CHEMICAL ENGINEERING TRANSACTIONS
VOL. 94, 2022
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
DOI: 10.3303/CET2294199
Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8 **ISSN** 2283-9216

The Resilience Barriers of Automated Ground Vehicles from Military Perspectives

Attila Hajdu[a], Rudolf Krecht[b,*], Alex Suta[b], Árpád Tóth[b], Ferenc Friedler[b]

[a]Hungarian Defence Forces Modernization Institute, Head of Electronics and Information Technology Development Branch 1118 Budapest PO Box 25

[b]Széchenyi István University, Vehicle Industry Research Center, H-9026 Győr, Egyetem Sq. 1, IS-201

krecht.rudolf@ga.sze.hu

In the case of autonomous and semi-autonomous unmanned ground vehicles (UGVs), the military application of these systems is becoming more evident and is expected to play an increasingly important role in the future. This paper aims to present and analyse the military applicability and resilience of currently available autonomous ground vehicle perception and control systems. It is important to underline that the paper, after a comprehensive literature review and a presentation of the currently applied methods, attempts to provide a methodological classification of these complex vehicle platforms from the resilience perspective. The methodological classification is based on observations from both economic and engineering perspectives as a result of the systematic review. Furthermore, possible results of resilience are also discussed: survivability, supportability, agility and reusability of the analysed autonomous ground vehicle systems. All these factors can be significant from the point of view of sustainability. As UGVs used under challenging conditions get damaged or outdated, they tend to be dismissed without reusing expensive components, thus generating additional waste. UGVs designed with resilience in mind could be kept in service for a longer period, or their components could be reused more successfully, which supports sustainability. Based on findings there are not yet widely adopted estimation methods to measure the long-term resilience of autonomous military ground vehicles. Thus, a possible theoretical solution for system-autonomy resilience quantification was discussed relying on sensory components and perception methods extracted from the literature as input variables.

1. Introduction

The field of UGVs is a largely researched area of robotics and cybernetics. From small mobile robots to autonomous passenger vehicles, nowadays there are many UGV developments and market-ready products that offer new solutions for diverse transportation problems.
Autonomous vehicle systems can be considered the most promising solutions in the field of dual-purpose transportation and locomotion. Since these systems are characterised by high complexity and high costs, more questions regarding their applicability are appearing along with the overall readiness of the technology.
Use-cases connected to dual-use and defence applications have highlighted some outstanding benefits of UGVs. Various tasks and missions that impose unacceptable risks on human operators are proven to be effectively solvable by unmanned vehicles. Since these missions usually have to be carried out in harsh environments and with critical results, dual-purpose and defence applications impose many new challenges regarding the survivability, supportability, agility and reusability of UGVs. These factors appear both in the hardware and software domains of autonomous ground vehicle systems, arising research questions linked to resilience as follows (Bagchi et al., 2020).

(i) Survivability: is the robustness of the applied system designed to survive unexpected inputs or maliciously induced failures?

Paper Received: 23 May 2022; Revised: 10 June 2022; Accepted: 15 June 2022
Please cite this article as: Hajdu A., Krecht R., Suta A., Tóth Á., Friedler F., 2022, The Resilience Barriers of Automated Ground Vehicles from Military Perspectives, Chemical Engineering Transactions, 94, 1195-1200 DOI:10.3303/CET2294199

(ii) Supportability: can the autonomous system be operated in the case of unfavourable, dangerous conditions, avoiding cascading effects caused by malfunctions?
(iii) Agility: can natural or externally induced failures of hardware or software be avoided by system redundancy?
(iv) Reusability: is the applied system reusable enough to make its application economically viable and more sustainable?

The current article's main aim was not on answering the above questions, but to take steps in the theoretical grounding of mathematically modeled autonomy resilience research. Using a technical point of view defined by the systematic literature review (SLR), the main general components of UGVs were reviewed as potential input variables to a processing system of tasks resulting in autonomous functions. During this analysis, two main categories of UGVs were discussed: (1) fully autonomous vehicles, and (2) vehicles with human-in-the-loop control systems–semi-autonomous, or fully teleoperated UGVs.

