A CAPABILITY FRAMEWORK VISUALISATION FOR MULTIPLE HETEROGENEOUS UAVS: FROM A MISSION COMMANDER'S PERSPECTIVE

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Abstract

There is an increased interest in Uninhabited Aerial Vehicle (UAV) operations and research into advanced methods for commanding and controlling multiple heterogeneous UAVs. Research into areas of supervisory control has rapidly increased. Past research has investigated various approaches of autonomous control and operator limitation to improve mission commanders' Situation Awareness (SA) and cognitive workload.

The aim of this paper is to address this challenge through a visualisation framework of UAV information constructed from Information Abstraction (IA). This paper presents the concept and process of IA, and the visualisation framework (constructed using IA), the concept associated with the Level Of Detail (LOD) indexing method, the visualisation of an example of the framework. Experiments will test the hypothesis that, the operator will be able to achieve increased SA and reduced cognitive load with the proposed framework.

1 Introduction

Uninhabited Aerial Vehicles (UAVs) have been used for many years. Advancements in technology and state-of-the-art research have allowed the capabilities and functionalities of UAVs to expand [1]. Research has identified that more complex missions can be achieved by combing the capabilities of heterogeneous UAVs [3].

There is an increased interest in multiple UAVs, which are heterogeneous in physical form and/or capabilities, to work together. A generic problem of supervision, or management of these UAVs, especially in the *one-operator-to-multiple-UAVs* $(1 : n)$ paradigm is an active area of research [2].

Past research has focused on different aspects of a single operator managing multiple UAVs, including human operators' mental resources in supervisory control of multiple UAVs [3]; establishing automation to assist with command and control [4]; and task scheduling for managing current and future mission schedules [6].

Cummings and Guerlain [7], and Cummings and Mitchell [3] studied the operator mental capacity and demonstrated that an operator has the mental capacity to supervise up to eight homogeneous UAVs. In their research, it was also identified that operator workload can be reduced [8] with assistance from automation.

Other researches have also investigated supervisory control of multiple UAVs through scheduling of tasks [1, 9]. Task scheduling involves managing the time and information, taking into account the different reaction and wait times of the human mental performance [3], and automatically generate schedules for the machines to perform tasks, thus reducing the operators' workload during a mission [9].

Although these approaches contribute to improve managing multiple heterogeneous UAVs, they have not directly addressed "what" information and "how much" of this information should the operator know when the UAV is at a certain Level Of Autonomy (LOA), or the situation the UAVs are being surrounding by (ie. unpredicted weather behaviour which could affect UAV performance).

To address this challenge, this paper proposes a method of abstracting the information of each UAV to form a framework in which information is selectively displayed to the operator according to its functional LOA.

2 Visualisation Framework

A framework of a generic UAV's functional (sub)systems and capabilities is constructed through the application of an Information Abstraction (IA) process (further discussed in section 2.1). This framework consists of high Level Of Details (LODs) of a UAV's functional (sub)systems, layering down to more of lower LOD.

In this paper, Level of Detail is the level descriptor which indicates the how much in-depth details about the UAV are to be visible to the operator, the higher numerical value of the LOD, the less information that is visible to the operator.

LOD can also be understood as layers, and in each of the layers, more information is revealed about the particular subsystem which it stemmed from. And as shown in appendix A1, the components in the framework are represented visually (discussed in section 2.4).

2.1 Information Abstraction

IA is a process which determines the UAV's entire system and functional subsystems (which outlines the UAV's capability) to produce a structured framework based on the LODs of the system and its subsystems. This process is similar to the Abstraction Hierarchy (AH), in which a hierarchy is formed based on abstracting system functions [10, 11].

In the example shown in figure 1, UAV health consists of many components, such as; the status of the signals from ground communications, positioning sensors, the latency or errors associated with imagery data or telemetry communication, as well as internal (sub)system information. From this, the UAV's internal systems will contain further subsystem information, such as the control system health, fuel status, propulsion system health/efficiency, and hydraulic system health. This information is abstracted from a very broad system level, down to more a raw information data, thus this process is called IA.

Viewing from a high LOD, the operator will be exposed only to the main system components, in a way which indicates whether that system component is healthy and functional. If the system is functioning correctly, an indication will be shown, reporting to the operator that the system component is operating as normal. Otherwise, less healthy status will be displayed (using different indicators) to the operator that the system's health is abnormal.

