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Architecture Design and Performance Analysis of Supervisory Control System of Multiple UAVs

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ABSTRACT

Although UAV systems are currently controlled by a group of people, in the future, increased automation could allow a single operator to supervise multiple UAVs. Operators will be involved in the mission planning, imagery analysis, weapon control, and contingency interventions. This study examines the architecture and prototype of multiple UAVs supervisory control system. Firstly, the architecture for testing and evaluating human supervisory system controlling multiple UAVs is devised and each sub-system is described in detail. Then a prototype test bed of multiple UAVs supervisory control for demonstrating architecture and adaptive levels of autonomy is built. Finally, with the test bed, the impact of dynamic role allocation on system performance is studied based on quantitative criteria of wait times and operator utilisation. It is shown by simulation that dynamic role allocation can effectively shorten wait times, and eventually improve the system performance.

Keywords: Multiple unmanned aerial vehicles, supervisory control, levels of autonomy, wait times, operator utilisation

1. INTRODUCTION

With increased endurance, reduced radar signatures, and the removal of humans from immediate threats, unmanned aerial vehicles (UAVs) have recently reached unprecedented levels of growth in diverse military and civilian application domains. In particular, it is proven by the extensive use of the hunter and predator in recent conflicts that UAVs have become indispensable assets to militarised forces. Despite the absence of a pilot onboard any of these UAVs, human operators are still needed for supervisory control[1]. At the moment, UAVs control is operator intensive and can involve high levels of workloads.

While many operators are presently needed to control a single UAV, as technologies of autonomous control and artificial intelligence improve, automation will handle lowers level tasks, thus allowing the operator more time to control a number of UAVs. It is clear that if a single operator is going to control a group of UAVs, some tasks will have to be automated to some degree. While autonomous operations will play an important role in achieving multiple UAVs control, the human factor is very critical. In the concept of multiple UAVs supervisory control system, UAV flight control is autonomous, and the operator participates in mission planning, problem-solving, and contingency processing (for example, a system failure) with the help of automation systems.

Supervisory control of multiple UAVs has been an emerging issue for future applications to sophisticated military missions and have received significant attention in recent years[2-4]. The Office of the Secretary of Defense's Roadmap for Unmanned Systems calls for improvements in multi-vehicle supervisory control capabilities[5]. The Committee on Autonomous Vehicles in Support of Naval Operations also considers that it is important to carryout such research[6]. There is a great deal of literature available on different aspects of multiple UAVs control. For example, research in adjustable autonomy has investigated the aspect of role allocation between the operator and unmanned vehicles[7,8], research in vehicle-task assignment algorithms has investigated the aspect of task allocation in a multiple unmanned vehicles team[9,10]. Nehme[11] has developed a discrete event simulation model to examine the impact of operator attention allocation strategies on overall system performance when supervising heterogeneous unmanned aerial vehicle teams.

2. SUPERVISORY CONTROL OF MULTIPLE UAVS

Human supervisory control consists of higher level tasking initiated by the human but delegated to the automation systems onboard the unmanned vehicles. Human supervisory control is the process by which a human operator intermittently interacts with a computer, receiving feedback from and providing commands to a controlled process or task environment, which is connected to that computer[12], as depicted in Fig. 1.

Human supervisory control of UAVs is hierarchical, as represented in Fig. 2. The inner loop is the most critical loop that must obey UAV's physical laws of nature, such as aerodynamic constraints. In this loop, operators only need to focus on local control to keep the aircraft in stable flight, and generally, human control in this loop requires skill-based behaviours that rely on automaticity[13].

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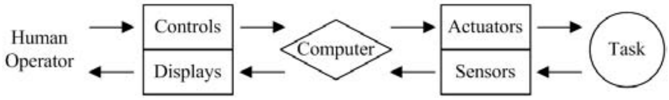


Figure 1. Human supervisory control.

The second loop is the navigation loop. In this loop, operators or automation systems must plan to meet mission constraints, such as time on targets, routes to waypoints, and avoidance of threat areas and no-fly zones. The outer loop represents the highest level of control, which is about mission and payload management. Finally, the system health and status monitoring loop requires the continual supervision that must be provided, either by a human or through automation, or both, to ensure that all systems are operating within normal limits.

