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Human Factor Analysis in Robotic and Autonomous Systems for Military Applications

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ABSTRACT

This paper aims to provide a human factor guidance for developing robotic and autonomous systems (RAS) in military applications. A systematic literature review was conducted to identify key aspects to characterise RAS teamed up with human operators. State-of-the-art researches on RAS are classified based on different characteristics, such as application context, RAS type, level of autonomy, network architecture, operational environment, and interface. Then, the effect of the RAS characteristics on human requirements such as trust, understandability, intelligibility, and obtrusiveness, is analysed by identifying their relationships. This study concludes with discussion points to be taken forward, identifies research gaps in current methodologies, and suggests future research directions.

Keywords: Robotic and autonomous systems, Human factor, Human-machine teaming

INTRODUCTION

Human Robotic and Autonomous Systems (RAS) have been getting much attention in recent years for their versatile applications both in military and civilian domain, such as aviation, manufacturing, and health care. Advancements in the computer science and robotics domains have enabled intelligent RAS to autonomously perform tasks, without requiring humans to monitor and prescribe every behaviour. However, it is widely agreed that full autonomy is not achievable at least for the foreseeable future (Department of Defence, 2012; Torossian, 2020), and RAS still requires human operators' intervention at certain points due to both technical and legal issues. Bringing the benefits of deploying RAS inevitably involves Human-Machine Teaming (HMT).

The importance of analysis and review on human factors teaming with RAS has been underpinned only in recent years. Although those review and analysis results revealed that appropriate consideration of human factors at an early design stage is key to the safe and successful adoption and operation of RAS (Torossian, 2020; U. S. Department of the Army, 2018), there is still a lack of reliable knowledge and practical guidance on which aspects should be evaluated for RAS considering human factors. The challenge lies in a wide range of different systems, with varying attributes and types of human involvement. To characterise different aspects of RAS and identify gaps in knowledge, a comprehensive and systematic review is required.

This paper aims to provide a human factor analysis in RAS, especially in military domain. To evaluate the potential impact of human factors in RAS design, we set up the following two research questions (RQs) and conducted a systematic literature review answering those questions:

- RQ1: What are the various characteristics of RAS that involve human roles?
- RQ2: How do the characteristics of RAS affect human requirements?

RQ1 involves identifying common design aspects to classify researches on HMT. This includes defining the characteristics of RAS, and identifying state-of-the-art studies with each characteristics. RQ2 analyses the impact of the RAS characteristics from the view of human operators. The impact is qualitatively analysed by identifying the relationship between the RAS characteristics and human requirements. Published research are summarised, and notable points that need to be taken forward are discussed to suggest future research directions.

METHODS

For a systematic review, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework was mainly used, as this creates a systematic review that is reproducible and unbiased by subjective standards (Page, 2021; Pahlevan, 2019).

The search terms were set as “RAS, military, and human”, including their synonyms. Records were searched through Scopus, with the limitation to be

Table 1. Results summary.

		Time period			Total
		2012–2015	2016–2018	2019–2022	
Summary	Studies on RAS with Human Factors	12	13	13	38
	Studies on review/survey	3	5	4	12
Application Context	Military	5	4	4	13
	Information & Intelligence (I&I)	7	6	4	17
	Service & Support	0	0	3	3
RAS Type	UAV	8	8	6	22
	UGV	2	2	1	5
	UMV	1	0	0	1
Autonomy Level	Remotely Controlled	1	1	1	3
	Operator Assistance	5	2	2	9
	Partial Autonomy	4	5	1	10
	Full Autonomy	0	1	1	2
Others	Distributed	0	1	1	2
	Centralised	3	2	2	7
	Harsh/Dynamic Environment	0	1	3	4
	Interface	5	4	5	14

written in English, and published within the last 10 years. Inclusion criteria were set as the RAS studies that explicitly state a human involvement, i.e., the studies that implicitly involve human operators are not included in this review. Exclusion criteria were the studies in ethical/medical fields, and non-accessible studies.

Using the PRISMA approach, 38 studies were selected for review. The summary of the selected studies is shown in Table 1. The studies are classified based on their focus in four main aspects to characterise RAS, where the criteria are set mainly from review/survey papers and technical reports (Seshia, 2016; Torossian, 2020; U.S. Department of the Army, 2018).

RQ1: RAS CHARACTERISTICS

RAS Type

Un-crewed Aerial Vehicles (UAVs). The majority of research studies on UAVs are either to increase the level of autonomy or to design efficient interfaces. Enhancing autonomous identification, Chitalia et al. (Chitalia, 2014) presented a three-tier human-in-the-loop classification scheme to identify objects of interest. A major research focus is to enhance the identification accuracy. Kalyanam et al. (Kalyanam, 2016) proposed a closed-loop structure to reduce the misclassification rates of UAVs compared with open-loop operator-only performance. The level of autonomy can also be improved in the path planning level to assist human operators to track the objects of interest (Ortiz, 2013). Secondly, a vast amount of research is dedicated to the interface of UAVs. Although most of the works are not platform-specific, a notable research has been made regarding the UAVs' camera surveillance to obtain high-level descriptions facilitating the human's understanding (Cavaliere, 2019; Pinto, 2017).

