DESIGN APPROACH FOR A VERTICAL TAKE-OFF UNMANNED AERIAL VEHICLE WITH INTEROPERABLE CAPABILITIES – PAYLOAD ISSUES

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Abstract

The range of Unmanned Systems (USs - aerial, ground, surface, or underwater), are at various stages of technological demonstration; from prototype development to induction trials, both for civil and military applications. This has resulted in a key issue of "interoperability" that needs to be addressed. This paper adopts a systems approach to develop the system hierarchy for identification of the mission payload components of an interoperable vertical take-off unmanned aerial vehicle (iVTUAV) within a network centric warfare (NCW) environment. NCW was considered as the total system and the combined mission systems of all unmanned systems were located at the lower levels of the hierarchy. Establishing a systems concept of the various hierarchy levels identified the attributes and relationships of the system components.

1 Introduction

The capabilities of Unmanned Systems (US), whether aerial, ground, surface, or underwater, are under various stages of technological demonstration; from prototype development to induction trials, both for civil and military applications [1]. The technological challenge ahead is the issue of interoperability – a) inter: between US; and b) intra: with manned systems. [2].

The mission payload of vertical take-off unmanned aerial vehicles (VTUAVs) is presently designed from a platform centric perspective. With the emerging network centric warfare (NCW) concepts [3], the design approach needs to be modified to address the requirements of an interoperable VTUAV (iVTUAV).

A VTUAV design methodology was attempted by modifying the process of mission analysis [4] to include network centric operations. This provided the avenue for investigating appropriate mission payloads by considering the following: a) pre-emptive missions: in which the iVTUAV is specifically deployed in cooperation with another asset and; b) situational missions: in which the mission of the iVTUAV is re-allocated [4]. In this paper, a systems approach is adopted to develop the system hierarchy for identification of the mission payload components of an iVTUAV. The components will ascertain the data fusion requirements across platforms, including functional redundancies of mission systems across networked platforms.

2 System Hierarchy and Elements

A system is composed of components, attributes, and relationships. The components are also referred as subsystems. The attributes are the functional characteristics of the components and also referred as mission requirements in the design of a system [5]. Relationships are the inter and intra relationships between components and attributes. A system may be part of a larger system in a hierarchy, and its components may be referred as a system. The purpose of the system is achieved by the system elements and their corresponding attributes [5].

The Vertical Take-off Unmanned Aerial Vehicle (VTUAV) design process has traditionally been platform centric and comprises of the vehicle, its mission systems, and the ground control station (GCS) as subsystems of the total VTUAV system. To provide VTUAVs with interoperability capabilities in a design process, the VTUAV system needs to be considered as part of a network centric system – total system.

2.1 Hierarchy Levels 1 to 3

The total system is at the top level of the hierarchy with several other subsystems and components at different levels of the hierarchy. These subsystems and the components needs to be further investigated.

The NCW battlefield comprises of manned and unmanned assets, making it the subsystems of the next level in the hierarchy (Level 1). As this paper's focus is on the unmanned assets, a partial system hierarchy is developed only for unmanned assets. The manned section of the hierarchy will need separate investigations. Within the unmanned domain, there are aerial, ground, and marine platforms – the next level of the hierarchy (Level 2). The iVTUAV is positioned at this level - referred as "aerial platform system" alongside the fixed wing.

The VTUAV system traditionally comprises of subsystems and included the vehicle, the mission systems (payload), and the support system - GCS. The control switch to transfer the iVTUAV's control station from manned aircrafts, to carriers, or submarines based on its mission, location, and/or situation will be critical. The iVTUAV will need to be connected to a non-specific operator for command, control, communication, computers, and intelligence (C4I) in a network centric environment, in accordance to control standards under development. Future control systems aim to achieve compliance to these standards, and the iVTUAV's mission payload will need to interface and interoperate with such control stations [2, 7-9].

Hence, the GCS as a component of the Aerial Platform system (presently considered as part of the UAV system) of the hierarchy at Level 3, is operationally not in-line and will include only the vehicle and the mission system components. The system hierarchy from Level 1 to 3, is presented in Figure 1.