From the human-in-the-loop perspective, if the inner loops fail, then the outer loops will also fail. The dependency of higher loop control on the successful control of the lower loops drives human limitations in control of a single, and especially multiple UAVs.

When implementing a supervisory control task, the amount and type of human interaction with the automated technology must be considered to determine the appropriate level of autonomy (LOA) to employ. To achieve the one-controlling-many goals for management of multiple unmanned vehicles in the future, it is important to determine if automation can be used to reduce workload, and to what degree, in each of the hierarchical control loops.

While numerous levels and scales of autonomy have been proposed, we chose the ten-level scale originally proposed by Sheridan and Verplank[14] (SV-LOA), as this is a commonly referenced taxonomy. Due to functional similarities, some categories in Table 1 can be combined[1]. Thus four different levels of autonomy can be obtained:

- Fully manual,
- Mmanagement by consent,
- Management by exception, and
- Autonomous control.

Further research has explored concepts (such as adjustable autonomy), which have considered more dynamic methods for the division of workload between a human and an UAV. Role allocation between human and machine could vary depending on operator state and tactical assessments, such that the most appropriate level of autonomy can vary given different situations or functions. For example, a UAV that under normal conditions awaits operator's approval for new trajectories could resort to management by exception under high cognitive load conditions (such that the automation system takes a more active role in synthesizing/executing decisions unless vetoed by the operator). This would ensure that the operator's high workload will not impact the vehicle's ability to achieve the goal.

Table 1. Levels of autonomy

SV-LOA	Suggested LOA	LOA Description
1	I	Automation system offers no assistance, and the operator must take all decisions and actions (fully manual)
2/3/4/5	II	Automation system suggests decisions/ actions, and executes the suggestions if the operator approves (management by consent)
6	III	Automation system offers an alternative and allows the human a restricted time to veto before automatic execution (management by exception)
7/8/9/10	IV	Operator is not involved in the decision process. Automation system decides and executes autonomously (autonomous control)

3. ARCHITECTURE OF MULTIPLE UAVS SUPERVISORY CONTROL SYSTEM

A generic conceptual architecture of a supervisory system which controls four UAVs is described in Fig. 3. It includes seven main components: Situation assessment, operator state assessment, event monitor, mission planning, mission management, variable autonomy engine, and operator machine interface. All these components operate within the context of a close-loop system in so far as there is a feedback loop that re-samples operator's cognitive state and situation assessment. Similar to perceptual control theory[15], the goal is to adjust the level of adaptation so that optimal operator states (e.g., performance, workload, etc.) are attained and maintained.

3.1 Situation Assessment

Situation assessment system monitors and tracks the current mission/goal state and aircraft/system status (e.g., heading, altitude, threats, etc.). The system provides information about the objective state of the aircraft/system within the context of a specific mission, and uses a knowledge-based system to provide aid and support to the operator.

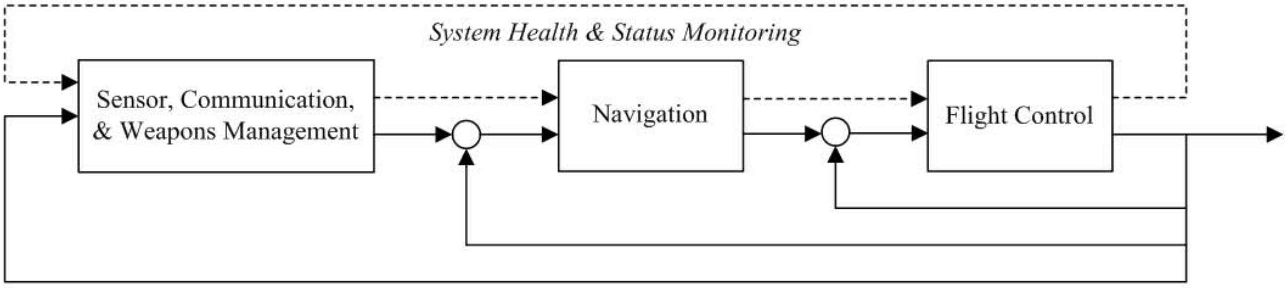


Figure 2. Hierarchical control loops for a single UAV.

