HUMAN-MACHINE INTERFACES AND INTERACTIONS FOR MULTI UAS OPERATIONS

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Abstract

Unmanned Aircraft Systems (UAS) offer many opportunities in a wide range of industries to support remote sensing and surveillance. While platform autonomy and intelligence have seen large advances in recent decades, a key challenge is the operation of multiple Unmanned Aerial Vehicles (UAV) by a single operator in 'one-to-many' operations. To support one-to-many operations, higher levels of human-autonomy teaming are required, where human operators collaborate with autonomous agents through the use of adaptive Human-Machine Interfaces and Interactions (HMI^2). In this paper, the one-to-many concept is applied to a bushfire-fighting scenario. The paper presents the UAV avionics systems design along with the Ground Control Station (GCS) design, which features a number of emerging HMI^2 concepts.

1 Introduction

Unmanned Aircraft Systems (UAS) provide new opportunities for cost-efficient, persistent airborne surveillance for a number of applications ranging from agriculture monitoring and industrial inspection to disaster management and military reconnaissance. While significant advances in UAS intelligence have supported higher levels of platform autonomy, current UAS operations still typically require multiple human operators to command a medium/large-size Unmanned Aerial Vehicle (UAV), with each operator assuming a different functional role (i.e., mission planner, remote pilot, sensor operator), also known as 'many-to-one' operations. Currently, the Federal Aviation Authority (FAA) has mandated that remote pilots or visual observers are only allowed to operate or command one unmanned aircraft at any time (14 CFR 107.35), as the simultaneous operation of multiple UAV might lead to reduced concentration for each individual platform and compromise the safety of operations.

A key challenge limiting the efficiency of UAS operations is therefore to invert the 'many-to-one' ratio to achieve a 'one-to-many' mode of operations, where a single human operator is responsible for the command and control of multiple UAV. Addressing the one-to-many challenge from a human-factors engineering perspective involves designing the UAS Ground Control Station (GCS) to address the human factors challenges unique to UAS operations [1, 2]. A significant area of research is the design of Human-Machine Interfaces and Interactions (HMI^2) for supervisory control, providing appropriate levels of automation and information to maintain optimal operator workload and situational awareness [3-7]. Increasingly, researchers are adapting this paradigm to incorporate aspects of human-autonomy teaming, such that instead of operating under rigid automation modes, the human operator interacts with intelligent systems capable of making decisions autonomously under the direction of Commander's Intent and querying the human operator when required [8, 9], or through the use of pre-defined playbooks [10, 11]. Technological Advances may facilitate novel multi-modal interfaces [12] or systems

incorporating physiological sensing [13-15] to drive system adaptation and to guide the user's allocation of attention.
In particular, the use of physiological sensing has the potential to support higher levels of human-machine teaming, through systems that can sense and adapt to the human user's cognitive states, therefore realising the Cognitive HMI^2 ($CHMI^2$) concept presented in previous research [13, 14]. This paper presents a bushfire-fighting scenario, which is used to prototype and evaluate the $CHMI^2$ concept. The following two sections present the concept of operations and UAS avionics system design along with the $CHMI^2$ concept and HMI^2 design.

2 Bushfire Fighting

The early detection and suppression of bushfires in Australia offer significant benefits for the agriculture, horticulture and farming industries by minimizing damage and enabling timely rescue operations. Early-stage bushfires can be detected and localized using a combination of passive and active avionic sensors mounted on various UAV platforms that periodically survey large bushland/forest areas. Upon detection of a bushfire, the UAV notify the Ground Control System (GCS), and remain in the vicinity of the hotspot to monitor the bushfire activity, characterize it and provide updates to the fire-fighting personnel on the ground. For larger fires, manned water bombers can be deployed from a nearby airfield and guided by an UAV which act as lead planes to the drop location and douse the area with retardants to contain the fire spread. Additionally, if needed, the flight crew of the water bombers can assume control of individual or a team of UAV through a handover/takeover process. Bushfire monitoring can occur over large swaths of land area and detection and fire extinguishing resources are finite. Thus dynamic planning to optimize resource allocation is a critical part of the decision making process and thus an area ripe for human-machine teaming.
The laser early detection technique is based on remote sensing of fire by-products, with a particular reference to carbon dioxide (CO_2) and carbon monoxide (CO) concentrations in surveyed regions. In particular, the CO_X measurement system uses a combination of active eye-safe laser emitters and passive imaging systems, in both mono-static and bi-static Light Detection and Ranging (LIDAR) layouts, allowing a direct measurement of atmospheric transmittance and, through suitable inversion algorithms, the determination of CO_X concentrations.
The speed and range limitations of current remote sensing systems (e.g. in-situ extraction sampling) can be overcome by these novel techniques based on the combination of passive IR and LIDAR systems retrieving CO_X species concentrations over specified high-risk areas.
A conceptual representation of the bushfire detection scenario is provided in Fig. 1.