By abstracting the UAV's system information and forming LODs, one can hypothesise that, through the use of this adaptive approach to display UAV information, which reflects the UAV's capability, it is possible to reduce cognitive load placed upon the operator, while allowing their Situation Awareness (SA) of the UAV and its surroundings to increase.

2.2 Framework Structure

As shown in the framework in Appendix A, the type of generic UAVs chosen for this study includes three primary systems: *UAV Health*, *On-*

board Data Systems, and *Payload*. At a very high LOD, the operator should be receiving very high level information and acknowledging the UAV's status and all its functionality is normal. The specific systems' status during operations (the visualisation of these information will be further discussed in section 2.4). That is, during operations, the operator will understand whether the UAV's *Health*, *Onboard Data Systems*, and/or *Payload* is at a functional and autonomous state.

In the next LOD, greater details are available for each of the main systems. For example, under *UAV Health*, three more functional categories are included, as seen in Figure 1. Each category/component reveals greater details of the UAV's particular system to the operator.

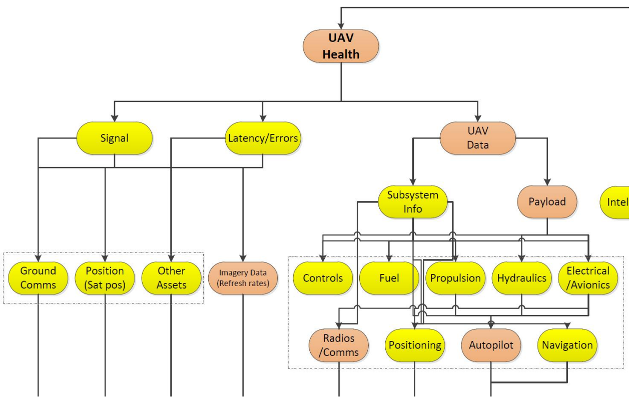

Fig. 1 UAV Health branch with its sub-categories from higher LOD (upper part of the framework) to lower LOD (lower part of the framework).

The amount of detailed information is displayed according to which LOD a specific subsystem should be displayed (depending on the functional LOA and external situation). The higher LODs of the framework indicate that higher level information is displayed, this for example is a single indication of whether a specific system, i.e. health monitoring system, is functional. The lower LODs of the framework indicates more detailed information such as the fuel levels of a UAV in numerical form is displayed.

2.3 Level Of Detail

During the application of the framework, the amount of detailed information about a (sub)system is classified using LODs. LOD is a method proposed along with the framework to index particular sub-branches' amount of details of the framework. During the theoretical analysis stage of research, LOD is used for analysing the suitable amount of information to present to the operator during each stages of the experiment scenarios.

The framework illustrated in Appendix A1, contains seven LODs. The lowest level in the framework illustrates the lowest LOD (LOD-1), which represents the most detailed and unaltered information about a specific subsystem. The highest level of the framework, namely LOD-7; illustrates minimal information about a particular system, except for *"how well can this system perform its duties?"*. An example of how the LOD is applied will be presented in section 4.4.

2.4 Component Visualisation

Each of the components in the framework will be visually represented to the operator during the operation. The LOD associated with each branch will depend on the mission situation and reflects the UAV's functional LOA.

For the purpose of detailed discussion, the *UAV Health*, and *UAV Data* sub-branch (as shown in figure 2) will be further illustrated through a series of figures. In this subsystem, there are two main sub-branches; *Subsystem Info* and *Payload*. For the purpose of illustration, only *Subsystem Info* sub-branch from an LOD-7 down to an LOD-5 will be elaborated.