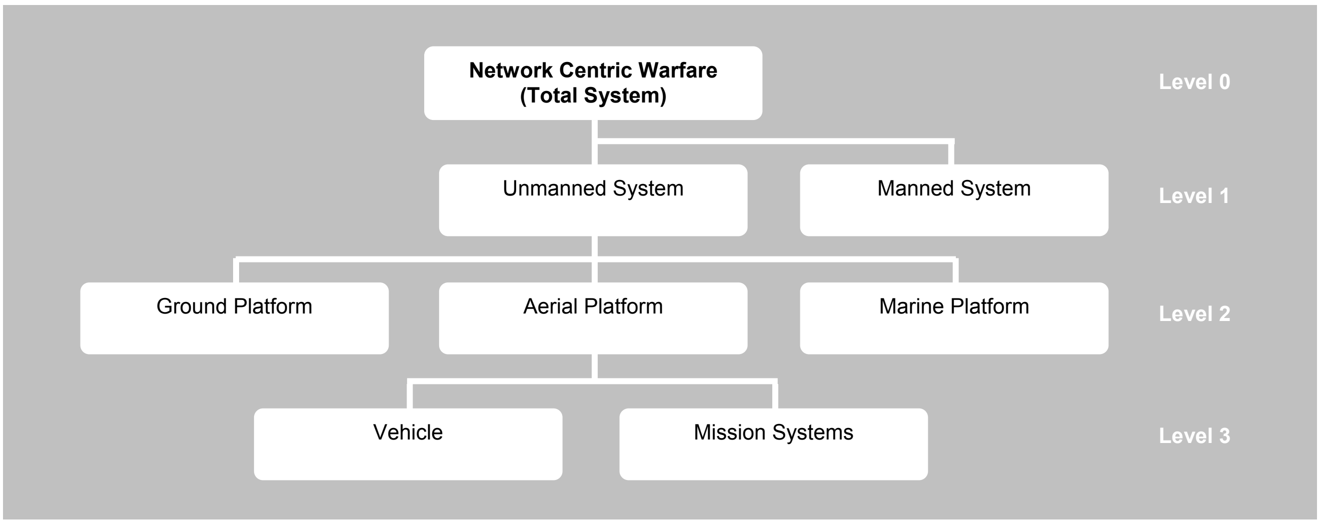

Fig. 1. System hierarchy – Levels 1 to 3

2.1.1 System Elements – Level 1

The identification of subsystems of the total system provides the avenue for analysis of the system elements – components, attributes, and relationships. At Level 1, the two components are the manned and unmanned systems with the principle difference of a pilot/crew on-board, and hence, the attributes are to be accordingly analysed. The analysis in brief of the iVTUAV's mission requirements for identification of the system attributes as an illustration is as follows:

- Human Factors: The pilot/crew on-board manned systems have human thresholds of concentration, over sustained operations [10]. Stressful conditions, intense concentration, or complex cognitive demands cause mental fatigue. Tiredness, illness, or poor nutrition causes physical fatigue. While an unmanned system in sustained operations has the flexibility of crew turn-over on-ground in case of GCS, command and control [11]. This is not applicable to iVTUAV (Sec 2.1). Thus, the attributes of the two components are as follows:
  - Unmanned: Sustainability.
  - Manned: Crew Fatigue.
- Design: The absence of crew on-board provides the design avenue for low observable unmanned systems [11] with the elimination of manned cockpit (seating and comfort systems). The UAV design may incorporate small sized airframes with seamless skins, windows and hatches reducing visual and radar signatures; thus enhancing survivability of the platform. The design gains in structures and materials reduce cost. A risk to crew on a manned system in highly dangerous missions [2] imposes design constraints on the vehicle contrary to unmanned systems. Thus, the attributes from a design perspective are as follows:
  - Unmanned: Design flexibility, survivability enhancement, and cost effective.
  - Manned: Design and survivability constraints.
- Communication and Response: Unmanned systems require uninterrupted communication link with an operator for near real-time data transmission, vehicle status monitoring, and receiving commands for mission management. This is critical in combat situations when the man-in-the-loop is to authorise weapon release to adhere to Rules-of-Engagement under the present operational doctrines [2]. This requires high communication bandwidth [11]. In manned systems, mission management occurs on-board the vehicle. This includes interpreting information, release of weapons on a target, and evasive manoeuvres from an incoming threat [10]. Thus, the response is in real-time, without the need to transmit data for response and decision making. It provides the manned systems a degree of independence. Thus, the attributes from a communication and response perspective are as follows:
  - Unmanned: Communication constraints, specific power, external decision dependence, and near real-time response.
  - Manned: On-board decision independence, and real-time response.
- Autonomy: Autonomy will decrease the workload of an operator and the communication bandwidth to a certain degree only, that being limited and governed by the present operational doctrines [2]. Autonomy may include from flight stability adjustments to adaptive behaviour. Increased on-board processing and specific computing power is the key enabler to enhance autonomous operations. This additional attribute is applicable to unmanned systems only and present scope is as follows:
  - Attributes: Specific power, and on-board processing.
- Situational Awareness: Manned system crew utilise imagery and data from onboard and networked sensors as well as their own

onboard real-view of the operation [10]. This provides higher degree of situational awareness in real-time with fusion of sensory imagery and crew view. In unmanned systems the situational awareness is in near real-time and is only sensor imagery based with no 'crew view' fusion; thus limited. Thus the attributes from a situational awareness perspective is as follows:

- Unmanned: Near real-time and limited awareness.
- Manned: Real-time enhanced awareness.

2.1.2 System Structure – Level 1

To develop the system structure in addition to the identification of the attributes of the components, the inputs, outputs, relationships, and environment needs to be identified. The environment may be classified as manmade and natural, as identified in the mission analysis [4], at the system levels 1 to 3 and may be further analysed in detail at the next levels of the hierarchy. The input to the total system mainly comprises of the military operational doctrines and that of output is network centric mission capabilities. The relationships are inter and intra – component & component, component & attribute, and attributes & attribute.

The system structure based on the identified system elements and the environment is presented in Figure 2.