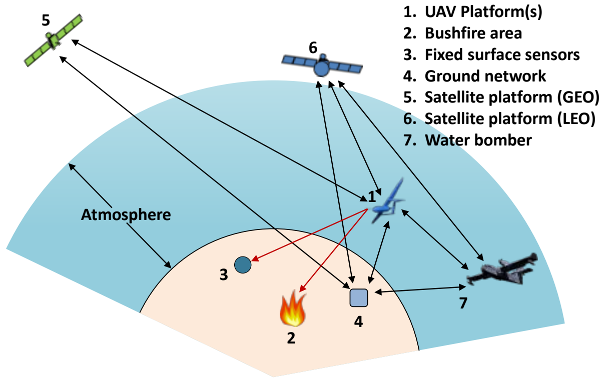

Fig. 1. Conceptual representation of the bushfire fighting scenario.

2.2 Avionics Systems Design

The selection of avionics system is typically driven by the following factors: Physical characteristics of the sensors (including minimum weight and volume), support requirements (such as electrical power, accuracy and precision), and system accuracy, integrity, availability and continuity. The Cost, Size, Weight and Power (C-SWaP) characteristics are particularly important for UAV and smaller manned aircraft. The key enabling systems include:

- Line-of-Sight (LoS) and Beyond LoS (BLoS) communication systems.

- High-integrity airborne and ground-based navigation systems and integrated fail-safe avionics architectures.
- Cooperative and non-cooperative surveillance systems incorporating collision avoidance and collaborative conflict resolution capabilities in a network-centric operational scenario.

The proposed system architecture for both manned and unmanned platforms as well as for the GCS is illustrated in Fig. 2, with subsequent sections providing a brief overview of the UAV Communications, Navigation and Surveillance (CNS) systems.