Un-Crewed Ground Vehicles (UGVs). Compared with UAVs, UGVs might be limited in traversibility, but with more payload to carry various sensors, UGVs can monitor and identify different types of threats. UGVs have their benefits in logistics distribution by enabling sustainable distribution and improved efficiency (U. S. Department of the Army, 2018). Recent research is found on setting low-level functional architectures (Beckers, 2019) for autonomous operation of UGVs. The developed architecture may also be applied to other un-crewed vehicles, but considering the sensor requirements, UGVs were selected to demonstrate its performance via simulations. Harris and Barber (Harris, 2014) focused on developing the UGV interface, using gesture and speech as an intuitive and natural interface for humans.

Un-Crewed Maritime Vehicles (UMVs). Despite their active deployment such as in Defense Advanced Research Projects Agency (DARPA) projects, no research paper was identified to address UMVs with human involvement. Apart from human involvement issues, it is stated in (Department of Defence, 2012) that real-time sensor processing for UMVs has been a key issue for the US Navy. Currently, a UMVs performs a mission in which it collects data, and then transferred for processing after the vehicle is recovered. Real-time data processing/dissemination in UMVs remains a key research challenge.

Level of Autonomy

The term 'autonomy' refers to the level of independence that humans allow a system to execute a given task in a stated environment. Although there is no universally agreed definition, we follow the definition in Table 2.

Remotely Controlled. Remotely-controlled RAS have been widely applied to autonomous military weapons. Despite abundant developments of RAS platforms, only a few research papers have considered remotely-controlled autonomy. An experimental study was conducted for mobile object control, where a prototype built using remotely controlled capability was designed and tested through hardware experiments (Kravchenko, 2017). Experimentation and evaluation capabilities were provided to support UAV operator training and airworthiness certification (Arrabito, 2020).

Operator Assistance. One of the state-of-the-art research trends is the wide and in-depth application of AI technologies considering the level of autonomy of operator assistance. Autopilots and navigation systems have advanced the autonomous capabilities ranging from take-off/landing and waypoint navigation to mode-specific manoeuvre and agility for next generation combat vehicles and robotic combat vehicles (Seshia, 2016). AI techniques are applied to the functions by considering the human collaboration, rapid object detection, and integrated perception and fusion (Robinson, 2015). For operation control, the autonomy employs operation assistance level to support the operator to relieve the work burden (Ortiz, 2013).

Partial Autonomy. Most of the studies researching the partial level of autonomy have been conducted for future I&I applications, which complies with the mid-term plans for the next-generation RAS deployments (Feickert, 2018). The research focuses on improved SA capability for HMT mission and advanced high-level control including task allocation, scheduling, and decision-making processes in operation control. In reconnaissance missions, cooperative multi-UAS systems were developed with capabilities of sensor perception management, plan rescheduling, and task coordination (Schmitt, 2019). AI techniques have been also applied to enhance the capabilities (Revesz, 2014) and a case-based reasoning algorithm was designed for a decision-making process in the surveillance system (Pinto, 2017). The proposed architecture was inspired by the biology of the human cognitive system and comprised low, middle and high levels to enable perception of the environment as well as comprehension of the scene.

Full Autonomy. There are limited cases of applications of the full level of autonomy in current military usages. The concept of RAS collaboration with

Table 2. Level of autonomy (Feickert, 2018).

Level of autonomy	Execution of core task	Monitoring environment	Fall-back performance
Remotely controlled	Operator	Operator	Operator
Operator assistance	System/Operator	Operator	Operator
Partial autonomy	System	System	Operator
Full autonomy	System	System	System

human and cyber-physical systems considers the human intervention as the essential option in automation (Seshia, 2016; Torossian, 2020). It appears that most of the RAS strategies do not advocate full automation as a current goal, although long-term plans are to mature RAS to high automation capabilities, but aim to retain human judgement in critical decision making when employing autonomous systems.

Other Characteristics

Network Architecture. The current works in multi-RAS commonly utilised centralised architecture, for path planning (Ortiz, 2013), task allocation (Rudnick, 2017), construction site monitoring (Ryu, 2015), and high-level description of the environment (pinto, 2017). However, more recent works are focused on decentralised architecture. Schmitt and Stuetz (Schmitt, 2019) developed a distributed on-board team perception system called Perception-Oriented Cooperation Agent, and its integrated signal and data processing algorithms for the highly automated multi-UAV reconnaissance of landing points. This resulted in positive human-in-the-loop evaluation, reducing the interaction and mission duration.