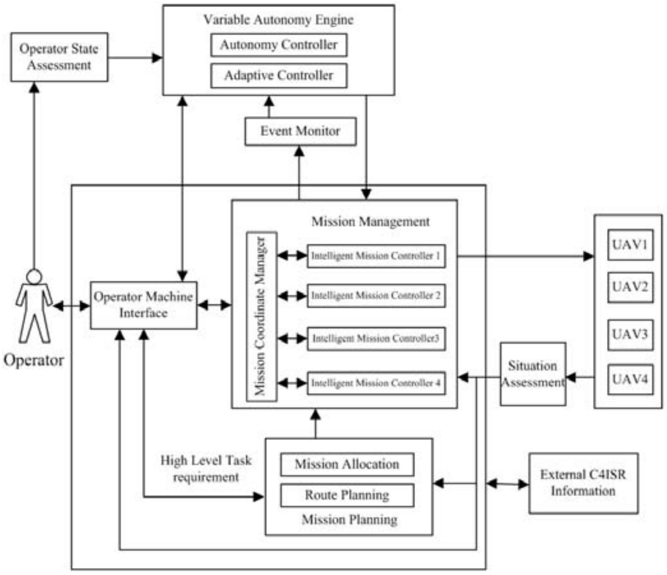


Figure 3. **Generic architecture of multiple UAVs supervisory control system.**

3.2 Operator State Assessment

Operator state assessment system must provide the operator with situation awareness and assess the operator's workload to allow the operator to perform planning, monitoring, and intervention duties effectively. The system provides information about the objective and subjective states of the operator within the context of a specific mission. Primary functions of this system can include continuous monitoring of workload, inferences about current attention focus, ongoing cognition and intentions.

3.3 Event Monitor

Event monitor system monitors the scenario for changes in mission phase (ingress, egress, target area, etc.) and events, such as popup threats, new mission tasks, or loss of a UAV, and feeds this information to variable autonomy engine.

3.4 Mission Planning

Mission planning system utilises advanced algorithms to allocate tasks to vehicles, develop route plans, evaluate vehicle-threat interactions, and analyse mission plans.

3.5 Mission Management

Mission management system consists of one mission coordinate manager and four intelligent mission controllers. Each intelligent mission controller is associated with one UAV. Mission coordinate manager can eliminate the conflicts caused by multiple UAVs when these execute the mission. Intelligent mission controller has basic functions as follows:

- Sensors management,
- Target identification,
- Weapon control,
- Navigation management,
- Vehicle health management , and
- Communication management.

3.6 Variable Autonomy Engine

Variable autonomy engine utilises higher-order outputs from the operator state assessment and situation assessment system, as well as other relevant aircraft/system data sources, to implement adaptive levels of autonomy.

The system consists of autonomy controller and the adaptive controller. The autonomy controller determines what information is displayed to the operator and what tasks the automation systems performs for a given autonomy level. The adaptive controller receives inputs from the event monitor about new events and changes in mission phase and will use such information to adapt the LOA. Current tasks performed by the operator must be factored into any decision about adapting LOA.

3.7 Operator Machine Interface

Operator machine interface is the means by which the operator interacts with the aircraft/system to satisfy mission tasks and goals. It includes decision aids and visual tools, so that the right data can be provided to the operator when it is needed, and in a form that is easily understandable.

4. PROTOTYPE TEST BED FOR MULTIPLE UAVS SUPERVISORY CONTROL SYSTEM

Due to the time-critical, complex event-driven nature of human supervisory control, discrete event simulation, which models a system, as it evolves over time, by representation of events[16], can be used to model supervisory control system.

Based on the architecture described in Fig. 3 and discrete event simulation model proposed by Nehme[11], the prototype test bed was built for supervisory control of multiple UAVs using the SimEvents toolbox in Matlab environment, as described in Fig. 4. The outputs of the prototype test bed include operator utilisation and wait times.

The concepts of operator utilisation and wait times are critical variables that are needed when modelling human supervisory control of multiple UAVs.

Operator utilisation is defined as the per cent of busy time, or the ratio of the total time the operator is engaged in tasks to the total time.