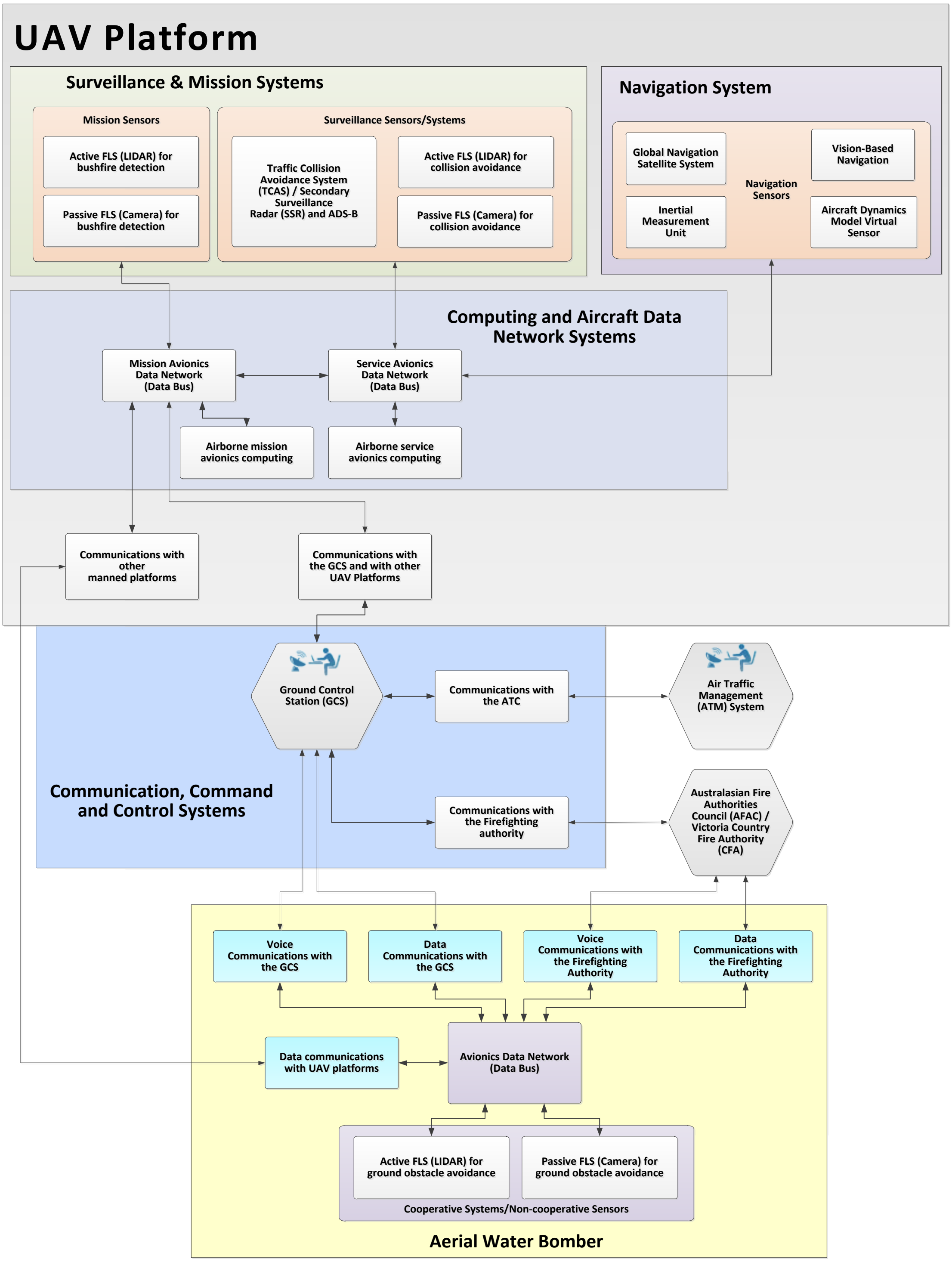

Fig. 2. Top-level system architecture for multi-UAS fire-fighting mission.

2.2.1 Communication, Command and Control Systems

Communication between the GCS, UAV and firefighting authorities is provided by direct Line of Sight (LOS) links, with Beyond LOS (BLOS) capability provided by satellite data links. Telemetry data is exchanged between the UAV and the GCS for aircraft control and downlinking of both flight parameters and fire information (for processing and communication with the fire-rescue nodes). Both LoS and BLoS links are exploited to provide voice and data communications between the GCS, the various UAV, the water bomber and Air Traffic Management (ATM) service. Air Traffic Controller (ATCo) clearances and instructions are dispatched to the UAV in two alternative ways:

- A relay arrangement, whereby the communication between the ATCo and remote pilot is achieved via the UAV but the UAV does not directly process the ATCo instructions.
- Autonomous processing, execution and readback of ATM messages by the UAV. Voice communication by the ATCo are typically provided by a VHF (air band radio). It shall be noted that whenever voice communications are implemented on the UAV, suitable Automatic Speech Recognition (ASR) and Synthetic Speech Reply (SSR) capabilities will have to be implemented.

Fig. 3 provides an overview of the various voice and data links.

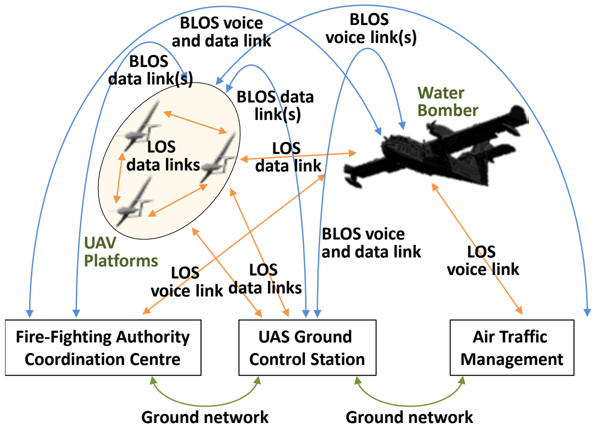

Fig. 3. Communication, command and control links.