Both categories were analysed from the same perspectives. The long-term applicability of UGVs was determined by assessing their resilience and reusability from the perspective of sensors, actuators and onboard high- and low-level computers. Furthermore, the transformability of existing manned vehicles was discussed, where the main logical components of UGV systems–as presented in Figure 1–, solely or as a set of variables, are subject to the question of influencing resilience in live applications and its barriers.

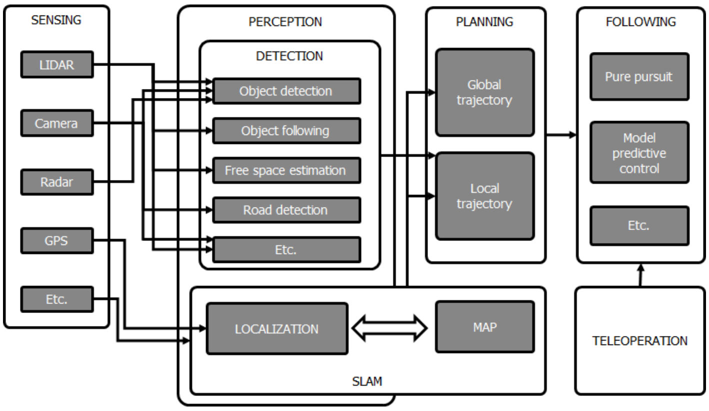

Figure 1: The main logical components of a UGV (Kőrös et al., 2020)

The final aim of the article is to propose a methodological classification for the assessed and discussed UGVs from the perspective of resilience, reusability and supportability and provide ground for further research by highlighting the results of existing literature. This classification is aimed to be successfully applicable from the point of view of the sustainability of UGV usage as well.

2. Systematic Literature Reviews in technological-focused military research

Taking into account the multidisciplinary nature of the research topic, we examined the list of literature that had previously used the Systematic Literature Review methodology in the related fields. The study areas themselves have already been subjected to similar review-type studies, however, the military applicability of autonomous systems is a moderately discussed area to date. The factor of resilience is a complimentary issue, i.e. the limits of entry and applicability of certain technological devices (sensors, telecom, and informatics) that enable autonomous operation independent of human intervention.

Global resilience research was reviewed by Yang et al. (2021) showing the most discussed topics in the last ten years were the concept of resilience, climate resilience, the social capital mechanism, macro-environment and disaster-reduction policies, with a total of 2,2 thousand articles, most researched in the U.S. and Australia. The literature on data-centric solutions (software-defined networks) in military and emergency response scenarios was reviewed by Gkioulos et al. (2018), where the most significant research contributions were categorized as architectures, basic evaluation, tools, services, control systems. Mostafa et al. (2019) carried out an SLR on adjustable (not absolute) autonomous systems that, as a tangential subject area to military and disaster mitigation missions, aid the literature on concepts, applications, and assessment of autonomy and unmanned systems. The question of autonomy was flagged as a challenge and timely research direction in its technical aspect, autonomous behaviour, security and authentication assurance, and integration into smart cities in the case of unmanned aerial vehicles (UAVs) (Mualla et al., 2019). Perception systems, as a vital part of the resilience of UGV operations, were reviewed by Mohammed et al. (2020) by their durability in extreme weather conditions such as snow, fog and rain.

3. Methodology

To conduct the Systematic Literature Review professionally, the key methodological steps of Pati & Lorusso, (2018) were used, through which the technical process of data standardized collection and basic analysis methodology were validated. This methodology was based on a systematic database search, where a single search term was defined. The search term comprised a set of concepts distinct in three thematic areas, the first being UGVs, the second being autonomous vehicle control, and the third being terms related to the research of resilience. All three sets of terms included, in addition to the key term, its synonyms for the effective use of database search algorithms. By testing the search term iteratively, the string *"(((autonomous OR automated OR unmanned OR driverless) AND (ground OR terrestrial) AND (vehicle OR car OR truck)) OR "UGV") AND (resilience OR survivability OR reusability OR supportability)"* was selected.
The most common use cases of some elements of the term (mainly UGVs) resulted in access to sources mainly related to defence and other military research topics. The elements of the inclusion criteria applied in the literature were as follows: only Scopus-indexed scientific journal articles and conference proceedings were used, aiming to use published results from the last 10 years (2012-2022). All database searches were executed on 15/03/2022, where Title, Abstract and Keywords were screened. The flowchart for the selection process, as a commonly used methodological graph for SLR implementation, was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) workflow graph (Moher et al., 2009), as follows.