In each of the framework components, there are two modes of visual representation; a non-autonomous visual (V) representation, and an autonomous visual (V') representation. The V representation will present only direct information on the particular framework component with minimal to no autonomous interpretation or warning features. The V' representation will not only present the basic information similar V, but an additional layer of aggregated information, information interpretation and/or warning features will be available, as the system will provide it's own autonomy for monitoring itself (and the re-

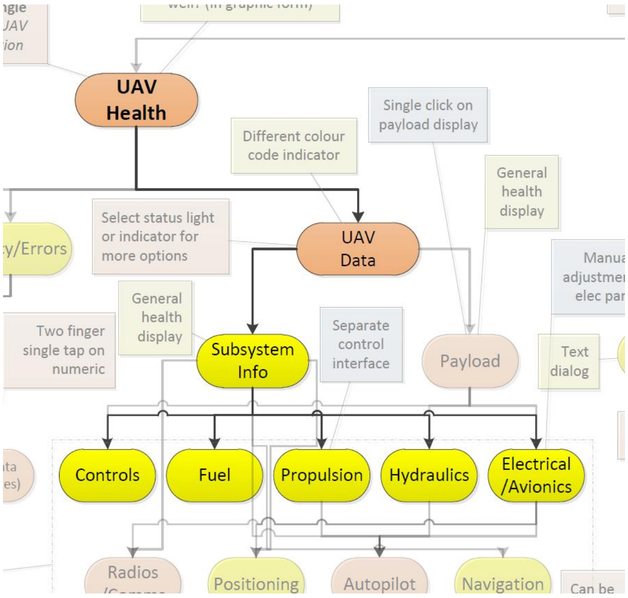

Fig. 2 An illustration of the lower levels of the *Subsystem Info.* sub-branch.

lated subsystems).

The LOD 7, 6, and 5 are: *UAV Data*, *Subsystem Info*, and *Control, Fuel, Propulsion, Hydraulics, and Electrical/Avionics* subsystems.

2.4.1 *Level 7: UAV Data*

Figure 3 displays a very high level indication of the UAV data subsystems' overall health.

Fig. 3 An illustration of the *UAV Data* sub-branch in both V (left) and V' (right) mode of representation.

- V Mode: Under V mode, the colour of the icon indicates the overall status of this framework component. Since there is no automation, the information shown on the icon will be as displayed.

- V' Mode: Under V' mode, in addition to the V representation, autonomous visual warning will be available to cue the operator during critical times.

2.4.2 *Level 6: Subsystem Info*

The *Subsystem Info* component is a sub-branch of the *UAV Data* subsystem, it is a high level representation of all the primary UAV's subsystems. This framework component (as illustrated in figure 2) consists of two sides; *Subsystem Info* and *Payload*. Since only *Subsystem Info* component will be illustrated in figure 4, the right-half of the visualisation is cross-hatched (with a highly transparent grey colour).

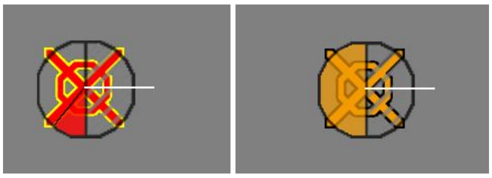

Fig. 4 An illustration of the *Subsystem Info* component in both V (left) and V' (right) mode of representation.

- V Mode: Under V mode, the colour of the semicircle will provide an indication to the overall UAV subsystems health status. It will not provide any aggregated information.

- V' Mode: Under V' mode, in addition to the V representation, an autonomous evaluation process of the subsystem health information is conducted within the elements of the subsystems. The result will be presented in the manner shown in figure 4 (right). Similar to section 2.4.1 an autonomous warning feature will also be available.

2.4.3 *Level 5: Control, Fuel, Propulsion, Hydraulics, Electrical/Avionics*

At this level, greater status information regarding each of the primary subsystems have been grouped. A colour-coded display arranged in a form of a central panel including individual subsystem status, is presented in figure 5.

The panel consists of mainly five elements, each corresponding to a component of the framework. For the ***C**ontrol*, ***P**ropulsion* and ***H**ydraulics* components (figure 5), the V mode

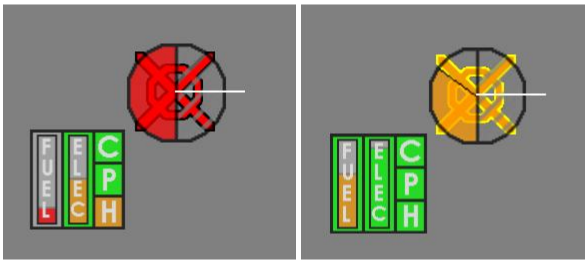

Fig. 5 An illustration of the individual health status of the UAV primary subsystems.

display will indicate the status of the respective subsystems with colour-codes. In V' mode display, an additional flashing glow effect is added when the system deems itself to be at a critical level of reliability, thus requiring the operator's attention (as illustrated in figure 5 (right)).