2.2.2 Navigation & Guidance Systems

The navigation system employs multi-sensor data fusion to achieve higher levels of accuracy during navigation. The navigation and guidance sub-systems include Vision-Based Navigation (VBN), Global Navigation Satellite System (GNSS), Inertial Measurement Units (IMU), as well as an Aircraft Dynamics Model (ADM) virtual sensor [16]. These sensors are integrated within the VIGA (VBN / IMU / GNSS / ADM) navigation system architecture. As part of the VIGA architecture, the Unscented Kalman Filter (UKF) is employed for multi-sensor data fusion as well as for obtaining best time a space position estimates for bushfire detection and collision avoidance [17].

2.2.3 Surveillance Systems

In order for the UAV to safely operate in the presence of other manned/unmanned platforms, ground obstacles and terrain, a UAV collision avoidance system, referred to as Sense-and-Avoid (SAA), is utilized to automatically detect possible conflicts by the UAV and resolve any existing collision threats by accomplishing safe avoidance manoeuvers. A combination of integrated non-cooperative sensors, such as active/passive Forward-Looking Sensors (FLS), as well as cooperative systems, including Automatic Dependent Surveillance Broadcast (ADS-B), Traffic Collision Avoidance System (TCAS) and Secondary Surveillance Radar (SSR) is exploited by the SAA system to detect obstacles and other traffic [18].

2.2.4 Mission Systems

On-board mission systems comprise both active/passive sensors which are used in combination with image processing algorithms for bushfire detection, localization and characterization. The FLS include a gimbal-mounted LIDAR operating in the near infrared range. On-board weight, volume and power requirements can be reduced using a bistatic configuration, where the airborne LIDAR beam is directed toward ground based receivers, which will compute the molecular and aerosol concentration of the beam column based on the Differential Absorption LIDAR (DIAL) method and transmit the computed information back to the UAS platform [19, 20]. In addition to the bistatic LIDAR, passive sensors are also used, which include multiple cameras operating in both the visual and short-wave infrared ranges. The cameras are exploited by both surveillance and mission systems to provide additional utility and C-SWaP savings. The GCS supports centralized mission planning by human operators, while distributed planning occurs between UAV teams via platform-to-platform communication links.

3 Ground Control Station

GCS implement a number of functionalities to support human operators in various "aviate, navigate, communicate and manage" tasks. These functionalities are reviewed in Table 1. As indicated in the table, there is an increased emphasis on functionalities supporting the management aspect of UAS operations to aid human operators in performing supervisory tasks and higher level decision making.
In the fire-fighting scenario, the human operator takes the role of a tactical coordinator, managing multiple UAV teams to detect, monitor, localize and characterize fires in the operator's Area of Responsibility (AOR), as well as to support both ground and airborne fire-fighting teams. In particular:

- *Detection and monitoring* refers to maintaining awareness of the number and location of fires in the AOR, as well as positive identification of new fires, hot spots and affected structures.
- *Localization* refers to identifying the geographic location of a fire and its relative distance from other objects of interest (e.g., buildings, roads, other fires).
- *Characterization* refers to identifying features of the fire, such as size, intensity, movement and rate of spread.
- *Provide support* refers to dispatching both ground and airborne fire-fighting elements to appropriate areas of the AOR, and providing appropriate surveillance for these fire-fighting elements.

Table 1. Summary of UAS GCS functionalities.

