Autonomic Computing for Autonomous Vehicles

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***Abstract*—Autonomous Vehicles (AVs) offer huge potential benefits to society in terms of safety, business opportunities and improved transport experiences. But AVs are very complex, and although prototypes have been successfully tested on public roads, major challenges remain before the technology can be rolled out to the mass market. This Systematization of Knowledge (SoK) paper looks at how the techniques and solutions developed in Autonomic Computing (AC) could be applied to AVs to help overcome some of these challenges. It gives some specific examples and concludes that while more research and development is needed, it is already clear that AC will need to be a central component of AV technology.**

Keywords—Autonomous Vehicle; Autonomic Computing.

I. INTRODUCTION

Autonomous Vehicles (AVs) offer huge potential benefits in areas, such as:

- *Safety*. The World Health Organisation estimates there are about 1.25 million fatal traffic accidents per year, and the US Department of Transport estimates 93% of accidents are caused by driver error [21]. AVs have the potential to significantly reduce these figures.
- *Business opportunities*. AVs have the potential to improve efficiency, and free up driver time for other tasks.
- *Improved consumer centric experience*. AVs will facilitate easier access to personal transport for disabled or young people, autonomous parking and improve traffic conditions.

AVs have been in development for several decades, and further development will be needed before they will be ready for the mass market. Section II of this paper looks at the history of AV technology. Section III gives an overview of Autonomic Computing. Section IV outlines the challenges still facing AVs and Section V looks at how the principles of AC could be applied to AVs to help overcome the challenges and achieve the benefits outlined above.

II. HISTORY OF AUTONOMOUS VEHICLES

An AV, sometimes referred to as a “self-driving car”, is a vehicle that can operate without input from a human driver. Early concepts proposed embedding guidance systems in roads. But, by the 1980s, car manufacturers and research universities had switched their attention to vehicles that were self-navigating, and this has been the main focus of attention since then.

The AV industry was given a big boost when the Defence Advanced Research Projects Agency (DARPA) in the United States organised a series of prize competitions for AVs from 2004 – 2007 called Grand Challenges. By 2007, the event was called the DARPA Urban Challenge, and teams had to design an AV that could navigate through an urban environment, while obeying traffic laws and avoiding obstacles.

The potential of AV technology for public use was starting to become clear, and numerous partnerships were formed between universities and industry to push it forward. Perhaps the most famous example is Stanford University’s Sebastian Thrun, a member of the team that won the DARPA Grand Challenge in 2005 [1][22]. He went on to co-found Google’s Self-Driving Car project in 2009. This is often seen as the start of the commercial phase of AV development.

By 2016, the Society of Automotive Engineers (SAE International) had defined a 6-level scale of automation, known as SAE J3016 [8].

- *Level 0 – No automation*. The driver is responsible for being aware of the environment, and for all driving tasks on a continuous basis. Some warning and emergency assist systems do fall into this category, e.g., park distance control, and anti-lock brakes.
- *Level 1 – Driver assistance*. Some tasks involving speed and steering are executed by the car, e.g., Adaptive Cruise Control (ACC) and Lane Keeping Assist (LKA). But the driver is responsible for all other aspects of driving.
- *Level 2 – Partial Automation*. The driver can “take their hands of the wheel” for some operations, e.g., Advanced automatic parking and Traffic Jam Assist. But the driver must still activate and deactivate the systems, and must monitor the environment at all times and be prepared to take full control at any point.
- *Level 3 – Conditional Automation*. The AV can manage all aspects of driving and safety in some circumstances, e.g., “Highway Chauffeur”. The driver does not need to constantly monitor the driving tasks, but does need to be able to take over control at short notice if conditions require it.
- *Level 4 – High Automation*. Similar to Level 3, but does not need the human driver to provide a fall back because the AV can slow or safely stop if necessary.
- *Level 5 – Full Automation*. The AV is capable of performing all driving tasks in all conditions. A human driver does not need to be present.