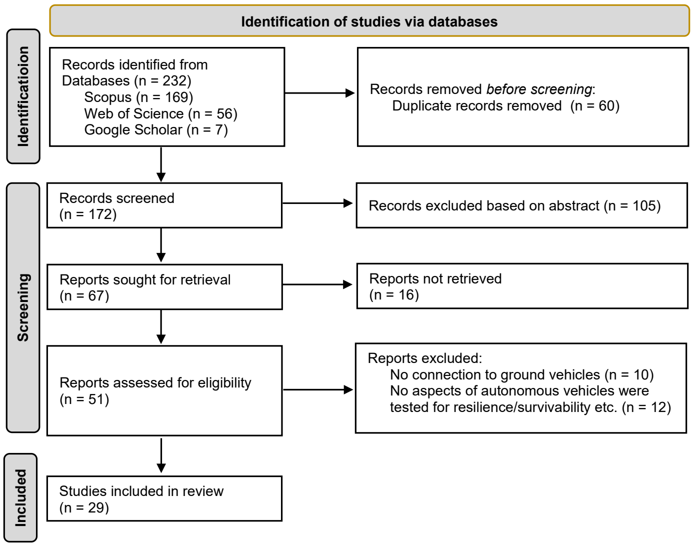

Figure 2: The PRISMA-workflow chart of the Systematic Literature Review

The research question and aim of this paper were to identify, based on the literature, what distinguishes the applicability and resilience of the commercial vehicle from the military vehicle in the military domain, and to complement findings with a multidisciplinary (defence, analysis of complex systems, and economics) approach. The results of the analysis are presented in several subsections, with a focus on the one hand on the authors of the literature dealing with this specific research question and their publication network, analysed with the VOSviewer software (van Eck & Waltman, 2017), and on the other hand the thematic classification of the main results of the literature.

4. Results

Due to the long-term nature of the research aim, the first step of the literature analysis included a brief scientometric summary. Results were then continued with a methodological classification of UGV components with a view to further applicability to the resilience model.

4.1. Analysis of research networks

In the case of the research networks, co-authorship occurrences were observed in the list of selected literature. Despite the number of 27 clusters, only 4 bigger research networks exceeding 10 co-authors were found. These, along with some smaller clusters (5 - 9 co-authorships), did not have significant research connections, and mainly occurred hence a high number of co-authors of single articles. Thus, we assume a silo-effect between institutions serving as a barrier to research, although the specific research topic has gained a wider ground in recent years, especially in 2020. Figure 3 furthermore analysed thematic keywords by frequency in paragraphs and their association by co-occurrence, extracted from the article title and abstract textual data. By specifying a >3 frequency, 4 clusters were automatically formed drawn by different colours, that indicate keywords from the 4 main topics of the list of selected articles.

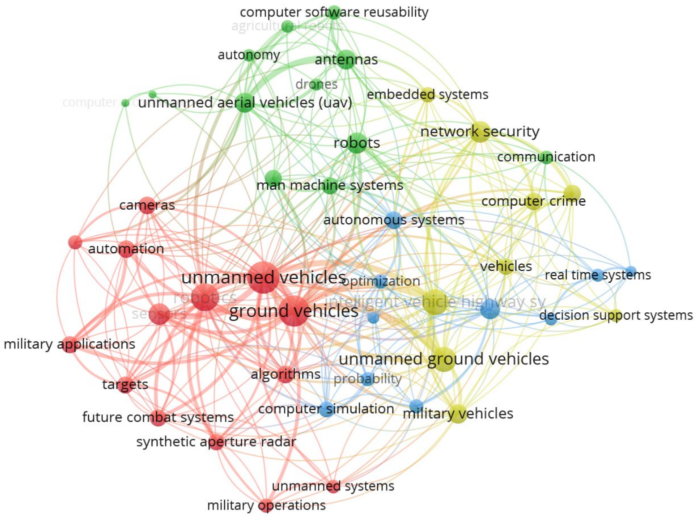

Figure 3: Clusters of most frequent keywords extracted from titles and abstracts (n=46, 4 clusters, occurrences: >3, normalization: association strength by co-occurrence)

