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Autonomous System Design Session – Benefits, Challenges and Risks in Various Application Domains

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***Abstract*—Autonomous systems have high potential in many application domains. However, most discussions seem to take place with respect to autonomous road vehicles. The automotive industry promised substantial progress in this field but many predictions have not come true. Companies have stepped back and corrected their predictions. However, autonomous behavior is obviously not limited to road vehicles. Various kinds of systems can benefit from autonomous behavior in various domains such as health and pharmaceutics, energy, manufacturing, farming, mining, and so on. We thus take a broader perspective on autonomous systems design and discuss benefits, challenges, and risks in various application domains.**

Keywords – autonomous systems, systems of systems, autonomy

I. Introduction

The automotive industry promised substantial progress in the field of automated driving but many predictions have not come true. Companies have stepped back and corrected their predictions. Does this mean that systems autonomy is not ready to drive innovation? Autonomous behavior is obviously not limited to road vehicles. Various kinds of systems can benefit from autonomous behavior in various domains such as health and pharmaceutics, energy, manufacturing, farming, mining, and so on. In this paper, we thus take a broader perspective on autonomous systems design as a driver of innovation and discuss benefits, challenges, and risks in various application domains.

This broader perspective is important because there is high potential for cross-fertilization between different domains. Many research questions in different domains are similar. Researchers working on these questions can benefit from each other. Furthermore, for progress to be made in autonomous systems design, it is advisable to focus on use cases with high benefits compared to the challenges and risks. Identifying these use cases requires means to compare them.

In the following, we will first briefly discuss notions of autonomy before presenting related benefits, challenges, and risks. Then we will reflect on the role of autonomy to drive innovation and conclude that further discussion is needed.

II. Notions of Autonomous Systems

The term "autonomous system" comes with different notions and there is no commonly accepted definition of "autonomous". In [2] and [3], the authors distinguish between two characteristics of autonomous systems: autonomy and autonomicity. Autonomy refers to flexibility in decision-making to reach goals based on knowledge and understanding of the world, the environment, and the system itself. Autonomicity refers to a system's capability to keep operating, for example, in the presence of failures. ISO/IEC 22989 [1] does not distinguish between autonomous and autonomy. Both are defined as "characteristic of a system that is capable of modifying its intended domain of use or goal without external intervention, control or oversight". This definition does not comply with the previous definitions. It is also questionable because deviations from human intentions are generally undesired. As there is no clear and commonly accepted definition of an autonomous system, we will briefly describe some aspects that are important for the following discussion.

A. Do not use the term "automated system"

We will not use the term "automated system" because one can only automate tasks, functions, missions, or the achievement of goals by means of technical systems but not a technical system itself.

B. Autonomy

We use the term autonomy to describe the complexity of the mission and the (required) flexibility to fulfill the mission. A high level of autonomy means high complexity of the mission and a high degree of flexibility in decision-making. If the mission has to be fulfilled in a complex open environment, then we consider this as part of the complexity of the mission.

C. Autonomicity

We use the term autonomicity to describe the capability of an autonomous system to keep operating. High autonomicity means that no or little human involvement is necessary during operation.

D. Uninterpretability

A high degree of autonomy typically results in system behavior that can hardly be interpreted by humans. Approaches such as machine learning and particularly online learning support the achievement of a high level of autonomy but at the cost of interpretability. This leads to the notion of a "programmed self". We refer to this aspect with uninterpretability.

E. Autonomous system

An autonomous system is a system that exhibits autonomy, autonomicity, and uninterpretability.

III. Use cases, Motivations and Benefits

The use cases of autonomous systems are domain-specific, but there are cross-domain motivations. For instance, a strong motivation is given **if humans are not able to perform a mission** that is indispensable for solving severe issues. The smart grid is an example of this kind of motivation. Humans are not able to match various kinds of energy demands and

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offers in an optimized and dependable way. The matching has to consider environmental impact, network instability, and many other aspects. This requires processing a lot of information very fast. This is a typical task in an increasingly connected world that easily exceeds human skills.

