentally, mobility is ensured by a three-component system: vehicle, driver and transport infrastructure (named in a broader sense environment). Over time, vehicles and infrastructure have evolved spectacularly through technological upgrades and improvements, but the only constant of the system has still remained the human driver. The term of autonomous car is equivalent with driverless auto, self-driving car or robotic car. So the autonomy of a vehicle is seen as its capability to run in traffic without a driver and generally without any human inputs. In technical terms, that means replacing the human driver with artificial subsystems which should be able to perform the specific tasks in a similar manner. Under this circumstance, the artificial system should have the right knowledge, have the ability to reason correctly and behave in line with the previous ones, and that means more than traditional automation and adaptive control. However, the recent literature keeps the generic term automatic as a basis of the concept in self-driving car.

This paper has three objectives: (i) to present the Advanced Driver-Assistance Systems concept in accordance with the standardization introduced by Society of Automotive Engineers for vehicle automation levels; (ii) to explain the intelligent system concept and the directions for implementing artificial intelligence in autonomous vehicles; (iii) to highlight some recent achievements in the field of driverless vehicles.
The SAE International’s new standard J3016: ‘Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems’ [http://standards.sae.org/j3016_201609/] uses the ‘automation’ as the key word to classify the levels of driving automation. There are identified six levels of driving automation from ‘no automation’ to ‘full automation’ that are defined based on functional aspects of technology. The first three levels, conventionally noted 0, 1 and 2 fall in to the category called ‘human driver monitors the environment’ and are defined as follow:

- Level 0 named ‘no automation’ provides only automated on board warnings but has no vehicle control.
- Level 1 named ‘driver assistance’ is a ‘hands on’ stage, where the control of some specific tasks can be shared between the driver and automated system. Typical examples for this level are: The Adaptive Cruise Control (ACC) where the driver controls steering and the automated system controls speed of the car, and Parking Assistance, where steering is automated while speed is controlled by the driver.
- Level 2 is named ‘partial automation’ and provides the so called ‘hands off’ capabilities when the automated system takes full control of the vehicle dynamics in terms of accelerating, braking, and steering. The driver must monitor the driving and be ready to promptly intervene in due time in case of automated system fails to respond properly.

The second category includes the next three levels representing systems able to monitor the driving environments, from Level 3 to Level 5 as follow:

- Level 3 named ‘conditional automation’ or literally named ‘eyes off’ provides functions that make the vehicle able to handle situations when the driver in generally turn their attention away from the current driving tasks. These functions are useful for critical situations that require an immediate response, like emergency braking.
- Level 4 is classified as ‘high automation’ and literally equated with ‘minds off’. This includes the extensions and improvements of functions from Lever 3 providing self-driving capabilities of the car in case of no driver attention exist, for instance the driver may safely go to sleep or leave the driver's seat.
- Level 5 named ‘full automation’ and so called ‘steering-wheel optional’. This level is reached when the system has the total control over the vehicle and no human intervention is required. A generic example might be the robotic taxi.

The above mentioned SAE’s document defines also some key terms that make up a matrix of compliance for the proposed automation levels. We reproduce this matrix in Table 1. The terms considered criteria of performance for driving automation systems are presented as they are mentioned by SAE:

- ‘Dynamic driving task’ includes the operational (steering, braking, accelerating, monitoring the vehicle and roadway) and tactical (responding to events, determining when to change lanes, turn, use signals, etc.) aspects of the driving task, but not the strategic (determining destinations and waypoints) aspect of the driving task.
- ‘Request to intervene’ is notification by the automated driving system to a human driver that s/he should promptly begin or resume performance of the dynamic driving task.
- ‘Driving mode’ is a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high speed cruising, low speed traffic jam, closed-campus operations, etc.).