Cars at level 1 are now widely available. Cars with level 2 capabilities are also on sale, although some functionality may be disabled, depending on local regulations – it can be switched on via “over the air update”. Vehicles with higher levels of autonomous behaviour are still in development. The latest Gartner hype cycle for Connected Vehicles and Smart Mobility (Figure 1) shows many of the key enabling technologies are in the trough of disillusionment. The SAE [7] is upbeat about this, suggesting it means that “the hard work of commercializing many significant technologies is underway. Over the next five years or so, many technologies on this Hype Cycle will become productive parts of the automotive and smart-mobility ecosystem.”

III. OVERVIEW OF AUTONOMIC COMPUTING

Computer systems are becoming increasingly complex, and also becoming increasingly important to people and businesses. This leads to the twin problems of increased costs

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of managing and maintaining the systems, and the increased cost implications of faults and failures. To address these twin challenges, the concept of Autonomic Computing was proposed, where "autonomicity implies self-managing" [2].

The goals of AC are to reduce the costs of managing and maintaining complex systems and reducing the likelihood and impact of faults and issues.

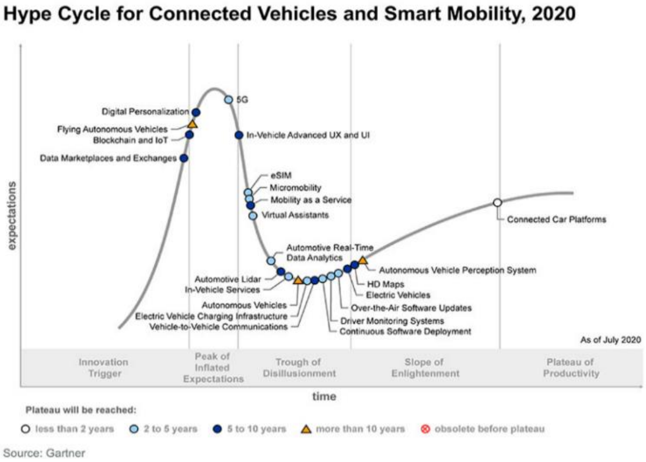

Figure 1. The Gartner™ Hype Cycle for AVs, 2020 [7].

"Self-managing" is often split into four autonomic system objectives [3]:

- *Self-Configuration* – the system re-adjusts itself to support a change in circumstances or new objectives.
- *Self-Healing* – the system can recover automatically when a fault occurs, or proactively avoid health problems.
- *Self-Optimisation* – the system can measure current performance, adjust to improve and react to policy changes.
- *Self-Protection* – the system can defend itself against accidental or malicious attacks, is aware of threats and can defend itself against them.

To achieve these objectives, an AC system needs to be self-aware, aware of its environment, and have the ability to monitor and adjust. An AC system, and in particular the policies that drive monitoring and adjustment, can be designed and built, or can learn and adapt using AI.

IBM did some of the initial work on AC. In 2003, they proposed the idea of an autonomic element, consisting of a managed element and an autonomic manager [4], see Figure 2. The autonomic element runs a continuous control loop that *Monitors* the managed element via sensors and *Analyses*, *Plans* and *Executes* updates based on *Knowledge* about the element. This is known as MAPE-K.

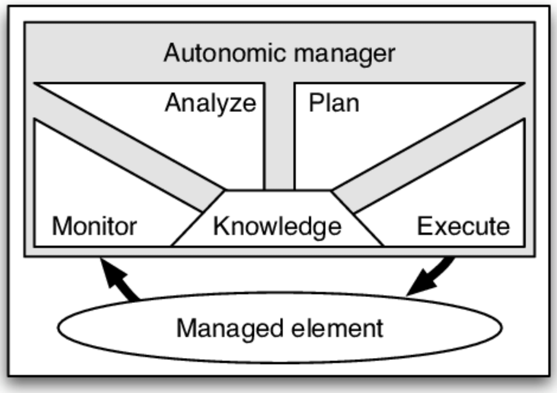

Figure 2. MAPE-K control loop [4].

There have been many impressive advancements in AC since the initial proposals in the early 2000s, but the breadth of the original vision, and the ever increasing complexity of computer systems, means there is still much to do [5]. There is a balanced review on some of the early successes of AC versus the hype in [6]. This "hype-cycle" (a term coined by Gartner) is common to many areas of technology (including AVs – see Figure 1 – as well as AC).