A second kind of motivation is given if an autonomous system can **perform a mission better** than a human. This means not only that it has to be better in terms of performance and costs, but also in terms of safety and other relevant aspects. Autonomous road vehicles would be an example if they would actually outperform humans in driving.

A third kind of motivation is given if autonomous systems can perform **very hazardous missions** or missions that humans should not do for other reasons.

IV. Challenges

Challenges in this area depend on the concrete use case but also on the type of autonomous system. Autonomous systems can be robots including vehicles, machinery, drones and so on. Autonomous robots come with research questions related to robotics and safety assurance. In many cases, autonomy cannot be limited to nominal behavior and has to include safety-relevant behavior. For instance, simple safety functions are not flexible enough to implement automated driving in cities. The required flexibility leads to reduced interpretability. This is challenging for safety assurance.

However, autonomous systems can be larger and require the involvement of disciplines beyond robotics and automation. Prominent examples are a smart city or a smart grid, but there are also other kinds of such large-scale "smart systems". Such systems autonomously control autonomous systems or the behavior simply emerges without centralized control. Large-scale autonomous systems (of systems) typically come with research questions related to cyber-physical systems, distributed systems or data spaces.

The loop of sensing, understanding, decision-making, and acting (SUDA model), or the cycle of monitoring, analyzing, planning, and executing based on knowledge (MAPE-K) is relevant for most all types of autonomous systems. A connected world and advancements concerning the dynamic allocation of functions to execution platforms open up opportunities for realizing MAPE-K cycles. This raises questions concerning the usage of these opportunities: Which patterns for distributed MAPE-K cycles exist in which domain and why? Which patterns exist for the vertical interaction of (distributed) MAPE-K cycles? Which patterns exist for building hierarchies? Is it possible to automate the application of such patterns and generate new cycles during operation? On the one hand, the control structure can be seen as something that belongs to the category of autonomous systems. On the other hand, there must also be a higher-level characteristic that motivates the selection of a certain control structure. Another design aspect concerns the realization of the steps in a cycle. The realization can benefit from advances in engineering data-driven models. In doing so, uncertainties of data-driven models need to be considered to assure dependability.

V. Risks

Different types of autonomous systems typically entail different kinds of hazards and risks. Autonomous robots can cause collisions resulting in physical injury or death. An autonomous Intelligent Transportation Systems (ITS) can cause a traffic jam and a smart grid can cause a power outage. It seems that the occurrence of a traffic jam and the occurrence of a power outage are more related to each other than the occurrence of a collision. The occurrence of a traffic jam or a power outage is an emergent phenomenon. The behavior of the autonomous robot might also be an emergent phenomenon, but the occurrence of a collision is rather a clear sequence of events. This is an important difference, because the way how loss events can occur has implications on the way how they can be avoided using design principles. Apart from risks related to loss events, there can also be risks related to the impact on society. Television and social media are good examples showing that it is hard to foresee how great the impact on society can be. News feeds show that the impact can strongly depend on the concrete behavior. This should be considered when designing the behavior of autonomous systems.

VI. Conclusion

Autonomy and autonomicity of autonomous systems lead to new opportunities for innovation but also to new design challenges and risks. It is hard to assure that uninterpretable behavior is always as intended. Automation has a long history contributed to economic wealth but also to ecological and other challenges in our VUCA world. The transition from conventional automation to autonomous systems has potential to solve some of these challenges but in spite of many investments, there is limited innovation so far. Why? Which use cases are promising and justify further investments? These are important questions that need to be discussed.

[1] ISO/IEC 22989: 2022-07: Information technology — Artificial intelligence — Artificial intelligence concepts and terminology; https://www.iso.org/standard/74296.html

[2] S. Saidi, D. Ziegenbein, J. V. Deshmukh and R. Ernst, "Autonomous Systems Design: Charting a New Discipline," in IEEE Design & Test, vol. 39, no. 1, pp. 8-23, Feb. 2022, doi: 10.1109/MDAT.2021.3128434 [Add to Citavi project by DOI]

[3] C. Rouff, Autonomous and Autonomic Systems: With Applications to NASA Intelligent Spacecraft Operations and Exploration Systems (NASA Monographs in Systems and Software Engineering), Berlin, Germany: Springer-Verlag, 2007.