Quantifying and Predicting Human Performance for Effective Human-Autonomy Teaming

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Abstract—The challenge of effective human-autonomy teaming lies not only in development of technology to facilitate autonomy but in understanding how human capabilities can be integrated with autonomous systems. In this paper, we describe a program of work to address this challenge by taking a multidisciplinary approach to quantifying human performance and developing adaptive interfaces and intelligent control algorithms that will enable effective human-autonomy teaming.

Index Terms—Human Performance, Human-Autonomy Teaming, Human-Machine Interface

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1 INTRODUCTION

EMployment of robotic ground vehicles for Defence purposes will likely require substantial redundancy in modes of control so as to support improved operational utility and resilience. Operators will need to maintain the ability to be in the loop, through tele-operation, or on-the-loop, through supervisory control. To provide increased resilience, while accounting for the challenges of sustaining robust communications links during operations, both tele-operation and supervisory control of robotic ground vehicles may need to entail localised control/oversight, alongside of longer range remote control/oversight.

Localised control/oversight could entail having a dedicated robotic ground vehicle operator travelling as part of a group of vehicles, such as a truck convoy composed of robotic trucks semi-autonomously following a crewed lead vehicle, referred to as platooning. When the platooning robotic trucks are performing effectively, the operator would have the task of monitoring. However, when environmental stressors surpass the capabilities of the robot then the operator would switch to tele-operation. The risks associated with military operations might also require additional redundancy such that tele-operation is able to occur beyond line of sight of the convoy. The nature of such local and remote robotic operator interactions presents substantial challenges for how to effectively support shared control in ways that minimise the chances of human or robotic system failures.

The operational use-cases described above lead to situations where the operator needs to be physically detached from the vehicle to assume either a tele-operation or a supervisory control role. Human machine interfaces (HMIs) play a significant role to situate the operator within the problem solving and decision contexts while being disembodied from the physical context. This problem brings two challenges to human-autonomy teaming (HAT). The first challenge involves the need to augment the vehicles with a level of local autonomy to manage its local context; especially with regard to low-level control tasks such as stability control, obstacle avoidance and local path planning. This need is brought by the necessity to manage the vehicle locally as a result of latency or drop of communication with the operator/supervisor. The second challenge involves the need to integrate human-cognitive assessment indicators within the HMI to enable a level of smartness in the HMI that allows it to adapt based on task demands and human cognitive states.

The above challenges demand better understanding of how a human interacts with and trusts a robot while also interacting with other humans in a team. To develop a smart, dynamic, adaptive human machine interface that facilitates effective use of the robot requires not only a keen understanding of task requirements but also non-invasive methods for quantifying and predicting human performance in real-time. To assess the suitability of candidate methods, some key criteria are listed below.

1) They should not interfere directly with the performance of the operator on the task. For example, methods that rely on freezing a simulation environment to collect data can't be used in a realistic scenario.
2) They need to offer a continuous stream of information to allow continuous monitoring of the operator's performance. Continuity needs to occur on a time-resolution that is sufficient for automation to intervene with the system if a negative risk arises.
3) They need to be sensitive enough to detect changes in those humans cognitive states that matter to the context and task at hand.

4) They need to have high time resolution to detect a change quickly.
5) They need to be body-posture and orientation invariant to allow the human to move freely without losing data.

The above criteria lead to a preference towards physiological metrics such as heart rate, skin conductance, skin temperature, eye tracking, and electroencephalography (EEG). The former three sources of data do not normally have sufficient time resolution, while the latter two satisfy all criteria; especially when we consider recent advancements in sensor technologies where eye trackers and EEG could be integrated with a helmet, although consistent performance in naturalistic settings still remains a challenge. Whilst the objective is real time operator state/performance monitoring, we need to augment and support such data with use of decision elicitation (e.g. Critical Decision Method) and observational/task analysis techniques to complement such monitoring approaches, as well as supporting their validation.