Besides standard classification the paradigm of autonomous vehicles is currently generating perspectives and new concepts. For example, at the recent 2017 IEEE Intelligent Vehicles Symposium (www.iv2017.org) the topics explore challenging fields of research like machine vision and interfaces in data fusion platforms for automated driving, multi-sensor fusion and extended object tracking, deep learning for vehicle perception, human factors in intelligent vehicles and cognitively inspired intelligent vehicles. The special topics approached is the hot issue of cyber-security and generally the models of short range vehicular communications and data exchanging between vehicles and the environment.
Table 1. The automation levels: Summary of compliance

| Level (SAE) | Type                  | Dynamic driving task | Monitoring of Driving Environment | Request to intervene (When fallback performance of Dynamic driving task) | Driving mode     |
|------------|-----------------------|----------------------|-----------------------------------|-----------------------------------------------------------------------|------------------|
| 0          | No automation         | Human driver         | Human driver                      | Human driver                                                          | n/a              |
| 1          | Driver assistance     | Human driver and system | Human driver                      | Human driver                                                          | Some driving modes |
| 2          | Partial automation    | System               | Human driver                      | Human driver                                                          | Some driving modes |
| 3          | Conditional automation| System               | System                            | Human driver                                                          | Some driving modes |
| 4          | High automation       | System               | System                            | System                                                                | Some driving modes |
| 5          | Full automation       | System               | System                            | System                                                                | All driving modes |

2. The paradigms of intelligent vehicle

The popular approach of the concept ‘intelligent system’ consists in reporting to the human intellect, so the artificial intelligence (AI) is the key field for modeling and developing intelligent vehicle in general. A system that receive the attribute ‘intelligent’ should meet simultaneously the following requirements:

i. To learn in ‘teaching mode’ but also from own experience. This is a necessary condition but not sufficient.

ii. To perform approximate reasoning. This suppose more than true/false logic in formal reasoning, it requires the use of multivalent logic that deals better with the uncertainty.

iii. To behave autonomously. This is the aggregate performance that includes many operational functions based on the first two conditions in order to put in practice the intelligence, which is equivalent with the intelligent behavior.

Now let’s nuanced the entire picture of the tasks that are currently performed for driving of the on-road vehicles. In Figure 1 are synthetically presented the main tasks and subordinated functions which are subject of automation and implementation in to the appropriate manner towards smart/intelligent car achieving.

Advanced Driver-Assistance Systems – ADAS briefly, defines the field of technology and concepts that currently guides the development of autonomous vehicle. ADAS functions added to the vehicle are thought to take on more and more tasks of the driver – his intervention became optional or exceptional. The level of functions implemented on vehicles has an impact on the six levels of the autonomous vehicle defined by the SAE. As we observe the Table 1 the latest two levels of automation require really advanced functions that make possible vehicle self-driving without human intervention in most scenario (Level 4) or even in all scenario (Level 5). Definitely, these levels require certain AI models to process the information and to have the human-like behavior.

Next, we review the functions and tasks in Figure 1 to highlight the level of intelligence needed to implement them in autonomous vehicles. At a glance it can be recognized that certain functions can be implemented with typical AI models like machine learning and expert systems, while others are subject to classical automation like error-based control or state-control. We discuss the issue of vehicle driving in terms of two information processing stages: decision and action (i.e. execution), and three hierarchic levels for problem solving: strategic, tactical and direct. In Figure 2 is depicted a classification of ADAS functions in connection with the levels of decision and execution. The candidate models and time requirement for execution are also specified.
Figure 1. Basic tasks and functions of vehicle driving

| Process Level | Decision                | Action              | Function                                                   |
|---------------|-------------------------|---------------------|------------------------------------------------------------|
| Strategic     | AI Models               | Near real time      | • Trip/route planning                                     |
|               |                         |                     | • Route optimization and selection                         |
|               |                         |                     | • Route reconfiguration                                    |
| Tactical      | AI Models & Adaptive    | Real time           | • Maneuver planning, including control of:                 |
|               | models                  |                     |   • steering, speed, distance, acceleration/deceleration   |
|               |                         |                     |   • All types of current perceptions and events            |
|               |                         |                     |   • anticipated in the environment                         |
| Direct        | Error-based             | Reflex (as short as possible) | • Breaking                                                 |
|               |                         |                     | • All types of current events sensed in the                |
|               |                         |                     |   environment                                               |

Figure 2. Classes of ADAS functions and their requirements for decision and execution

We note the vehicular automation involves the use of AI models as much the decision level is higher – at the strategic and tactical level where the cognitive decision making is strongly required. This is typical for the tasks considered difficult like navigation, and also for specific functions that involves perceptions of the environment and maneuver planning when the time requirements are not critical. On the contrary, the functions where time is critical like breaking and maneuver coordination for collision avoidance, involve basic models of automation for a certain and rapid discrimination instead of a nuanced and elaborated decision. This is required in order to implement into the autonomous cars the reflex mode based action specific to the human driver.
The concept of intelligent vehicle is only a part of the problem. In the real scenario, the vehicle itself is like a smart agent that closely interacts with the infrastructure including roads and intersections of transport routes, car parks, and many other facilities for moving vehicles. Under these circumstances the intelligent vehicles are able to exchange information with the infrastructure but also with the other vehicles in traffic. This is a kind of intelligence sharing and social intelligence that pave the road towards intelligent transport systems development.