<table>
<tr><th>Tasks</th><th>Nehme, 2007 [21]</th><th>Ashdown, 2010 [22]</th><th>Peschel, 2015 [23]</th><th>Ramos, 2016 [24]</th></tr>
<tr><td rowspan="2">Aviate and navigate</td><td>-</td><td rowspan="2">Vehicle operation</td><td>Tele-operation of vehicle</td><td rowspan="2">Aircraft command and control</td></tr>
<tr><td>Optimal position supervision</td><td>Navigation</td></tr>
<tr><td rowspan="2">Communicate</td><td rowspan="2">Negotiating with and notifying relevant stakeholders</td><td rowspan="2">Communications</td><td rowspan="2">Communications with other teams</td><td>Voice communications</td></tr>
<tr><td>Dissemination of payload products</td></tr>
<tr><td rowspan="4">Manage – systems</td><td>Monitoring UAV health and status</td><td rowspan="2">Vehicle systems management</td><td rowspan="2">Monitor technical condition of vehicle</td><td>Aircraft systems monitoring</td></tr>
<tr><td>Monitoring network communications</td><td>Data link command and control</td></tr>
<tr><td rowspan="2">Monitoring payload status</td><td rowspan="2">Payload systems management</td><td>Payload delivery</td><td rowspan="2">Payload command and control</td></tr>
<tr><td>Sensor operation</td></tr>
<tr><td rowspan="5">Manage - data</td><td rowspan="2">Analysing sensor data</td><td>Payload data management</td><td rowspan="5">Visual inspection and tactical direction</td><td rowspan="5">Exploitation of payload products</td></tr>
<tr><td>Data processing</td></tr>
<tr><td>Monitoring for sensor activity</td><td rowspan="3">Target detection</td></tr>
<tr><td>Positive target identification</td></tr>
<tr><td>Tracking target</td></tr>
<tr><td rowspan="4">Manage – mission</td><td rowspan="2">Resource allocation and scheduling</td><td>Asset tasking</td><td rowspan="4">Strategy, planning and coordination</td><td rowspan="4">Mission planning and replanning</td></tr>
<tr><td>Scheduling</td></tr>
<tr><td rowspan="2">Path planning supervision</td><td>Route planning</td></tr>
<tr><td>Sensor coverage planning</td></tr>
</table>

The relevant tasks are illustrated in Fig. 4. The fundamental task of the human operator is managing UAV teams, which translates to mission planning and monitoring the status of individual UAV. Mission planning entails assigning specific tasks to each UAV team and conducting path planning to maximize task performance. The type of task assigned to each UAV team determines the team's behavior as well as the type of algorithms used in path planning. The different tasks comprise area search, mapping of the fire perimeter, monitoring fires to obtain information on fire characteristics, as well as providing either ground or aerial support. Teams are assumed to have only one active task at any point in time. Additionally, by monitoring the status of individual platforms, human operators ensure that the available fuel and performance of on-board C/N/S systems are within allowable limits.

In addition to UAV team management, the human operator also assumes the role of a sensor operator to process incoming UAV data. The processed data is shared with other fire-fighting teams through information tags, which comprise the following items:

- *Fire presence*: a confirmed fire will be tagged with the time of detection and the location where the fire was initially detected.
- *Fire perimeter location*: confirmed fires are mapped and tagged with the fire perimeter location. The fire perimeter will be constantly moving based on prevailing wind and terrain conditions and therefore needs to be updated at regular intervals.
- *Fire size*: when the entire fire perimeter has been mapped, the fire is localized and can be tagged with the fire size. As the fire size changes over time, it must be updated at regular intervals.
- *Fire front velocity and spread direction*: in proximity to ground fire-fighting teams and objects of interest, the fire front velocity and spread direction must be constantly monitored and information tags must be updated regularly. Any changes in wind conditions can trigger a corresponding change in the fire front velocity and spread direction.
- *Fire threat level*: the fire threat level is a rating from 1 to 5 based on the fire intensity and the fire's proximity to objects of interest. Fires close to objects of interest must be tagged with the fire threat level.