In this paper, we present an overview of a program of work to understand the cognitive implications of HAT, including how to implement more effective HMIs with the use of EEG, eye tracking, artificial intelligence and machine learning, as well as insights about factors influencing decision making at transitions. Innovation in this space will come from multi-disciplinary work, because the questions are complex and sit at the intersection of multiple disciplines.

2 WHERE WE ARE SO FAR

In this section, we provide a brief overview of work recently completed or currently underway. We first describe our efforts to understand the cognitive implications of robotic ground vehicle use in the context of exploring the potential for a subset of the military field-vehicle fleet to have truck platooning capabilities, with a particular emphasis on the cognitive implications of an HMI. We investigated how human performance (including attention and trust) could vary as operators (participants) maintained control of a robotic vehicle using supervisory control or tele-operation, or transitioned between these two modes.

In this program of research, we have begun tackling the overall challenge of accounting for the cognitive capacities of humans so as to maximise effective HAT operations. The line of effort is split between basic research situated within quasi-naturalistic settings to inform the research program with validated cognitive indicators and metrics and a software infrastructure to allow for real-time analysis of these indicators. An example of a relevant quasi-naturalistic setting is driving. It is known that driving involves the use of certain characteristic patterns of eye movements as people scan the environment ahead. Predictions about how people may be deploying their attention as they complete tasks in the environment were tested using quasi-naturalistic simulations in the Virtual Battlespace (VBS) simulation environment, for both individuals and teams. Research is also underway that is drawing on a variety of psycho-physiological and behavioural measures to develop classifiers of human capacity and activities to support autonomous agents in dynamically adjusting to operator and task context.

Fig. 1: Example of an off path target

We developed a simulation to investigate the cognitive implications of using an HMI for supervisory control and tele-operations of a robotic land vehicle. Dr Luke Thiele (Rheinmetall Electronics) configured the Tactical Team Simulator at DST and developed an indicative HMI to support supervisory control and tele-operations.

We were particularly interested in understanding how humans perform at the time of a transition compared to times when they are within one mode. The sim provided contexts in which each mode of control was preferable, as well as opportunities to transition between the two modes. Research on the deployment of attention while making eye and hand movements during reaching and naturalistic tasks like driving suggest that attention will be deployed in parts of the display relevant to the task. We placed targets at locations likely to be part of natural attentional deployment (on path) and further afield (off path). Figure **??** shows an example of an on path target in a screenshot. The aim of this aspect of the design was to allow us to determine if the natural deployment of attention differentially affects target detection during different modes of operation and during transitions between the modes.

The operator was instructed to focus on their primary task of target detection of the UN bags and also to supervise and control the robot while occasionally performing a secondary task (e.g. verbally reporting map co-ordinates).

We measured trust, workload, and cognitive performance to quantify the impact of transitions between modes of operation (supervisory control and tele-operations) on human performance. We also measured attitudes towards technology and digital literacy. Our participants were educated (68 percent had tertiary level education) and 53 percent had previously taken part in a simulation. The digital literacy and attitudes towards technology questionnaires indicated that the participants used computers and electronic devices regularly, had a favourable attitude towards computers but also a mean score which indicated potential for complacency towards technology.

A key aim of this study was to investigate the cognitive implications of supervisory control and tele-operation, and transitions between these two modes of control. We used target detection (of the UN food bags) as an indication of cognitive performance and first tested if there was an effect of mode of control, and target placement. Results showed that there was a significant effect of mode of control, with more targets detected during supervisory control than during tele-operation. We next tested whether performance at the time of a transition was significantly different to that outside a transition. We found that performance was actually higher at the time of a transition compared to outside a transition. We also found that target detection at locations where people look naturally during a task (on path) is significantly higher than those off path and that this is generally consistent across modes of control. Trust increased after scenario completion and reported workload was low-moderate. The results suggest that there are cognitive implications for HMIs and that use of icons placed where people look naturally during a task could be robust to these cognitive demands. This pattern of results demonstrates a combination of experimental approaches and quasi-naturalistic simulations can be used to investigate the cognitive implications of HAT [8]. We are using this approach to conduct follow up studies.