In supervisory control, any sequence of tasks requiring complex cognition will form a queue and consequently, wait times will build. Wait times occur when a vehicle is operating in a degraded state and requires human intervention to achieve an acceptable level of performance. In the context of a supervisory control system of multiple vehicles, wait times are significant in that as these increase, the actual number of vehicles that can be effectively controlled decrease. Cummings and Mitchell[17] proposed a modified equation of the concept of wait times, as shown in Eqn (1) as

$$WT = \sum_{i=1}^{X} WTI_i + \sum_{j=1}^{Y} WTQ_j + \sum_{k=1}^{Z} WTSA_k \tag{1}$$

WT imposed by human interaction can be decomposed into three basic components: wait times due to interaction (*WTI*), wait times in the human decision-making queue (*WTQ*), and wait times due to operator loss of situation awareness (*WTSA*). In Eqn. (1), *X* denotes the number of times an operator

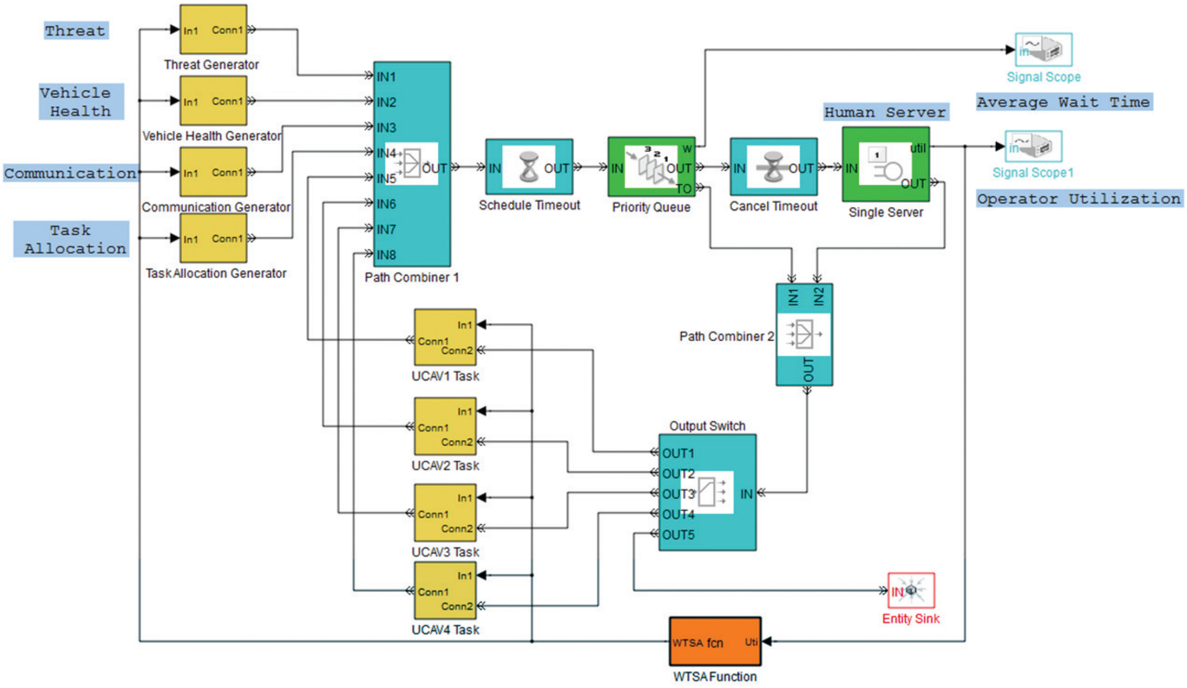


Figure 4. Simulation model of prototype test bed for multiple UAVs supervisory control system.

interacts with a vehicle while the vehicle is in a degraded state, *Y* indicates the number of interaction queues that build, and *Z* indicates the number of time periods in which a loss of situation awareness causes a wait time.

5. SIMULATION

To determine the accuracy and robustness of the proposed architecture and to evaluate the performance of supervisory control system under different role allocation modes, three simulation experiments were carried out.