2.1. Cognitive technologies
The cognitive systems are models for human brain function that try to reproduce in machines the human-like decision and action. Nowadays, the cognitive technologies represent the practical part of artificial intelligence that merge techniques like traditional rule-based algorithms, neural networks, deep learning and natural language processing. These techniques are currently tested and evaluated into the relevant environments on the prototypes of the autonomous vehicle. The key issue of the autonomous vehicle is monitoring and processing of driving environment in real time using an appropriate sensorial system. The massive quantities of data should be provided in real time by artificial vision systems and should be also rapidly processed such as the required actions to be executed in due time. The vision sensorial systems are currently based on video cameras or radar and lidar sensors but the practice shows the combining them is better approach [7]. The vision sensors are deployed on the autonomous vehicle in order to ‘see’ omnidirectional around it performing environmental mapping. The basic processing tasks are: continuous image acquisition, image processing, features extractions and classification, detection and recognition. At this moment the technology is not validate in relevant environment for any driving mode. The challenge is to perform these tasks in the real traffic context with the lowest error rate. One of the recent reported test on vehicle autonomy comes from Drive.ai, a start-up company whose slogan is ‘Building the Brain of Self-Driving Vehicles’. They involve the deep learning technique trying to touch the SAE’s Level 4 of autonomy and possibly beyond [1]. Knowing by definition that self-driving with Level 4 is supported only in limited areas (‘geofenced’) or under special circumstances, like traffic jams, it is remarkable that Drive.ai drivers have forced the use of their system into urban traffic at night, in the rain. (demo available at https://www.drive.ai/). However, the experiment shows that in certain ambiguous situations, the temporary intervention of human driver was necessary.

2.1.1. Deep learning. This is the advanced technique in machine-learning that involves more complex artificial neural networks (ANN) in terms of number of neurons and number of hidden layers. The main distinction of this kind of neural network, named convolutional neural network (CNN) consists in their capacity to make simultaneously both the recognition and detection of the objects into the image, based on a great number of features extracted automatically thanks to a huge number of training images that were preliminary processed. For instance, deep learning is able to detect and classify different moving entities into the scene: cars, pedestrians, pets or a ball rolled down the road. This is a major improvement over ordinary neural networks that are able to recognize only simple object features (shape, orientation) based on supervised learning with manually-entered templates. This makes deep learning perfect for classifying objects within arbitrary scenes like traffic scenes are. Deep learning based on CNN is a major step towards artificial perceptions and so it is suitable to implement the human-like ability of pattern recognition and detection. Basically, their performance depends only on the quantity of data for training, but in practice should be solved few essential problems like dealing with ambiguity and sensors failing.

2.1.2. Knowledge representation. Knowledge are raw materials for AI models just like equations and numbers are for the mathematical models. The knowledge for vehicle driving are usually represented as rules, but in general the human driver is able to processes unstructured knowledge coming from environment as various stimulus, sensorial and perceptual images composed of objects with certain features, facts and events, seemingly arbitrary. The success of the actions is depending by the mode of the rapid interpretation of such unstructured complex information – the capacity to turn them into structured knowledge, as subject of formal reasoning, or to turn them into right actions via the subtle
intuitive reasoning. Thus, another challenge in the development of fully autonomous vehicles is the use of deep learning to extract knowledge from data and the formation of specific concepts.

There are few tasks of vehicle driving that can be implemented by classical rule-based systems that are representative for Level 1 to Level 3 of vehicle automation like follows: Adaptive Cruise Control (ACC), Parking Assistance with automated steering, Lane Keeping Assistance (LKA) Type II and a combination of ACC with LKA Type II systems, Traffic Jam Assistance and Key Parking, Traffic Jam Chauffeur. All these tasks include functions that reproduce the human expertise as a limited rule-based inference engine, and eventually need a reduced set of data for training. On the contrary, once the training data becomes huge, as in deep learning technology, the knowledge representation can be scaled and nuanced using a larger set of features and objects’ attributes. That is way we consider deep learning technology very promising for intelligent systems engineering and their applications. However, since learning (even deep) is just a necessary but not sufficient condition for the system to be intelligent, then it is imperative to implement a reasoning module with an appropriate basis of inference rules. In Figure 3 are depicted three basic ways in knowledge processing for vehicles driving. We note the bottom path is only that can be completely automatize into a full intelligent driving system on the autonomous vehicles. Formal reasoning is used here in the extended sense, including also analog reasoning and approximate reasoning including fuzzy logic, [3], [4], [6].