The two bars position to the left of the three vertically aligned indicators show the fuel and electrical system status.

- **FUEL**: A total level of fuel indicated by the amount displayed. In V' mode, a thick outline surrounding the fuel display will flash and glow, indicating whether with the current fuel level, the UAV is able to complete the present task. This is estimated autonomously.
- **ELEC**trical/Avionics: Similar to the fuel system, the amount displayed will indicate power remaining in the system. The thick outline surrounding the display indicates the overall electrical/avonics systems' status. In V' mode, during critical events such as when onboard electrical/avionics systems are malfunctioning, this outline will flash and glow, similar to the other LOD 5 components.

3 Quantitative Measurements

Three quantitative measurements are used to validate the proposed framework; the LOA, using Sheridan and Verplanck's Scale of LOA (Ten LOAs) [12], SA measurement, using Endsley's three levels of SA and the SA Global Rating Technique (SAGAT) [13], as well as cognitive load, using NASA-TLX [14].

Three measurements, LOA will be used as an independent variable, while SA and cognitive load will be used as dependent variables (indicators of operator performance).

3.1 Functional Level Of Autonomy

LOA was originally developed to classify how autonomous an Uninhabited System (UMS) is [12] with respect to manual input. This was first explored by Sheridan and Verplanck (SV) in their 10 LOA [12].

Since then, LOA metrics, scales and taxonomies have been researched quite extensively from different approaches; these include an increased granularity and dimensions of decision making in LOA in the Autonomous Control Level (ACL) by Clough [15], or the incorporation of three primary aspects of an autonomous machine in the environment (environmental complexity, mission complexity, and human independence in Huang et al's proposed Autonomous Level For Unmanned Systems (ALFUS) [16], or through more human machine collaborative approaches like the Human-Automation Collaboration Taxonomy (HACT) proposed by Bruni et al [17].

All of these approaches attempt to classify the unmanned system's autonomy as a whole, while the capability of a UAV should be reflected with LOAs applied to each UAV's (sub)system functions, or *Functional LOAs*. In this research, the SV scale will be adopted and applied to the functional (sub)systems, to acquire the functional LOAs of the UAV.

LOA is a dependent variable in this study, Which defines the capability of the UAV as mentioned above. The UAV's capability can be seen as the relationship: *Capability* = *Functional LOA* $\times$ *Situation Environment*; where the *Situation Environment* is the environmental condition which the UAV is experiencing at the time of query. Combining the *Functional LOAs* and the *Situation Environment*, the capability of the UAV can be obtained.

3.2 Situation Awareness

One of the dependent variables in the validation experiment (section 4) is SA. SA as defined by Endsley is a person's *perception of the elements of the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future* [19]. In this research, the concept is applied to how aware the operator is of his/her mission assets/UAVs' status and capabilities, or internal SA, as oppose to of the SA acquired by the UAVs themselves [18], or external SA.

To assess the SA experienced by the operator during an experiment, the SAGAT, proposed by Endsley [13] will be used. SAGAT allows the experimenter to probe into the test subject and administer a series of queries during an experiment in a minimally intrusive manner (if conducted correctly) [19]. The set of queries can be designed and modified according to the information that is considered important to the operator. The operator answers the queries to the best of his/her knowledge, thus demonstrating the SA the operator has at a specific point in time.

3.3 Cognitive Load

A second dependent variable used in this work is cognitive load. In this research, cognitive load is defined as the *mental stress experienced by a person when he or she is attempting to comprehend all the information that are presented to him or her*, that is, the mental workload induced by attempting to comprehend too much information at the same time.

The cognitive load can be captured by using NASA-TLX [14]; a set of procedures proposed to detect mental workload of an operator through self-reporting, similar to the SAGAT, except a fixed set of queries will be used.

In the past, this method had been administered post-experiment. But for the purpose of obtaining a result of the cognitive load throughout the experiment, queries will be asked during the experiment along with acquiring the SA of the operator, thus periodic data points can be collected for result analysis.