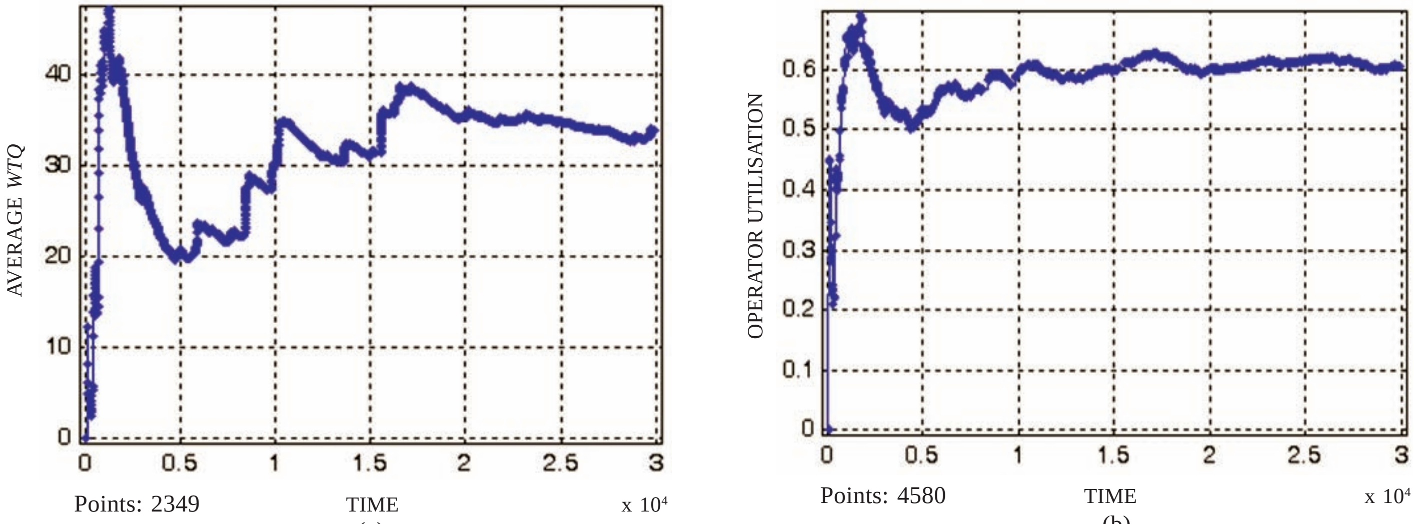
Experiment I: Using static role allocation between operator and automation systems in the multiple UAVs control prototype test bed; and the levels of autonomy is I (LOA I).

Experiment II: Using static role allocation between operator and automation systems in the multiple UAVs control prototype test bed; and the levels of autonomy is IV (LOA IV).

Experiment III: Using dynamic role allocation between operator and automation systems in the multiple UAVs control prototype test bed; and the levels of autonomy may be any choice.

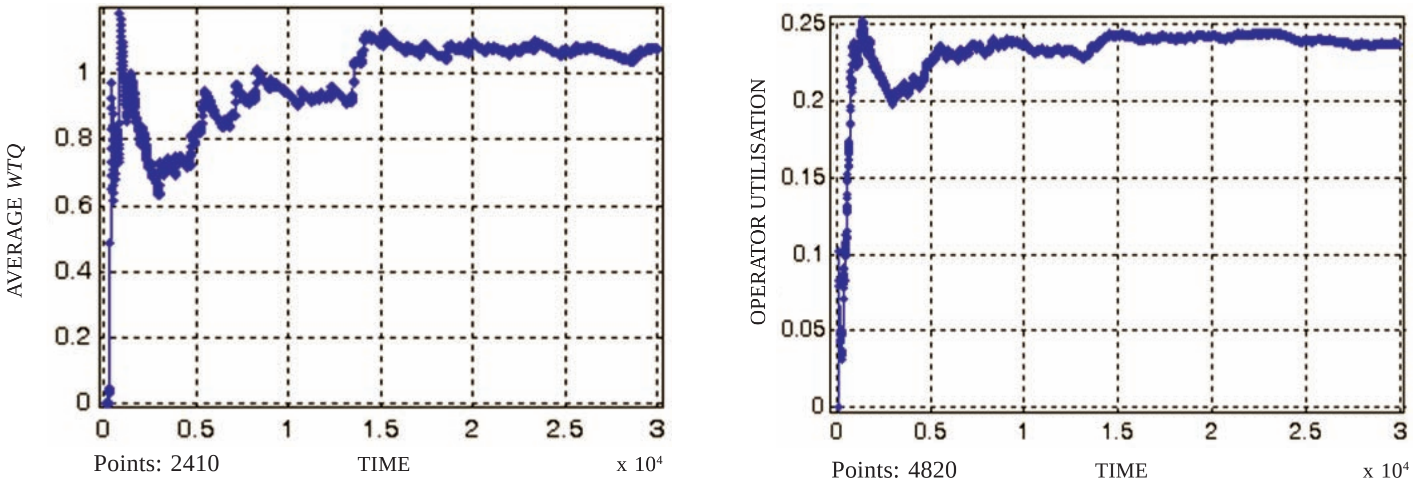
Figure 5 shows the results of average *WTQ* and operator utilisation in Experiment I when the test bed utilises static role allocation with the lowest LOA (I). The average *WTQ* is 35s and operator utilisation is 0.6. It means that the operator is at a busy state, and the time for events in the waiting queue is very long.