Human-autonomy teams in a military context will also be nested within a broader military capability, such as a convoy of trucks. To address this a study was conducted to identify plausible ways in which robotic ground vehicles could be employed in the next 10 to 20 years. These concepts of employment were then used to explore the nature of the interactions between robot and operator whilst conducting convoy tasks, as well as the cognitive affordances and constraints associated with embedding a robotic ground vehicle as part of a human crewed convoy. Over a number of days, the view of the robotic ground vehicle evolved from one of being an asset needing to be protected because it was viewed as the weak link, to being a capability with unique properties that could facilitate earlier detection of enemy and reduce the risk of being ambushed. We believe this approach is fruitful as it supplies an additional opportunity to surface the tactical implications of employing such platforms in the context of undertaking indicative future operations (truck platooning in contested environment) with a particular emphasis on the implications of incorporating autonomous systems within human teams. Such tactical investigations by military participants ensures that consideration of potentially unintended negative consequences for achieving military objectives are not undermined by inadequate consideration of the tactical affordances and constraints of robotic ground vehicles by robotic system developers. Understanding how collective vehicle behaviour might occur when robot ground vehicles are involved also serves as an important behavioural input to inform HAT HMI and autonomous systems development.

In a related body of work, the Human Factors Operational Picture (H-FOP) is being developed. The aim of this work is to bring together the disparate cognitive metrics that exist in the literature and integrate them so as to offer decision makers actionable information on human performance in real-time operational settings. This is an Artificial Intelligent (AI) agent (H-FOP-AI) currently being designed to extract cognitive indicators from humans and human teams in real-time operational settings to support decision makers in having situational awareness of the cognitive states of team-members. The concept is University of New South Wales IP and is depicted in Figure 2.

The dark blue boxes represent the two components of H-FOP: the visualisation and reporting tools that offer a common operational picture of human states and the AI tools that offer both analytic capabilities to mine the large stream of data arriving from sensors on humans and tasks, and control capabilities with ability to influence the environment or the user interface to adapt to human cognitive states. The green boxes are third-party systems representing the control devices that the user relies on to interact with the HAT environment, the DIS data stream representing the data streamed out of the simulation server, and the data synchronisation layer which is responsible for synchronising the multi-modal data collected in real-time. The red box represents the third-party simulation environment used for the experiments. This box could equally represent the autonomous system that the user is interacting with.

The use of H-FOP for HAT builds on top of our previous work in Air Traffic Control, where success was achieved in using real-time cognitive indicators from human air traffic controllers to improve the efficiency of the overall system [1], [4]. To transform these multi-modal data into actionable information, real advances in this area will come through integration of approaches from both organisational and human sciences (e.g. management science, psychology, vision science and neuroscience) as well as approaches from engineering and computer science (eg machine learning and artificial intelligence).

It is worth mentioning the evolution of different pieces of work in the literature that led us to this innovation. This evolution started with Biocybernetics project [17], and evolved through a series of chronologically-ordered innovations including Brain Computer Interfaces [16], Adaptive Aiding [13], Adaptive Automation [10], Human-Machine Teaming, Augmented Cognition [14], Cognitive-Cyber Symbiosis [2], [3], and Human-Autonomy Teaming [6].

3 WHERE TO NEXT

Effective human-autonomy teaming will be achieved by balancing how the human interacts with the system and how the system interacts with the human. To achieve this goal, it will be necessary to develop a paradigm/approach in which it is possible to quantify task demands, task context and human performance. We believe characterisation of human performance with real time monitoring of operator state and sensors powered by machine learning techniques coupled with an intelligent agent that brokers the balance of work between a human and an autonomous system will lead to significant gains in the efficacy of HAT. The advantage then will be a system that can dynamically adapt to events in the environment and to operator states.