4 Validation Experiments

To validate the framework proposed, three experiments will be conducted. There are two baseline experiments, followed by one investigation experiment. Each of these experiments will include two parts. The first part will consider with no change in the functional LOA of the UAV, the second part will consider a change in the functional LOA, that is, a change in the UAV capability.

4.1 Baseline Experiments

Baseline experiments are used to establish the operator's baseline performance (SA and cognitive load). The baseline experiments will establish a baseline result for further investigation.

There will be two baseline experiments as mentioned earlier:

- The **first baseline experiment** which involves the lowest LOD information of the framework will provide a base result on the operators' SA and cognitive load when complete information is available to the operator at all times.

- The **second baseline experiment** which involves the highest LOD information of the framework will provide a baseline result on the operator's SA and cognitive load when only minimal information regarding the UAVs will be available for the operator at all times.

The results collected through these and the investigation experiments (which will be further discussed in section 4.2) will be used to analyse the validity of the hypothesis on the benefits and drawbacks of utilising an information framework designed through IA.

4.2 Investigation Experiment

The investigation experiment is aimed at evaluating the presence of the framework in a mission scenario, as well as the impact it has on the operators' SA and cognitive load. Results collected in this experiment will be compared with the two baseline experiments. The alternative hypothesis (H_A) is that an increase in SA and a decrease in cognitive load will take place with the addition of the framework when applied adaptively.

The scenario will be analysed on paper prior to being conducted. During each significant segment of the scenario, a specific set of information will be available according to application of the LOD (further discussion on LOD (section 2.3) and applying the LOD in section 4.4).

4.3 Scenarios

One primary scenario will be used for the three experiment. The scenario will involve the test subject (the UAVs' operator) to manage two heterogeneous UAVs searching for personnel in distress. There will be three groups of distress zones clearly indicated by "distress beacons". These beacons are activated via simulated persons in the vicinity, with an indication of how many persons there are in the area of the beacon.

There will be three distress beacons deployed, and the operator is asked to attend all of those stress beacons and identify all the persons within the approximate region (calculated by their estimated distance travelled according to the time it takes for the UAV to arrive at the scene to form a radius of the approximate region). The UAVs used for the tasks are different not only in its capability, but also the type of the platform.

One of the UAV platform is rotary wing (UAV_R). It is capable of conducting detailed search of stress areas, and is able to make decisions on the type of search pattern to conduct for each of the distress zones. However, it is not able to ensure the environment which it operates in will always be safe for operations, that is, it is not able to obtain sufficient external SA for it to operate safely, nor can it travel very fast. Thus this UAV should only be used for detailed searches of distress persons when adequate external SA is acquired from the other UAV.

The other UAV platform is a fixed wing UAV (UAV_F). This type of platform is capable to cover large areas of land in a comparatively short amount of time, but it is not able to perform detailed searches. This UAV is not equipped with the same location and identification equipment as that for UAV_R, but it has strong capability to detect external SA as well as prediction of future events. This capability allows the operator as well as UAV_R to acquire adequate level of external SA to perform the tasks required.

During each of the experiments, there will be variables which change depending on the scenario description described in sections 4.1 and 4.2.

4.4 Applying LOD Index

For illustration purposes, a segment of UAV_R's flight path is chosen. Figure 6 illustrates the task model of this chosen segment (segment 5). This is the *post search* segment, it is the series of tasks the operator must perform after completing a search in the distress zone (with all persons located and identified).

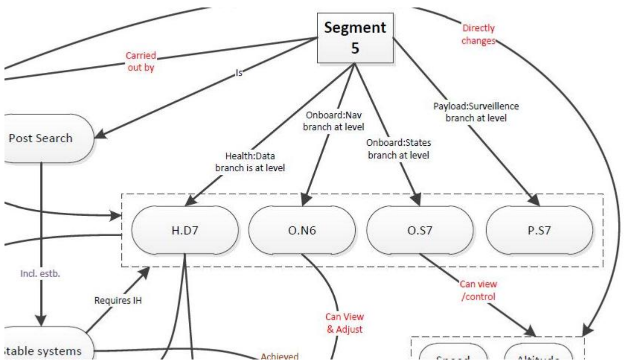

Fig. 6 An extract of the task model for segment 5 of the UAV_R's mission.