Figure 6 shows the results of average *WTQ* and operator utilisation in Experiment II when the test bed utilises static role allocation with the top LOA (IV). The average *WTQ* is 1.1s and operator utilisation is 0.23. It means that the operator is at an idle state, and the time for events in the waiting queue is very short.



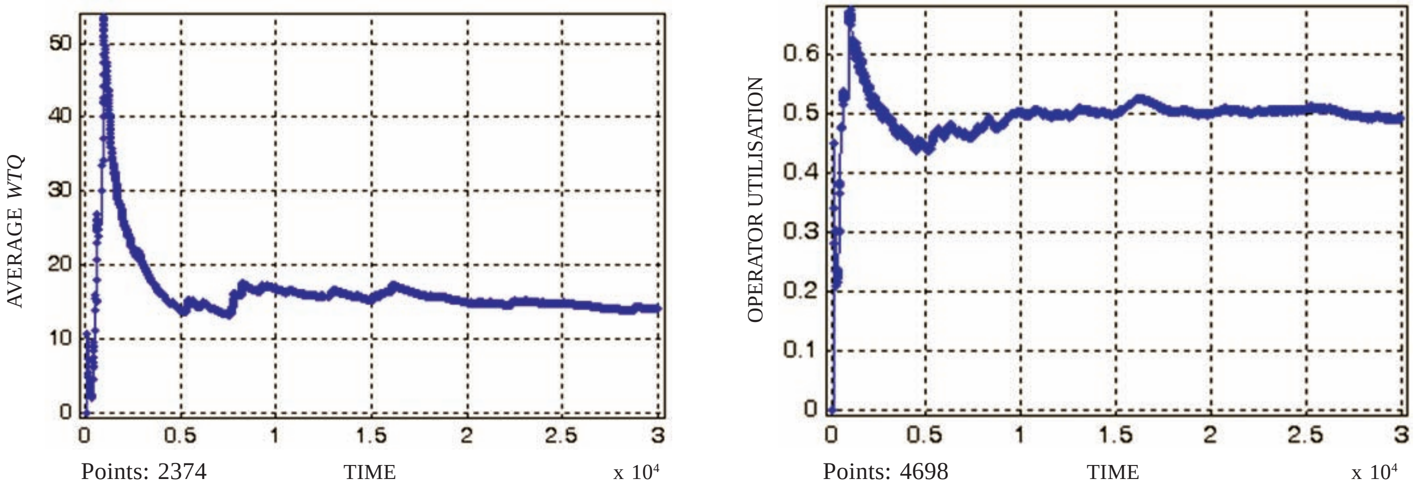
(a) (b)

Figure 5. Results of: (a) average *WTQ* and (b) operator utilisation in experiment I.



(a) (b)

Figure 6. Results of: (a) average *WTQ* and (b) operator utilisation in experiment II.



(a) (b)

Figure 7. Results of: (a) average *WTQ* and (b) operator utilisation in experiment III**.**

Figure 7 shows the results of average *WTQ* and operator utilisation in Experiment III when the test bed utilises dynamic role allocation between operator and automation. The average *WTQ* is 13s and operator utilisation is 0.49. It means that the workload of operator is moderate, and the time for events in the waiting queue is much shorter than that in Experiment I.

By comparative study, we can conclude that both average *WTQ* and operator utilisation are the lowest in Experiment II. But when the operator utilisation is too low, it will generate the phenomenon of ‘human-out-of-the-loop’, and cause longer *WTSA*. Cumming[17] points out that *WTSA* contributes significantly more than the other elements in *WT* when operator utilisation is too low or too high. Therefore, although *WTQ* in Experiment II is the lowest, the corresponding *WTSA* may increase greatly. On the contrary, the *WTQ* in Experiment III is moderate so that it will not cause longer *WTSA*, and its *WTQ* is very short. In conclusion, dynamic role allocation in supervisory control of multiple UAVs can improve the system performance.