4.2. Approaches to achieving resilience and survivability

Friedler et al. (2022) defined the resilience of processing systems as after any expected or unexpected failures, the system is (1) able to perform its designated functions in full or on a partial level, and (2) able to return to its original state. According to sources, the term Reusability is often discussed in the field of space technology and science, studies rarely reviewed its ground vehicle aspects. Due to the strict inclusion criteria, also many studies were excluded dealing with satellites and connected high precision remote sensing technologies, however, research on radar technology was included in the study as part of sensory equipment. In the following sections, articles were assessed by the main factors serving as a barrier to the adaptation of UGVs and related autonomous functions in military applications, along with the question of resilience during operation.

In the case of semi-autonomous and autonomous ground vehicles, resilience and survivability can be achieved by multiple different design approaches. To start with, there is a resilience-by-design and a resilience-by-reaction approach (Bagchi et al., 2020). Resilience-by-design aims to avoid failure by designing cyber systems with resilience in mind, while resilience-by-reaction is a method of how the system can react and adapt when a failure happens. Another approach targets human-machine semi-autonomous systems. In this case, critical decision-making can be solved by the human operator, but unexpected perturbances that human operators cannot process can be overcome by control systems (Zieba et al., 2011). In addition to the technical approaches presented before, there is a methodology that is based on models from cognitive sciences, psychology and biology, more specifically animal behaviour. This approach affirms that the unmanned system has to be able to identify its survivability factors as its needs that have to be fulfilled. As the system fulfils its survivability needs, it automatically increases its resilience (Quek et al., 2006).

4.3. UGV system components as factors of autonomous resilience

As mentioned before, our long-term research goal is to create a theoretical model for scoring autonomous or semi-autonomous UGVs from the point of view of resilience. In order to find possible inputs for this model, some technical aspects of UGVs are discussed. Many semi-autonomous UGVs rely on a human-in-the-loop system which requires stable, reliable telecommunication. In these cases, telecommunication quality can be mission-critical, thus, the key aspect of resilience and dependability. In some cases, UGVs use wired links for stable communication, which leads to limited mobility. Wireless solutions offer better mobility and range, but these systems have to be tested to prevent unexpected errors (Arendt et al., 2021).

To increase the level of resilience of an autonomous system from the point of view of sensors, the fusion of the sensed data is necessary. Fusion decreases the vehicle’s dependency on specific sensors (Baruah et al., 2020).

Furthermore, many autonomous solutions highly rely on outer information sources, such as GPS/GNSS. From the perspective of resilience, it is highly different if the vehicle becomes unusable or only loses some minor functionalities when an outer data source becomes unavailable (Vai et al., 2021). On the other hand, autonomous systems have to be reliable in case of attacks or targeted disturbances as well. In these cases, sensor input is purposely compromised. For example, GPS or wheel odometry data can be disturbed to decrease the UGV's performance or even take over its control. Control system techniques can lead to resilient systems which can guarantee the UGV's operation, even if under reduced efficiency (Bezzo et al., 2014). Another approach can be the redundancy of main sensors. A 2D laser range finder and a millimetre-wave radar sensor can be used for the same purpose (Castro and Peynot, 2012). Redundancy is properly achieved if the applied sensors use different technologies.
Based on the information described above, in order to create a model regarding the resilience of an autonomous or semi-autonomous UGV, the main hardware and software components (Figure 4) have to be analysed and scored, then the UGV has to be considered as a system, and it has to be assessed from that perspective. Thus, the suggested inputs for resilience assessment are:

- Resilience of the individual components (sensors, high-level and low-level computers, telecommunication devices, actuators)
- Level of modularity of the system
- Level of redundancy of the components
- Grade of software fault handling
- Physical protection of hardware components

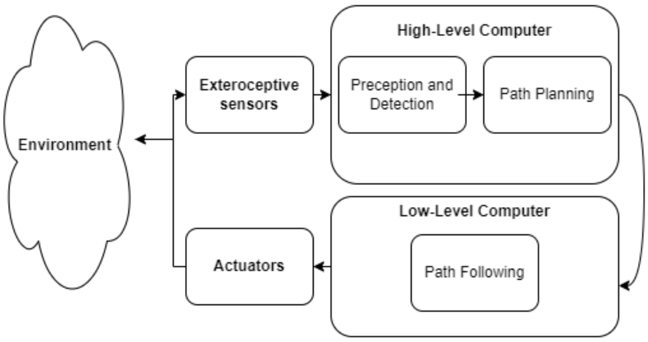

Figure 4: Main hardware components of a UGV

5. Conclusions

In conclusion, UGVs designed for military purposes are required to fulfil the requirements of resilience, dependability and sustainability at the same time. Despite usually being contradictory, these requirements can be simultaneously fulfilled by the following techniques:
Resilience is ensured on a system level. Military UGVs do not necessarily require specific hardware products for sensing or telecommunication, possible faults are tolerated by the control system.
Sustainability is achieved by using off-the-shelf civilian, and industrial solutions. Sensors often used in the case of industrial robots or self-driving passenger vehicles, like lidars or cameras can be and are successfully applied for military purposes.
The main difference between civilian and defence is the proportion between reliability and accuracy. Civilian autonomous applications are intended to solve and optimise repetitive tasks, thus precision is highly desired, but minor failures are not critical. In the case of military applications, a critical mission might not require the highest level of preciseness regarding unmanned navigation, but failure can compromise the outcome of the mission. When applying civilian or industrial products for military applications, these differences can be overcome by suitable system design. These design processes are successfully supported by computer simulations (Krecht et al., 2021).
As a concluding remark, in addition to the theoretical summary, it is important to highlight the practical examples that have already been implemented and which confirm our conclusions so far. Some market-ready defence UGV solutions successfully apply commercially available components, such as the Rheinmetall Mission Master UGV family and the Milrem Robotics THeMIS UGV family.
There is no official, published and referenced source for the use of commercially available products, components and sensors for these products, which can be attributed to a number of factors that also affect resilience (interference, countermeasures, etc.). Nevertheless, this fact is clearly visible from the photos and equipment parameters.

Acknowledgements

Project no. TKP2021-NVA-23 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NVA funding scheme.

References

Arendt, C., Patchou, M., Bocker, S., Tiemann, J., Wietfeld, C., 2021, Pushing the Limits: Resilience Testing for Mission-Critical Machine-Type Communication. IEEE Veh Technol Conf

Bagchi, S., Aggarwal, V., Chaterji, S., Douglis, F., El Gamal, A., Han, J., Henz, B., Hoffmann, H., Jana, S., Kulkarni, M., Lin, F., Marais, K., Mittal, P., Mou, S., Qiu, X., Scutari, G., 2020, Vision Paper: Grand Challenges in Resilience: Autonomous System Resilience through Design and Runtime Measures. IEEE OPEN JOURNAL OF THE COMPUTER SOCIETY, 1, 155–172.

Baruah, S., Sarathy, P., Wolf, M., Lee, P., 2020, Achieving Resiliency and Behavior Assurance in Autonomous Navigation: An Industry Perspective. PROCEEDINGS OF THE IEEE, 108(7), 1196–1207.

Bezzo, N., Weimer, J., Pajic, M., Sokolsky, O., Pappas, G. J., Lee, I., 2014, Attack resilient state estimation for autonomous robotic systems. IEEE Int Conf Intell Rob Syst, 3692–3698.