As it is visible through the model shown in figure 6, there are three codes of interest; *H.D7, O.N6, O.S7, P.S7*. These codes indicate the LOD associated with each of the main system branches of the framework.

- First Position **(H/O/P)**: The first position of the code indicates the main branch of the overall framework; UAV **H**ealth, **O**nboard Data Systems, and **P**ayload. As it can be seen in figure 2, there are two instances of *Onboard Data System*. This is due to the two sub-branches of this main system branch used in this UAV platform. This is further elaborated in the next point.

- "Period" Second Position **(.D/.N/.S/.S)**: The "period" is used as a marker for separating the main and sub-branches of the information framework. This is followed by an alphabetical character indicating which sub-branch is being referred to. In the four cases illustrated, they represent; UAV **D**ata, **N**avigation, **S**tates, and **S**urveillance. The following numerical index is used to indicate the LOD of the particular sub-branch to be presented to the operator.

- Third Position **(7/6/7/7)**: This numerical index indicates the LOD of the corresponding sub-branch. Level 7 indicates a highest LOD, with minimal information. This can be used in situations where the corresponding subsystem is performing well, thus requiring little to no attention from the operator. The reserved operator's attentional resources could be used on subsystems which require more mental resource. This will help the operator to focus on (sub)systems that require greater attention to perform specific tasks and objectives.

By applying the LOD to the framework (analysed subjectively), it is foreseeable that an overall improvement of operator's SA and cognitive load will take place. This will be verified through actual experimentation.

5 Future Work

This proposed framework is expected to improve the SA and reduce cognitive load of the operator while managing multiple heterogeneous UAVs. However, it still requires the three experiments to be conducted to evaluate the validity of the hypothesis, and these experimental descriptions were presented in section 4.

Ongoing work focuses on the implementation and experimentation with results analysed and discussions made on whether by adopting this framework, SA and cognitive load will have a positive impact as hypothesised.

6 Conclusion

Due to an increased interest in utilising multiple UAVs that are capable of performing heterogeneous tasks to perform missions, the problem of operator SA and cognitive load in controllability is an issue. Previous research in investigating the command and control of multiple heterogeneous UAVs has contributed with a number of different approaches to address this issue. However, these have not been able to provide a structured approach to hierarchically displayed systems and functional information about the UAV assets, therefore this paper has proposed a visualisation framework which aims to address this challenge. With this framework, it is foreseeable that there will be a possible impact on the operator's SA and cognitive load.

Through the application of the IA process, a visualisation framework is defined. This framework (as illustrated in Appendix A1) provides a structured approach to illustrate necessary information for the operators to comprehend, thus increasing their SA of the necessary information and reducing their cognitive load.

In future research, the experimental validation results of the framework will be analysed and disseminated.

Acknowledgement

The first author would like to acknowledge Dr Matthijs Amelink from D-CIS Lab, Netherlands for the valuable discussions on Abstraction Hierarchy, and Mr Julien Gaye from Télécom Bretagne, France for his contribution in generating the visualisation graphics presented in the paper.