6. CONCLUSIONS

A generic architecture for testing and evaluating adaptive levels of autonomy in human supervisory control of multiple UAVs is developed. To demonstrate the architecture and LOA implementation, a prototype test bed of multiple UAVs supervisory control system is built. Simulation results demonstrate that dynamic role allocation between operator and automation systems can shorten the wait times effectively, increase operator utilisation reasonably, and eventually improve the system performance. For the future work, how to analyze *WTI* in experiments with different levels of autonomy is important. Besides, some other quantitative measure characterising the ‘human-out-of-the-loop’ phenomenon will also be studied.

REFERENCES

1. Cummings, M.L.; Bruni, S.; Mercier, S. & Mitchell, P.J. Automation architecture for single operator, multiple UAV command and control. *Int. C2 J.*, 2007, **1**(2), 1-24.

2. Cummings, M.L.; How, J.; Whitten, A. & Toupet, O. The impact of human-automation collaboration in decentralised multiple unmanned vehicle control. *In* Proceedings IEEE, 2012, **100**(3), 660-671. doi: 10.1109/JPROC.2011.2174104
3. Clare, A.S.; Maere, P.C.P. & Cummings, M.L. Assessing operator strategies for real-time replanning of multiple unmanned vehicles. *Intelli. Deci. Technolo.*, 2012, **6**(3), 221-231.
4. Cummings, M.L.; Mastracchio, C.; Thornburg, K.M. & Mkrtchyan, A. Boredom and distraction in multiple unmanned vehicle supervisory control. *Interacting with Computers*, 2013, **25**(1), 34-47.
5. DoD. Unmanned systems integrated roadmap FY2011-2030. Office of the Secretary of Defense, Washington D.C., 2011.
6. Naval Studies Board. Autonomous vehicles in support of naval operations. National Research Council, Washington D.C., 2005.
7. Miller, C. & Parasuraman, R. Designing for flexible interaction between humans and automation: Delegation interfaces for supervisory control. *Human Factors*, 2007, **49**(1), 57-75. doi: 10.1518/001872007779598037
8. Parasuraman, R.; Barnes, M. & Cosenzo, K. Adaptive automation for human-robot teaming in future command and control systems. *Int. C2 J.*, 2007, **1**(2), 43-68.
9. Alighanbari, M. & How, J.P. Robust decentralized task assignment for cooperative UAVs. *In* AIAA Guidance, Navigation, and Control Conference and Exhibit, Keystone, Colorado, 2006.
10. Valenti, M.; Bethke, B.; How, J.; Farias, D.P. & Vian, J. Embedding health management into mission tasking for UAV teams. *In* IEEE American Controls Conference, New York, NY, 2007.
11. Nehme, C.E. Modelling human supervisory control in heterogeneous unmanned vehicle systems. Massachusetts Institute of Technology, Cambridge, MA, 2009. PhD Thesis.
12. Sheridan, T.B. Telerobotics, automation and human supervisory control. Massachusetts Institute of Technology, Cambridge, MA, 1992.
13. Rasmussen, J. Skills, rules, and knowledge: Signals, signs, and symbols, and other distractions in human performance models. *IEEE Trans. Sys., Man, Cybernetics*, 1983, **13**(1), 257–266. doi: 10.1109/TSMC.1983.6313160
14. Sheridan, T.B. & Verplank, W.L. Human and computer control of undersea teleoperators. Man-Machine Systems Laboratory Report. MIT, Cambridge, MA, 1978.
15. Powers, W.T. Behaviour: The control of perception. Aldine: Chicago, 1973.
16. Law, A.M. & Kelton, W.D. Simulation modelling and analysis (Ed 3). Boston: McGraw-Hill International Series, 2000.
17. Cummings, M.L. & Mitchell, P.J. Predicting controller capacity in supervisory control of multiple UAVs. *IEEE Trans. Sys., Man, Cyber., Part A: Sys. Humans*, 2008, **38**(2), 451-460. doi: 10.1109/TSMCA.2007.914757

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