Castro, M., Peynot, T., 2012, Laser-to-radar sensing redundancy for resilient perception in adverse environmental conditions. In W. Browne, D. Carnegie (Eds.), Proceedings of the 2012 Australasian Conference on Robotics and Automation, 1–8.

van Eck, N. J., Waltman, L., 2017, Citation-based clustering of publications using CitNetExplorer and VOSviewer. Scientometrics, 111(2), 1053–1070.

Friedler, F., Orosz, Á., Pimentel Losada, J. (2022). Enumeration-Based Properties of Processing Systems: Reliability and Resilience. In P-graphs for Process Systems Engineering (pp. 123-142). Springer, Cham.

Gkioulos, V., Gunleifsen, H., Weldehawaryat, G., 2018, A Systematic Literature Review on Military Software Defined Networks. Future Internet, 10(9), 88.

Kim, J., Park, S., Kim, K., Lee, S., 2019, Environmental Implications on Energy and Emissions oft he use of a Connected and Autonomous Vehicle Environment, Chemical Engineering Transactions, 72, 97-102.

Kőrös, P., Szakállas, G., Gulyás, P., Pusztai, Z., Szeli, Z., Horváth, E., 2020, Self-Driving Vehicle Sensors from One-Seated Experimental to Road-legal Vehicle. In 2020 IEEE 24th International Conference on Intelligent Engineering Systems (INES), 97-102.

Krecht, R., Pusztai, Z., Kőrös, P., 2021, Modulrendszerű, önvezérlésre alkalmas, távvezérelhető, könnyű páncélvédettségű félplatós terepjáró katonai és katasztrófavédelmi célú terepjáró bázisjármű és kapcsolódó cserefelépítmények fejlesztése. In Innováció és fenntartható felszíni közlekedés: XV. IFFK 2021. Magyar Mérnökakadémia, 21.

Mohammed, A. S., Amamou, A., Ayevide, F. K., Kelouwani, S., Agbossou, K., Zioui, N., 2020, The Perception System of Intelligent Ground Vehicles in All Weather Conditions: A Systematic Literature Review. Sensors, 20(22), 6532.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Group, P., 2009, Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Annals of Internal Medicine, 151(4), 264–269.

Mostafa, S. A., Ahmad, M. S., Mustapha, A., 2019, Adjustable autonomy: A systematic literature review. Artificial Intelligence Review, 51(2), 149–186.

Mualla, Y., Najjar, A., Daoud, A., Galland, S., Nicolle, C., Yasar, A.-U.-H., Shakshuki, E., 2019, Agent-based simulation of unmanned aerial vehicles in civilian applications: A systematic literature review and research directions. Future Generation Computer Systems, 100, 344–364.

Orosz, Á., Pimentel, J., Friedler F., 2020, General Formulation for the Resilience of Processing Systems. Chemical Engineering Transactions, 81, 859-864.

Pati, D., Lorusso, L. N., 2018, How to Write a Systematic Review of the Literature. HERD: Health Environments Research & Design Journal, 11(1), 15–30.

Quek, B.-K., Ibañez-Guzmán, J., & Lim, K.-W., 2006, A survivability framework for the development of autonomous unmanned systems. Int. Conf. Contr. Autom. Robot. Vis. 9th International Conference on Control, Automation, Robotics and Vision, ICARCV ’06, Singapore.

Vai, M., Whelihan, D., Denney, K., Lychev, R., Hughes, J., Kava, D., Lee, A., Evancich, N., Clark, R., Lide, D., Kwak, K. J., Li, J., Schafer, D., Lynch, M., Tillotson, K., Tirenin, W., 2021, Agile and Resilient Embedded Systems. Proc IEEE Mil Commun Conf MILCOM, 715–720.

Yang, Q., Yang, D., Li, P., Liang, S., Zhang, Z., 2021, A Bibliometric and Visual Analysis of Global Community Resilience Research. International Journal of Environmental Research and Public Health, 18(20), 10857.

Zieba, S., Polet, P., Vanderhaegen, F., 2011, Using adjustable autonomy and human-machine cooperation to make a human-machine system resilient—Application to a ground robotic system. Information Sciences, 181(3), 379–397.