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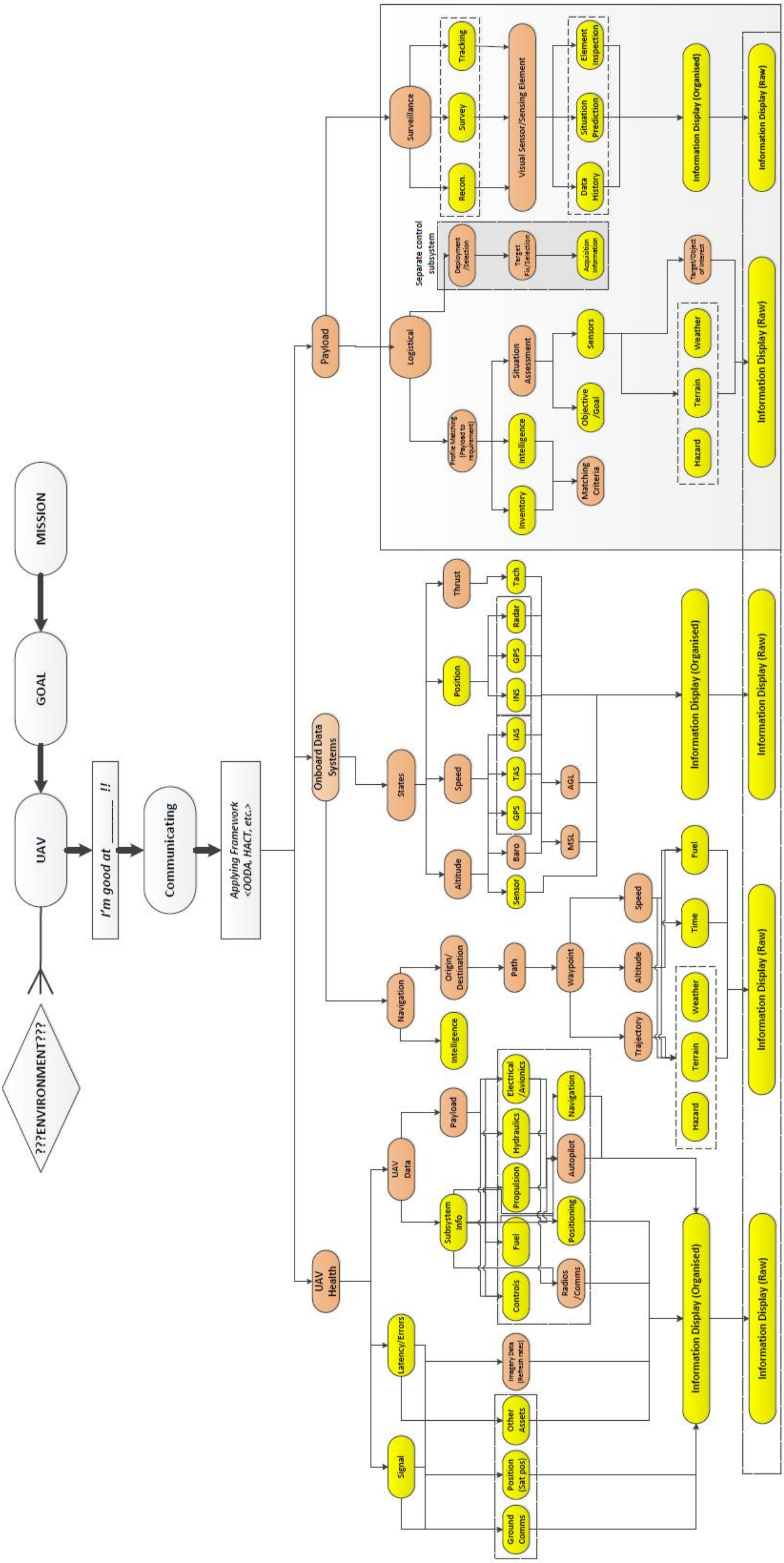
6.1 Copyright Statement

Appendix A1

Full visualisation framework constructed through Information Hierarchy (IA). Intended for clearer illustration referenced throughout the paper.


MISSION
GOAL
UAV
???ENVIRONMENT???
I'm good at ______ !!
Communicating
Applying Framework
<OODA, HACT, etc.>
UAV Health
Onboard Data Systems
Payload
Signal
Latency/Errors
UAV Data
Subsystem Info
Payload
Ground Comms
Position (Sat pos)
Other Assets
Imagery Data (Refresh rate)
Controls
Fuel
Propulsion
Hydraulics
Electrical /Avionics
Radios /Comms
Positioning
Autopilot
Navigation
Navigation
Intelligence
Origin/ Destination
Path
Waypoint
Trajectory
Altitude
Speed
Hazard
Terrain
Weather
Time
Fuel
States
Altitude
Speed
Position
Thrust
Sensor
Baro
GPS
TAS
IAS
INS
GPS
Radar
Tach
MSL
AGL
Logistical
Surveillance
Profile Matching (Payload to requirement)
Inventory
Intelligence
Situation Assessment
Matching Criteria
Objective /Goal
Sensors
Hazard
Terrain
Weather
Target/Object of interest
Separate control subsystem
Deployment /Selection
Target Fix/Selection
Acquisition information
Recon.
Survey
Tracking
Visual Sensor/Sensing Element
Data History
Situation Prediction
Element Inspection
Information Display (Organised)
Information Display (Raw)