2.2. Intelligent vehicle technology

Intelligent vehicle is a largest paradigm that advances the artificial intelligence, the electronics, software and communications in the field of vehicular technologies with impacts on energy saving, reducing pollution, increasing safety and improving comfort of the vehicle and transport. The autonomous vehicle is a part of this paradigm being similar to robotics. In the field of automotive, the pillars of the intelligent technologies can be classified as is following:

a) Intelligent driving systems, including two categories:
   i. Intelligent driver assisting systems (with subcategories: warning systems, infotainment and telematics systems, ‘smart’ devices like advanced front-lighting system – AFS, etc.)
   ii. Systems capable of taking over the driver's tasks.

b) Communications systems, supporting intelligent technologies (known as V2V, V2I, and V2X).

Category (a) includes the most technologies which is currently implementing ADAS but also the technologies that will come to reproduce human intelligence in driving vehicles. Communication technologies (b) are an essential part on the intelligent vehicle so that the fully autonomous vehicle won’t be implemented without a strong data connectivity. Thanks to standardization, V2V and V2I
technologies are ready to move from projects and isolated experiments to commercial. SAE has introduced the name Dedicated Short-Range Communications (DSRC) for many kinds of communications technologies to serve as the basis for connected vehicle safety and mobility application integration. Vehicle-to-everything (V2X) is a vehicular communication system introduced by the American Society for Testing and Materials under the initial name of Wireless Access in Vehicular Environments (WAVE). This technology is dedicated for vehicular ad-hoc networking integrating more specific types of communications V2V, V2I, V2D (vehicle-to-device) and V2G (vehicle-to-grid). Currently, V2X technology exploits the family of standards IEEE802.11 for WLANs, working in 5.9GHz range and it is tested with promising results in relevant pre-deployment projects in US [10] and EU [8]. Worldwide stakeholders promote new hardware and software solutions and reshape communication technologies to prepare the market for a massive using of vehicular communications. Under these circumstances EU elaborate ‘5G Action Plan’ [2] which see the 5G the next generation system to support communication services of the intelligent transport systems. Electronics and software evolves towards powerful architectures to support internal and external connectivity on the cars. For instance, Harman’s propose a scalable approach to meet consumer demands for greater functionality of infotainment and connectivity systems developing a V2X card to be use with the same hardware and software pre-integrated platform [9].

3. Conclusions

Driverless car or autonomous vehicle is a paradigm of robotics and represents an ambitious project which requires the fusion of many technologies like electronics and communications, mechatronics, software engineering and artificial intelligence. However, more disciplines and fields of activity contribute to the development of this aspiring project, which is essentially a multidisciplinary and interdisciplinary one. Not only does the development of the stand-alone vehicle pose problems, but also the development of infrastructure for the movement of self-driving vehicles raises many challenges. The major issue is safety and a huge effort is done to make sure the technologies involved are robust. This effort is mainly concentrated to test the safety of the ADAS but there is also a sustained work on standardization, the development of models and algorithms, the appropriate constructing solutions for implementation, as well as for ethical issues. ADAS systems are currently tested using hardware-in-the-loop methodology, but from safety reasons the human factors should be considered in tests, so the simulations of specific driving scenarios have to use driver-in-the-loop. Introducing the driver in the test loop make possible to see if the ADAS systems respond differently to a human driver and what is comparatively the effect on vehicle’s dynamics. As the matter of fact, a strong argument in favor of autonomous vehicle development is the quantity of testing data obtained virtually that will encourage as more introducing of ADAS systems to an increasing degree of vehicle autonomy.