Consider a group of ground vehicles spread in an urban environment to distribute supplies that is remotely supervised by a human. The human receives information on the group through a graphical user interface and uses a control device to prevent a group member from getting closer to a danger zone that has been identified by other group members. The human also issues high-level guidance when needed. A team member of the human operator, such as a convoy commander, is receiving workload indicators about the human collected from real-time EEG and eye tracking data via H-FOP. When the system senses that the situation is becoming more than what the human can handle, it activates a recommender AI system that advises the convoy commander to either add a second human to supervise the group of vehicles or to authorise an autonomous software system (an AI Assistant) to assist the human in managing the group. The commander authorises the AI assistant to support the human on the task. H-FOP communicates in real-time information on human cognitive states to the AI assistant to help the latter to identify the best balance of division of labour needed that will neither overload the human nor under-load the human. The human and the AI assistant continues to synchronise actions and work together enabled by H-FOP that allows the AI assistant to appreciate and understand human cognitive states and the commander to maintain full situation awareness on human and system performance.

To reach the above vision, we will use a multidisciplinary approach to characterise human performance in a dynamic environment that requires teaming with autonomous systems. This multi level approach will be used to understand (and therefore be able to predict) human performance in complex, dynamic environments within the context of human-autonomy teaming and HMI use. We will use basic experimental approaches to quantify and characterise human states and performance on task, using real time measures of human performance including EEG and eye movements. The H-FOP described above offers an opportunity to translate this operator characterisation into changes to HAT

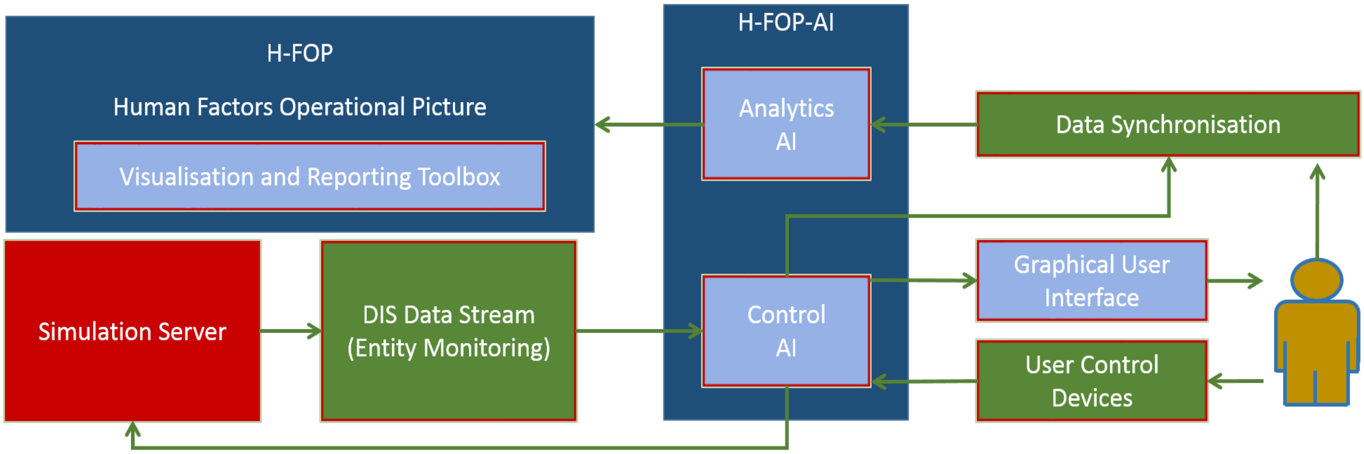

Fig. 2: Human Factors Operational Picture.

workload distribution or even HMIs. We will also continue the development of H-FOP by integrating the approaches discussed above with other approaches from the literature such as our previous work [1], [4], [5], [7], [9], [11], [12], [15]. The use of a simulation environment offers an excellent opportunity to guide the development of H-FOP in an environment that is complex enough to offer the essential aspects of the environment while still being controlled enough to allow careful collection of high quality data from multiple sensors. The integration of this quasi-naturalistic approach with measures of human performance, assisted by artificial intelligence and machine learning will enable the development of HMIs that can monitor and help anticipate changes in human performance. Concurrently, we will continue to investigate plausible land domain concepts of employment and associated cognitive affordances and constraints so as to ensure the pathways for realising benefits from this research program are Defence relevant.