Environments. Unlike civil applications of RAS, the environment of RAS in military applications evolves continually, sometimes drastically, so the design and operation of the system must account for dynamic conditions. In dynamic/harsh environments, remotely controlled systems can be useful, as adaptiveness of RAS is less required to be validated (Arrabito, 2020). However, this involves a drawback that the communication between the centre to RAS should be secured. To enable higher adaptivity of RAS, Beckers et al. (Beckers, 2019) have developed low-level functional architecture for autonomous operation in dynamic unknown environments. In urban environments specifically, the technical challenges to enable autonomous operations in urban environments are listed in (Northrop, 2018): preventing collateral damage, enabling seamless communication, and providing SA in limited line-of-sight.

Interface. Key challenges in designing human-machine interfaces are listed as flexibility, decision authority, transparency, and human operator differences (Barnes, 2014). One of the major streams of interface research is on employing multi-modal inputs: gesture interfaces (Cheng, 2015; Mantecon, 2014; Muezzinouglu, 2021), a speech interface (Robb, 2019), a speech/gesture interface (Harris, 2014), speech/touch/multimodal interfaces (Barber, 2016; Levulis, 2018) and a single operator/multi-UAV interface (Dawson, 2012). Also, the systems should ensure that operations guarantee performance and resilience even in those situations where humans' attentional resources are limited. For example, a contingency planning tool (Mueller, 2017) and a task-based guidance (Rudnick, 2017) was developed to enable autonomous operations when the communication to human is denied. Human fatigue monitoring methods were also studied, e.g., tracking the eye movements of the operator (Niu, 2020), physiological monitoring (Sibley, 2016) and facial expression (Atone, 2021), and these analyses could be used to optimise the interface.

RQ2: EFFECT ON HUMAN REQUIREMENTS

Based on the identified RAS characteristics, how the characteristics influence the human requirements is evaluated by identifying the relationship between them. Human requirements can be defined as performance requirements for human-system integration to guarantee correct autonomous operation, from an operator's point of view, listed as (Gil, 2020):

- Trust: the extent human operators rely on automation
- Intelligibility: insurance of diverse and advanced cognitive capabilities to effectively execute tasks in dynamic environments
- Understandability: the extent the system can provide reasoning behind its actions
- Obtrusiveness: not intervening human operator's decision, so that humans can override the system and return to autonomous operations seamlessly

Relationship With Level of Autonomy. Among the identified RAS characteristics, the level of autonomy is the most closely related to human requirements, as they depend on the amount/type of interaction needed. Although levels of autonomy do not have a concrete definition, low autonomy levels generally imply that human operators have more control over RAS. In the low-level of autonomy, cognitive capability of the system such as intelligibility is less required, but the focus is more on the seamless data communication for monitoring and executing the tasks. More natural and intuitive interfaces would be needed to reduce the operators' workload and decision-making responsibilities, and human fatigue monitoring methods can be also useful to keep the operational performance, e.g., tracking the eye movements of the operator (Niu, 2020), physiological monitoring (Sibley, 2016) and facial expression (Atone, 2021).

On the other hand, high levels of autonomy imply that human operators perform high-level supervision and decision-making tasks. In high autonomy systems, the system should be able to successfully perform its mission with dynamic tasks and environments with less need for intervention from human operators. This may require greater adaptability or even learning capability of the system, which would complicate the cognitive functionalities of RAS. This may reduce the operators understanding of how the system work, negatively impacting their mental model of the system which could have consequences during non-routine events. Therefore, understandability becomes more critical, and in partial/conditional levels of automation, the system's obtrusiveness becomes a critical aspect as switching between autonomous and piloted modes happens more frequent.

Relationship With RAS Application/Mission Type. At the expense of the increased level of autonomy in many cognitive components, the delegation of responsibility in operational control will yield new requirements to the operators in the obtrusiveness and understandability aspects (Department of Defence, 2012; Gil, 2020). Understandability may contain more extended context than the teaming mission in that the operators should be able to be aware of how each autonomous component works, be knowledgeable about how to amend the logical flow and balance the delegation of the responsibility as a negotiator. Obtrusiveness may also become a crucial requirement in military applications. The adaptability of situations demands that the human take charge of all control authorities and intervene in autonomous components (Torossian, 2020).

Relationship With Other Characteristics. Distributed architecture and the capability to deal with a dynamic/harsh environment may help reach higher levels of autonomy. Using distributed communication and control, large-scale RAS can be automated while enhancing and retaining the robustness to partial failures or anomalies. For instance, a cooperative multi-UAV system has been developed to high automation level, utilising distributed perception management (Schmitt, 2019).