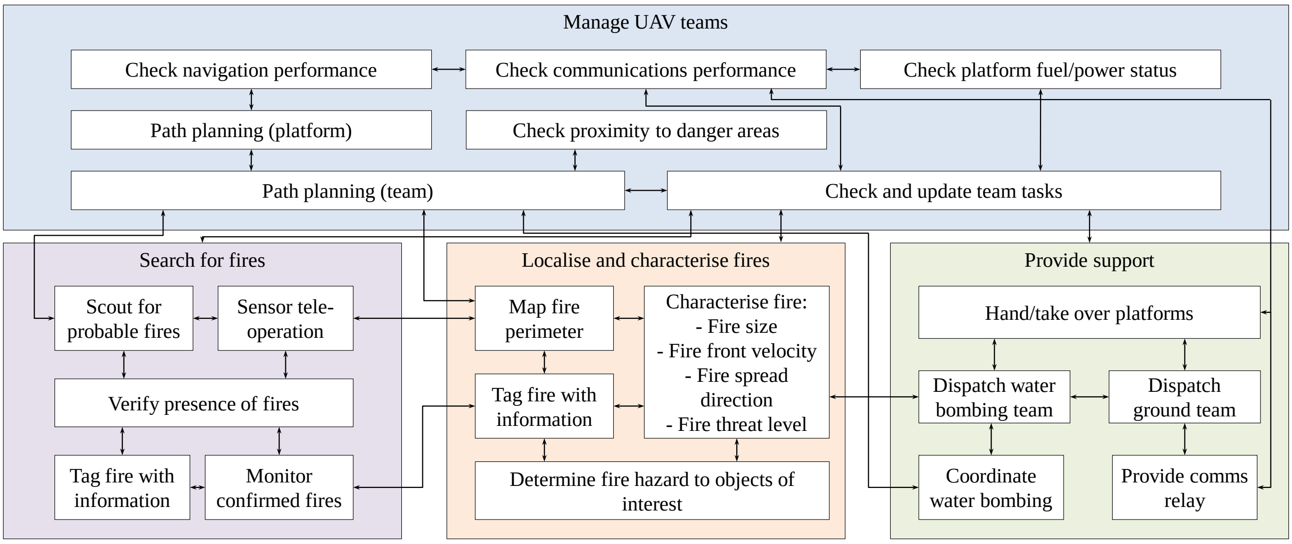

Fig. 4. Task flowchart for the tactical coordination.

3.1 GCS HMI^2 Design

The design of the GCS HMI^2 incorporates emerging concepts in the literature, including glyph portrayal of information [9] and timeline interfaces [8]. Glyphs are avatar-like icons which allow system and mission information to be displayed in a compact manner. The visual attributes of glyphs can be varied according to mission context, reducing clutter while enhancing the situational awareness of human operators. Timeline interfaces are used to coordinate the actions of teams or individual platforms across time-sensitive tasks. Timeline interfaces allow operators to anticipate upcoming tasks and action items. Additional decision aid can be provided by recommending particular platforms for the given task.

The GCS HMI^2 conceptual design is shown in Fig. 5. The single display contains six interfaces.