IV. CURRENT STATE OF AV TECHNOLOGY

An Autonomous Vehicle architecture is made up of three functional blocks [21]:

- *Data Acquisition*. This can be through sensors like RADAR, LIDAR and camera, and via communication with other cars or the internet.
- *Data processing*. This takes in the data and uses it for situational and environmental awareness. It then merges that with navigation and path planning logic to determine the next actions to take.
- *Actuation*. Carry out the actions to ensure a safe and smooth journey.

There are two basic architectural approaches [23]:

- *Centralised System Architecture*, where the sensors and data inputs feed into a single computation unit, which in turn drives the actuators.
- *Distributed System Architecture*, where functional subcomponents of the overall system are implemented in separate local units, and are connected using a shared communications bus.

The centralised approach is relatively simple in theory, with all logic collocated and no communications delays to manage. But an overall AV solution is very complex, and a centralised approach is difficult to build and test incrementally. There is also a single point of failure (the central computation unit) and it is difficult and expensive to design and build a backup.

In contrast, the components in a distributed system can be designed and tested separately, and can be removed, replaced or upgraded independently. The system can also be made more robust to point failures, and redundancy can be built in more easily and at lower cost.

In spite of rapid progress, and broad consensus on the best architecture, numerous challenges still need to be overcome before AVs will be ready for commercial roll out. These include:

- *Software reliability*. A recent Which? report [9] found that electric car manufacturer Tesla – a major AV innovator – was the least reliable car brand in the UK in 2021. And most of the faults reported were "software problems" and not problems with the electric motors or batteries. This suggests that major improvements in the design, implementation and operation of vehicle software systems will be needed before more complex, safety critical AV solutions can be launched.
- *Interpretable and Verifiably Safe solutions*. AVs must be safe and efficient. Rule based systems, designed manually by humans, are explainable and testable, but tend to behave overly cautiously. On the other hand, solutions based on machine learning often give better results but are hard to explain and do not offer any formal safety guarantees.
- *Reliability of Communications*. AVs require fast and reliable communications, and will place large and unique demands on the emerging 5G network.

- *Legal and regulatory issues*. Some countries and states allow limited testing of AVs on the public road, but the wider legal and regulatory framework for public use of AVs still needs to be sorted out. In particular, insurance and legal liability in the case of accidents remain difficult areas.
- *Data Privacy*. AVs collect huge amounts of data about their own vehicle and other road users, and this can lead to complex ethical issues. Two examples highlighted in [11] are:
  - If an AV detects another car that is owned by a driver that the insurance company knows has had multiple accidents, should the AV take an alternative route to avoid the risky car?
  - If an AV detects another car performing a dangerous or illegal manoeuvre, should it report it to the police? Or to their insurance company?

  These issues need more debate, and potentially some sort of industry wide ethical framework, to resolve.
- *Public perception*. AVs are already much safer than human controlled cars in terms of accidents per million kilometres driven. But there have been some high profile incidents that have dented public confidence in computer based solutions. These include one in 2016, when a Tesla in automatic mode crashed into a truck killing the driver, and one in 2018, when an Uber autonomous car hit and killed a pedestrian [13].

V. THE FUTURE – APPLYING AC PRINCIPLES TO AVS

Autonomous Vehicles overlap with several big technology trends, including Artificial Intelligence (AI), Internet of Things (IoT), mobile communications (5G), security and personal data. And looking at the issues outlined in the previous section, it is apparent that the principles of Autonomic Computing would also be crucial to making AV technology a success.

A recent Institution of Engineering and Technology (IET) comment article [10] highlighted the importance of “Start Early and Think Big” when it comes to getting the benefits of automation. We need to spot the systemic issues early and address them before the implementation approach becomes irreversible. To ensure the right strategy, we first need to understand any commercial constraints, such as cost, attitude to risk and regulatory restrictions. We then draw out the high-level technical requirements and constraints, and feed those into the core solution.