Capability to operate in dynamic/harsh environments, which is linked to flexibility and adaptability, will broaden the range of applications, e.g. climate, weather and terrain. Although RAS currently excel in executing specific tasks, humans remain more flexible for most of the other tasks, and flexibility of RAS is extended through human-machine interaction (Department of Defence, 2012). This dynamic is likely to change as developers continue to innovate current systems. For example, current deployments that deal with harsh environments are remotely controlled (Arrabito, 2020), whereas research studies are ongoing to enable high automation in dynamic environments (Beckers, 2019).

Interfaces are more directly linked with human requirements. More efficient interfaces can directly help optimise levels of human operator workload, and can be particularly useful in low levels of autonomy where more frequent human-machine interaction is required. Studies have shown that the use of speech interface in operator assisted level can significantly improve situational awareness and transparency (Robb, 2019), and a user testbed that enables physiological monitoring of the operator has been developed for the operator assisted level (Sibley, 2016).

DISCUSSION

Application Context. Overall, most studies focus on the I&I application. Key research gaps are identified in collaborative components and cooperation, as most of military RAS are operated with remotely controlled and partial autonomy (Department of Defence, 2012). To date, the most extensive use of RAS has been scoped at the individual control of vehicle/platform. However, even at the lower level, applications have not taken full advantage of proven autonomous capabilities in automated take-off and landing, waypoint navigation, automatic return to base upon loss of communications and path planning. As the level of autonomy matures, validation and verification will follow to increase the fidelity of such capabilities for implementation and deployment in RAS.

RAS Type. Majority of the searched studies is on UAV, of which objectives are either to increase the level of autonomy or design efficient interface. Both are contributing to relieve human operator's physical and cognitive workload. Remaining challenges are identified as training framework for human operators, and integration of command and control. Performance of UAVs with human involvement heavily depends on UAV pilots and sensor operators, if appropriate high-fidelity training environments are not provided. Developments in interface will compensate this issue up to a certain degree, but not all. When it comes to the interface, integration of command and control of UAS to existing command systems is not well understood (Feickert, 2018).

Level of Autonomy. Asymmetries in level of autonomy exist according to different types of RAS. The US Army (U. S. Department of the Army, 2018) reported that most UGS and UAS operate between teleoperation and semi-autonomy, but the current use of autonomy was inconsistent across platforms. The main limitations in the level of autonomy were attributed to the restricted adoption of levels of autonomy. Survey papers and technical reports have clarified there will be limited adoption of autonomy in military contexts to comply with human involvement and all autonomy levels should maintain Humans 'In-The-Loop' (HITL) or 'On-The-Loop' (HOTL) of current and future RAS (Feickert, 2018; Torossian, 2020). HITL is defined as the systems that will allow final decisions to be determined by a human operator on whether to proceed further in an activity, whereas HOTL is defined to allow humans to intervene in RAS systems such as automated vehicles. These results indicate that RAS inevitably concerns adopting autonomous operations in terms of HMT.

Other Characteristics. Most of the current studies are based on centralised architecture. Considering the scalability and robustness of the RAS systems, the remaining challenges are to decentralise the functionalities in communication, control, monitoring, and decision making. Information processed in a distributed architecture should be efficiently gathered for human operators to understand.

Broadening the range of operational environments is getting more attention recently. There are many remaining technical challenges in navigation, sensing, control, and guidance in dynamic and harsh environments. A high-fidelity validation framework needs to be developed to employ state-of-the-art technologies, which may include nonlinear and stochastic characteristics making the validation and analysis difficult.

Many natural and intuitive human-machine interfaces are studied, along with the developments in AI. Remaining challenges will therefore be similar to difficulties in AI: test and validation of the interface can be difficult, providing only empirical guarantee. Further research is needed to rule out unexpected faults and anomalies.

Effect on Human Requirements. Among identified RAS characteristics, level of autonomy and interfaces have direct impact on human requirements, whereas application, distributed architectures and capability in various environments are indirectly related. Once RAS characteristics are matured, RAS will significantly reduce human cognitive and physical workloads and therefore widen the range of applications. However, this may require other additional characteristics such as trust, understandability, and obtrusiveness, to satisfy human requirements and be used in military contexts. Flexibility and adaptability of RAS should be developed in such a way that the systems behave in an expected and understandable way, not disturbing human operators' critical decision making.

CONCLUSION

RAS that involve human roles were classified with their application context, platform type, level of autonomy, and other characteristics. Then, the effect of different RAS characteristics on human requirements was identified by investigating the relationship between each RAS characteristics and human requirements. Direct relationship was established with respect to level of autonomy, requiring trust, intelligibility, understandability, and obtrusiveness for human requirements. RAS application context and other characteristics were indirectly contributing to different human requirements, by requiring or supporting different levels of autonomy. Key challenges were identified for future research as interactions with human, integration to existing systems, asymmetries in level of autonomy, and validation and verification of different subsystems.

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