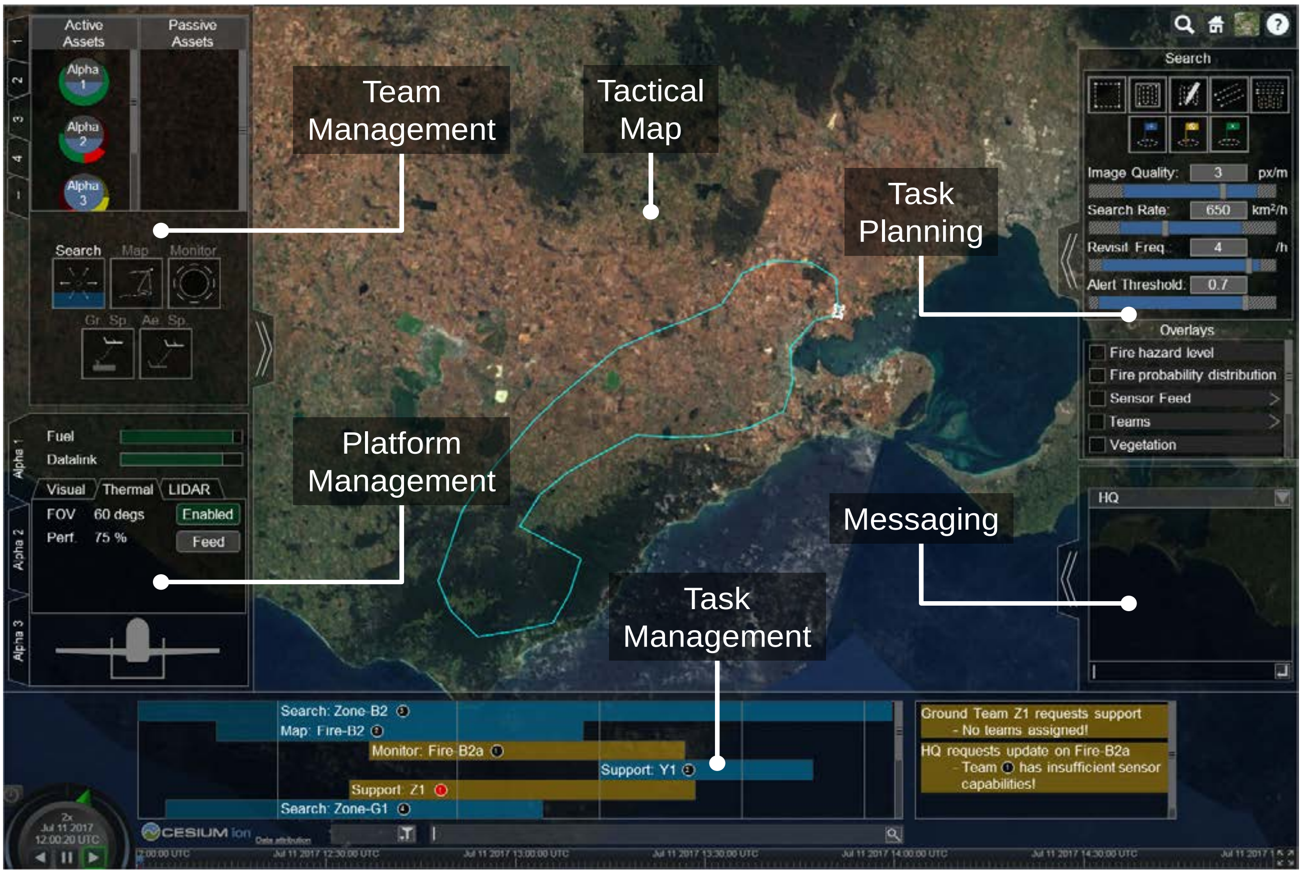

Fig. 5. GCS HMI^2 conceptual design.

The center of the GCS display contains the *Tactical Map*, where the human operator selects different UAV, makes modifications to team boundaries or platform trajectories, reviews sensor data, or adds information tags.

The *Team Management Interface*, located on the top-left of the GCS display, provides relevant information on different manned/unmanned teams. The tabs on the left of the team management window allow different teams to be selected. The asset windows display relevant information on team assets in the form of glyphs. Team assets can be either active, which are actively managed by the human operator, or passively operating outside of the human operator's command authority. The set of available tasks is indicated below the two asset windows, and progress along the current active task is highlighted in blue.

The *Platform Management Interface*, located on the middle-left of the GCS display, provides information on each UAV system and sensor status for a selected UAV team. From the sensor window, the human operator can review past sensor feed or activate different sensors for tele-operation.

The *Task Management Interface*, located at the bottom of the GCS display, contains the timeline interface used to coordinate tasks between different teams. Each bar in the task bar window indicates a team task, with the team number indicated next to the task description.

Tasks can be queued so that teams automatically start a new task when their current task is complete. Human operators can sort/filter tasks within the task bar window by task type, location or team, and can also search for tasks based on keywords. Tasks requiring the human operator's attention are color-coded in amber, with detailed information provided in the task detail window.

The *Task Planning Interface*, located at the top-right of the GCS display, provides support for automated path planning. Based on the given task type, human operators adjust a number of parameters, in the planning window. The parameters are then fed into a path planning algorithm which automatically computes feasible paths for each platform in the UAV team. The overlay window below the planning window allows operators to toggle on/off various overlays to support task planning.

The *Messaging Interface*, located at the middle-right of the GCS display, allows messages to be exchanged between different agents in the mission. Human operators can receive and view requests from other agents via the messaging window, and can also send requests via this window.

3.2 Cognitive Human-Machine Interface and Interactions

The framework for driving HMI[2] adaptation is illustrated in Fig. 6 based on previous research undertaken in this area [13, 14]. In the framework, the cognitive state of the human operator is estimated in real time, allowing for dynamic reconfiguration of system automation levels and human-machine interfaces. The framework utilises a three stage process involving sensing, estimation and reconfiguration. In the sensing stage, a suite of sensors is used to monitor both the human operator and external conditions. Raw data is processed to extract suitable features, which are then fed into the classification layer to estimate the operator cognitive states, such as workload, attention, stress and fatigue. The estimated cognitive states are used to drive HMI[2] adaptations in the reconfiguration layer.