The similarities between AV technology and AC are striking. At the core of both is the need to collect data on their environment, interpret that data and then plan and take appropriate action. Both have evolved towards a distributed architecture, and to using Artificial Intelligence (AI) to improve the analyzing and planning stages of the process. And both have worked to balance the potential of machine learning against the need for explainable and verifiable solutions. It therefore makes sense that AC should be at the core of AV design, and that AVs should look to AC for ideas and inspiration.

The following subsections outline some future AV trends and possible areas where AC principles could add value.

A. *Internet of Things (IoT)*

Autonomic Computing was originally proposed for relatively static systems like computer networks in an office, or the nodes in a telecommunications network. More recently researchers have looked at how to apply AC techniques to the more dynamic architecture of the IoT [14]. An AV can be thought of as a complex object in the IoT, and some of the principles being considered for IoT in general will also apply to AVs.

In the original context of AC, the managed resources were typically clusters of machines in a grid, application servers, routers, and so on. An IoT environment is made up of a far wider range of heterogeneous devices, which may often be mobile. And the number of devices and their arrangement can be highly dynamic. This is particularly true of AVs, where the AV can be talking to a wide, and rapidly changing, variety of AVs and roadside devices as it drives along. Similarly, the autonomic managers in the original AC context were often software components in a relatively centralized solution, whereas in an IoT environment the autonomic managers are more likely to be distributed across many different types of devices.

This leads to new challenges, including:

- How to implement and manage device to device communication.
- Additional self.* objectives, like self-adaptation and self-organization, are more important in a dynamic IoT context.
- Decision making is more likely to be de-centralized.
- Security and device identification.
- Failure recovery and adaptation strategies will be different, because IoT environments are often remote with fewer options for remote human intervention.

AVs should study and adopt AC techniques developed for IoT.

B. *5G Mobile Communications*

AVs are a classic example of the IoT goal that envisages the interconnection of objects that have historically been offline. The term Vehicle to Everything (V2x) has been coined to cover this interconnectivity, including Vehicle to Vehicle (V2V), Vehicle to roadside infrastructure (V2I) and Vehicle to the internet, including links to backend systems like car manufacturers and insurance companies (V2N).

All this communication requires bandwidth and flexibility and is increasingly being enabled using 5G networks. A study [12] of one million connected cars, found that “connected cars have distinct sets of characteristics, including those similar to regular smart phones (e.g. overall diurnal pattern), those similar to IoT devices (e.g. mostly short network sessions), but also some that belong to neither type (e.g. high mobility)”.

AVs will place new demands on 5G networks, which in turn will place new demands on the autonomic management of those networks. Research is already underway on how to use “Machine Learning for Autonomic Network Management in a Connected Cars Scenario” [15] to address these new challenges. One critical factor for AVs is performance. Network degradations could impact safety, so the 5G autonomic management systems needs to detect this in advance and take action, for example by being aware of rush hour traffic patterns, or more irregular hot spots caused by road works or accidents and adjusting 5G capacity in anticipation.

C. Safety Critical Engineering and MAPQE-K

There is a view that Autonomic Computing is not an entirely new concept, but is related to existing concepts like dependability, and builds on existing engineering principles like fault tolerance and safety critical systems standards and design [19].

Safety and dependability are critical considerations in the aircraft industry, and the increasing complexity of aircraft suggests that the self.* properties of AC could be desirable in avionics software platforms. But the rigid aircraft certification processes, and the current requirements for static and pre-determined behaviour, are at odds with the flexible, adaptive nature of AC.

One paper [20] proposes a novel architecture that modifies the typical AC MAPE-K approach by adding in a "*Qualifier*" step – creating MAP-*Q*E-K. Safety critical aircraft systems are based on Design Assurance Levels (DAL). The proposal is that the M, A and P steps could be low-level DAL, but the new *Qualifier* step along with *Execute* would be high level DAL and would act as a robust gatekeeper for any changes being carried out on the managed element. By isolating the complex MAP stages in a low DAL partition, with only the simpler Q and E steps requiring high DAL, it is hoped that an acceptable solution could be reached. The updated architecture is outlined in Figure 3.