4 CONCLUSION

This program of work offers the promise of a truly integrated multi-disciplinary approach to understanding complex human behaviours to improve efficiency of human-autonomy teaming. This program also adopts a multi-level approach that considers operator states, the human-autonomous system dyad and associated HMI implications, and the organisational context within which a military team explores and exploits the use of robot ground vehicles to achieve their mission.

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REFERENCES

[1] H. Abbass, J. Tang, R. Amin, M. Ellejmi, and S. Kirby, “The computational air traffic control brain: computational red teaming and big data for real-time seamless brain-traffic integration,” *Journal of Air Traffic Control*, vol. 56, no. 2, pp. 10–17, 2014.

[2] H. A. Abbass, *Computational red teaming*. Springer, 2015.

[3] H. A. Abbass, E. Petraki, K. Merrick, J. Harvey, and M. Barlow, “Trusted autonomy and cognitive cyber symbiosis: Open challenges,” *Cognitive computation*, vol. 8, no. 3, pp. 385–408, 2016.

[4] H. A. Abbass, J. Tang, R. Amin, M. Ellejmi, and S. Kirby, “Augmented cognition using real-time EEG-based adaptive strategies for air traffic control,” in *Proceedings of the human factors and ergonomics society annual meeting*, vol. 58, no. 1. SAGE Publications Sage CA: Los Angeles, CA, 2014, pp. 230–234.

[5] D. Cateley, “Csst participation in defence science and technology group (dstg) hx77 and autonomous vehicle study - 23-27 oct 17 post activity report,” Australian Department of Defence, Tech. Rep.

[6] M. Endsley, “Autonomous horizons: System autonomy in the air force–a path to the future (volume i: Human autonomy teaming),” *US Department of the Air Force, Washington*, 2015.

[7] J. Fidock, D. Pomeroy, A. W. Evans, O. Abedin, K. Briggs, and S. Hill, “Trusted operation of robotic vehicles in contested environments trial 1 human-system integration evaluation,” Defence Science and Technology Group, Tech. Rep. DST-Group-GD-0981, 2017.

[8] A. Ma-Wyatt, J. Fidock, and S. Hill, “An investigation of alternative hmis for teleoperation and supervisory control of robotic land vehicles under simulated motion: Final report on ITC PAC project,” US Department of Defence, Tech. Rep.

[9] A. Ogonowski, “Trust and the visual display of uncertainty: The impact of multi-level icon systems on operator trust,” Master’s thesis, School of Psychology, University of Adelaide, 2016.

[10] R. Parasuraman, T. Bahri, J. E. Deaton, J. G. Morrison, and M. Barnes, “Theory and design of adaptive automation in aviation systems,” DTIC Document, Tech. Rep., 1992.

[11] D. Pomeroy, J. Fidock, L. Thiele, and L. Carter, “Using immersive simulation to understand and develop warfighters’ cognitive edge,” in *British Ergonomics and Human Factors*, UK, 2016.

[12] T. Price, “Using trust to guide design: How individual context and experience can inform the development of a navigation system interface,” Master’s thesis, School of Psychology, University of Adelaide, 2016.

[13] W. B. Rouse, “Adaptive aiding for human/computer control,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 30, no. 4, pp. 431–443, 1988.

[14] D. Schmorrow and A. A. Kruse, “Darpa’s augmented cognition program-tomorrow’s human computer interaction from vision to reality: building cognitively aware computational systems,” in *Human Factors and Power Plants, 2002. Proceedings of the 2002 IEEE 7th Conference on*. IEEE, 2002, pp. 7–7.

[15] L. Thiele, E. Aidman, L. Carter, and J. Fidock, “Decision making under tactical surprise,” in *50th Australian Psychology Society Annual Conference*, Gold Coast, QLD, 2015.

[16] J. J. Vidal, “Toward direct brain-computer communication,” *Annual review of Biophysics and Bioengineering*, vol. 2, no. 1, pp. 157–180, 1973.

[17] N. Wiener and J. P. Schadé, *Progress in biocybernetics*. Elsevier Publishing Company, 1964.