Another issue is related on sensors and their integration on the vehicle. Here are two aspects that aim, on the one hand, at the reliability of the sensors in difficult traffic and weather conditions and, on the other hand, the integration of sensors on the serial car, (e.g. day and night video cameras, microwave radar and laser scanners). Constructive engineering solutions for mounting sensors on the vehicle must take into account sensor safety, maintenance issues and ergonomic aspects. As we can see in prototypes so far, sensory equipment is usually concentrated in a distinct nacelle attached to the roof. This solution is expected to be redesigned for commercially autonomous vehicles to integrate sensors in optimal positions.

The following issue addresses models and algorithms in terms of their robustness, accuracy and completeness. Deep learning has the main advantage of recognizing and detecting in complex scenes and learning is continuous, while the system works. Starting from here, the development of data analysis tools for specific use cases in traffic is very necessary. Practice has also proven the need for models to deal with uncertainty and ambiguity. Therefore, a considerable research effort must be done to develop advanced inference engines for the conversion of sensory information and perceptions into concrete and correct driving actions.
Another issue for intelligent vehicles is the communication. V2X technologies will enable vehicle hyper-connectivity to improve cognitive level for correct decisions and safe traffic actions. Two major challenges are: information management in ad-hoc networks and cybersecurity. The first challenge relates to the use of data for the development of cooperative behavior between vehicles. This will require a lot of research in the area of multi-agent systems and a lot of testing and validation efforts in this context on communication quality of service (QoS), message latency, data perishability, etc. The cybersecurity problem is critical anywhere, but for the domain of autonomous systems is crucial. Cybersecurity strategy is expected to evolve in conjunction with internet of things (IoT) technology, and with the related technologies big-data and cloud computing.

Last but not least, the ethical aspect is a sensitive issue for driverless vehicles. Furthermore, there is currently no legislation on the use of autonomous vehicles. Legal and ethical issues in this area are not yet seriously addressed. The autonomous vehicle can be made to act by the rules, but the rules (laws) are not always moral. For example, a car can park on a free space that is not intended for it, or parked at an entrance. An autonomous car will suddenly stop, for instance when there is a tree branch on the road, but for the drivers coming from behind this is an immoral act. These examples show possible conflicts between legal and ethical correctness. In addition, the technology of autonomous vehicles could conflict with privacy rights of the users. In this case, legislation needs to be reconciled with ethical issues. A notorious aspect is related to civil liability for accidents caused by autonomous vehicles. This issue also addresses the criminal law area as well as the insurance issue. All this requires the creation of new regulations and the alignment of the three components: policies, laws and ethical norms. Some insights on two faces of the artificial intelligence – technology and ethics can be found in [5]. However, things will go on the right way because of in the near future amazing developments are expected in the field of intelligent transport systems: "cars will talk, then collaborate", as guru designers say. Definitely, the autonomous vehicles will just share data at first, but later they will cooperate more actively.

References

[1] Ackerman E March 2017 How Drive.ai Is Mastering Autonomous Driving with Deep Learning, IEEE Spectrum, March. (On line: http://spectrum.ieee.org/cars-that-think/transportation/self-driving/how-driveai-is-mastering-autonomous-driving-with-deep-learning).

[2] European Commission 2016 5G for Europe: An Action Plan – COM (2016) 588, (http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=17131).

[3] Ionita S 2005 A Fuzzy Approach On Guiding Model For Interception Flight, in Fuzzy Systems Engineering Theory and Practice, Series: Studies in Fuzziness and Soft Computing, Vol. 181, Chapter 4, pp.87-111, Springer.

[4] Ionita S 2004 Elements of knowledge engineering with applications in expert systems (in Romanian) Ed. MatrixRom.

[5] Ionita S 2015 Artificial Intelligence – Between Technology and Ethics (in Romanian), Studii și comunicări – Divizia de Istoria Științei, Academia Romana, Vol.VIII/, pp.105-117.

[6] Ionita S 2004, Fuzzy Systems (in Romanian), University of Pitesti.

[7] Lambert F 2016 Google’s self-driving car vs Tesla Autopilot: 1.5M miles in 6 years vs 47M miles in 6 months, (https://electrek.co/2016/04/11/google-self-driving-car-tesla-autopilot/).

[8] Ross E P 2015 Thus Spoke the Autobahn, IEEE Spectrum, Jan., pp.50-53.

[9] Scoltock J 2016 Electronics: Infotainment, in Automotive Engineer, May, pp.22-23.

[10] US Department of Transportation: Team Report, June 2015, Safety Pilot Model Deployment - Test Conductor, (https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812171-safetypilotmodeldeploydeltestcondtrmrep.pdf)