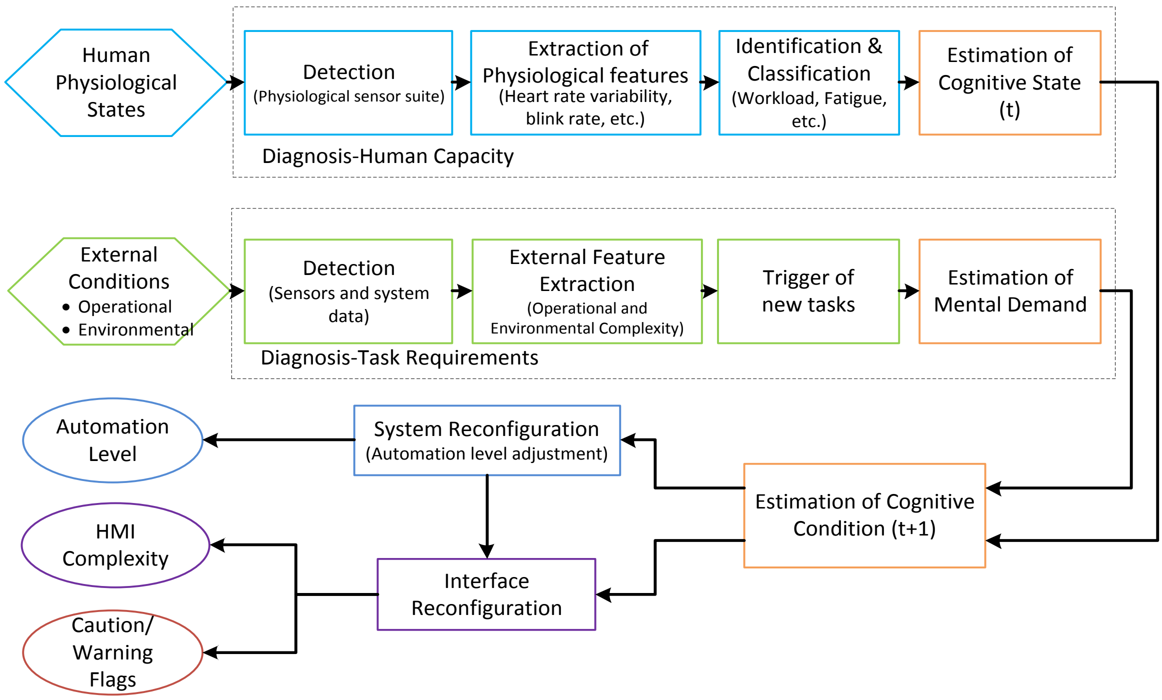

Fig. 6. Cognitive HMI[2] conceptual framework [13].

In particular, four independent HMI[2] adaptation mechanisms are defined, with each mechanism addressing one aspect of automation support for the fire-fighting mission. These mechanisms are:

- *Task management*: HMI^2 adaptations supporting the human operator in identifying relevant tasks to achieve the mission objectives; in prioritizing different tasks to maximize mission performance; in making modifications to task parameters; and in tracking progress and performance across all active tasks.
- *Team management*: HMI^2 adaptations supporting the human operator in identifying optimal UAV team configurations and task assignments for a given set of tasks; and in re-tasking of teams or in re-allocating UAV to different teams.
- *Path planning*: HMI^2 adaptations supporting the human operator in generating and selecting optimal paths for UAV teams to complete their assigned task in the most efficient manner; and in modifying active paths due to changes in the mission environment.
- *Information Management*: HMI^2 adaptations supporting the human operator in maintaining appropriate situational awareness on current tasks and teams.

4 Conclusion

This paper presents the concept of operations and systems design for a multi-platform Unmanned Aircraft System (UAS) bushfire-fighting scenario. The paper outlines the key Communications, Navigation and Surveillance (CNS) and mission system functionalities for an Unmanned Aerial Vehicle (UAV), as well as the design of the Human-Machine Interfaces and Interactions (HMI^2) for the Ground Control Station (GCS). The GCS HMI^2 is designed to support the management of multiple UAV by a single operator. The GCS design incorporates a number of emerging HMI^2 concepts to enhance human-machine teaming through adaptive automation. In particular, the use of physiological sensors allow HMI^2 adaptations to be triggered by changes in the human operator’s cognitive states. Ongoing research is evaluating the Cognitive HMI^2 (CHMI^2) concept through human-in-the-loop studies.

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