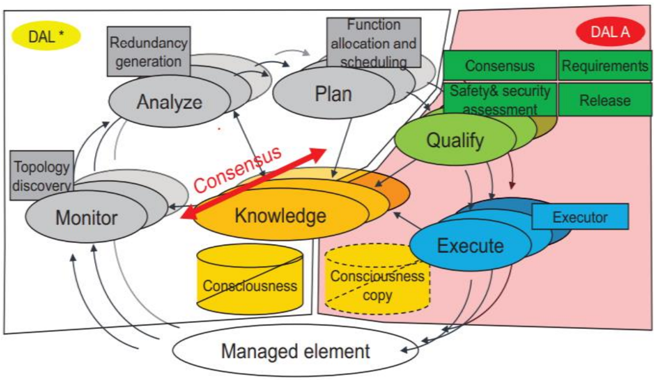

Figure 3. MAP-QE-K with DALs (from [20]).

A similar approach could be considered for AVs, to help balance the often-competing demands of verifiable and explainable solutions and acceptable levels of performance.

D. Reinforcement Learning

AVs must be safe and efficient. Manually designed rule-based systems are explainable and verifiable but need to act conservatively to ensure safety. On the other hand, Machine Learning (ML) based solutions often give better results but are hard to explain and do not offer any formal safety guarantees.

One paper [16] looked at a novel form of Reinforcement Learning (a type of ML) that can generate safe and efficient policies, while also being easy to interpret and open to formal proofs of safety. The paper focuses on the specific scenario of an AV over-taking other vehicles, but the "Verifiable Software Reinforcement Learning" approach proposed could be adapted to other challenges in AV, including how to use AC principles in an AV context.

E. Other areas

There are numerous other areas where AC techniques (both new and adapted from other domains) could be applied to AVs. Here are three examples.

- *Security* is a big concern for AVs, including cyber security, denial of service attacks (DOS), and protection of personal information. There has been some work done in this area, for example the "COSCA framework for CONseptualising Secure Cars" [25], but more work is needed. AVs could potentially adopt AC techniques like ALice (Autonomic License Signal) for positively identifying actors.
- *Fix Over the Air (FOTA).* This is already possible in some modern cars (e.g. Tesla), to both fix problems, and to enable new (potentially paid for) features. AVs are likely to require much more interaction with the manufacturer and other businesses and authorities, for example to update the vision system to recognise new road signs, and to update the AC MAPE-K control loop with new strategies.
- *Swarm intelligence and AC* have been studied in the context of space exploration [17]. Some of the concepts could be applied to AVs [18], including ideas around cooperation (e.g. to improve traffic flow) and sharing of information (e.g. about slippery road surfaces). Other proposals (e.g. self-destructing a faulty satellite) might not be so appropriate in an AV context.

VI. CONCLUSION AND DISCUSSION

Autonomous Vehicle technology is hugely complex and ambitious, but there are big potential rewards in terms of safety, business opportunities and better customer experiences.

There is a lot of overlap between AVs and other big technical areas, particularly Artificial Intelligence (AI), Internet of Things (IoT) and Fifth Generation Mobile Networks (5G). To this list we should add Autonomous & Autonomic Computing (Figure 4).

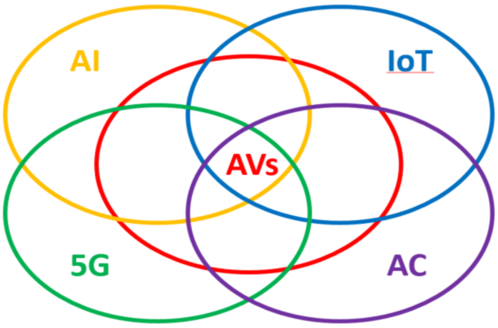

Figure 4. the complex interactions and overlaps between five technical areas.

This paper has outlined the current state of AVs and some of the challenges that still need to be overcome before AVs are ready for "prime time". These include technical, ethical and legal challenges. The paper has also highlighted the similarities and overlaps between AV technology and AC, and has identified several areas where AC techniques and practices could help address AV challenges (and in some cases there has already been progress). Many more examples exist, and more research and development are needed, but it is clear that AC principles will need to be a central part of AV technology if it is to be a success.

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