2.1.3 System Elements – Level 2

The formulation of the system structure at Level 1 identified the components, attributes, and relationships. The system hierarchy (Fig 1) identified the components at Level 2, which comprised of the following: a) aerial platform; b) ground platform; and c) marine platform. These platforms to be designed are to meet the stipulated mission requirements - the functional characteristics (attributes) of the components.

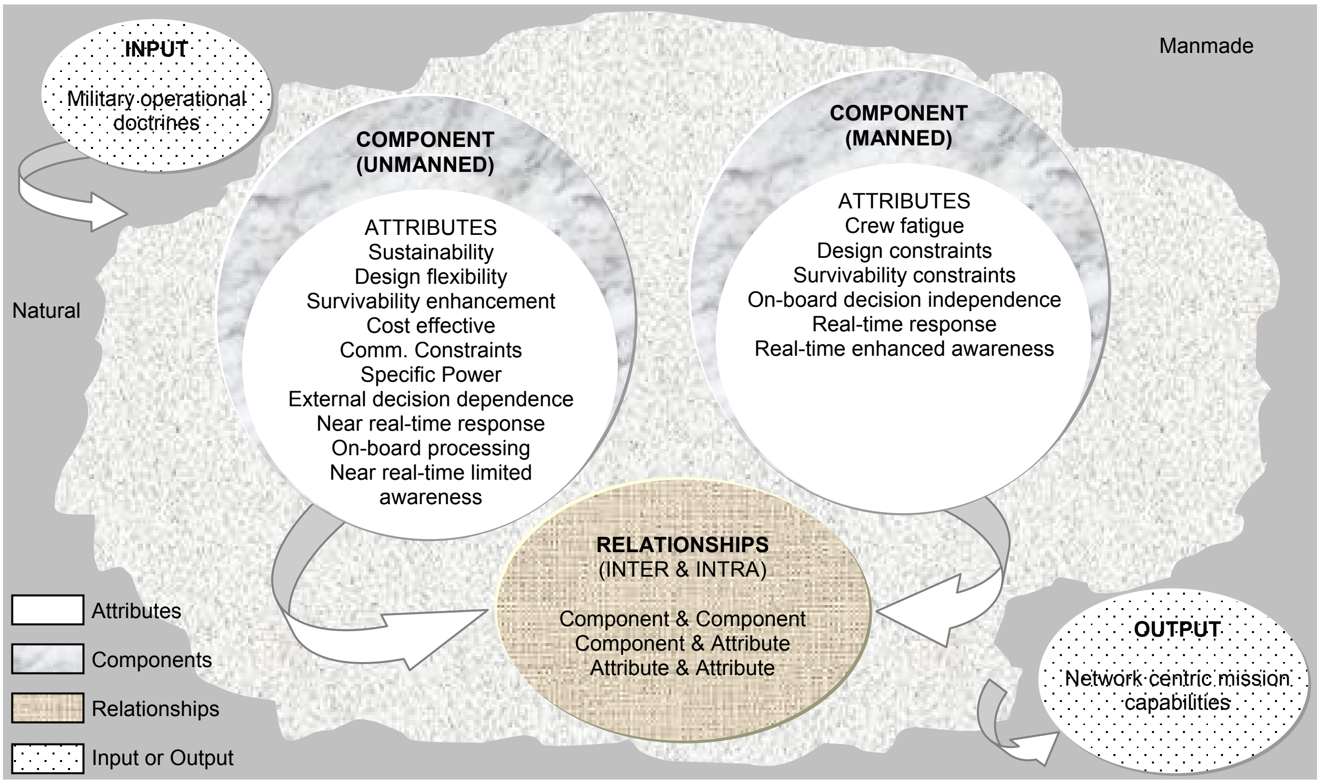

Fig. 2. System structure – Level 1

The mission requirements identified and categorised in previous investigations [4] were the following: a) long endurance; b) hazardous exposure; and c) hostile action. These are the attributes of the three platforms at Level 2.

2.1.4 System Structure – Level 2

The system structure is developed similarly to Level 1 by identifying the inputs, outputs, relationships, and environment. The environment at Level 1 (manned and unmanned) is further analysed in detail and identified as time, weather, threat, terrain, and NCW [4]. The input is the network centric operations (NCO) of the unmanned systems, and the output is iVTUAV mission capabilities. The relationships are as previously stipulated inter and intra – component & component, component & attribute, and attributes & attribute.

The system structure at Level 2 based on the identified system elements and the environment is presented in Figure 3.

2.2 Hierarchy Levels 3 to 5

The functional characteristics (attributes) of the aerial platform system (Level 2) are; long endurance, hazardous exposure, and hostile action. These attributes are to be met by the vehicle or the mission system component (Level 3) of the aerial platform system. The commercial-of-the-shelf (COTS) available mission systems technology need to be grouped based on their functional characteristics, to identify the components at the next level of the hierarchy.

An investigation of the functional characteristics of the COTS [12] resulted in the following categorisation:

- Navigation: Systems that that aid in flight control;
- Sensors: Systems that sense, track, locate, and identify a source;
- Computers: Systems that enable more responsive flight control systems, onboard sensor data processing, and autonomous behaviour;

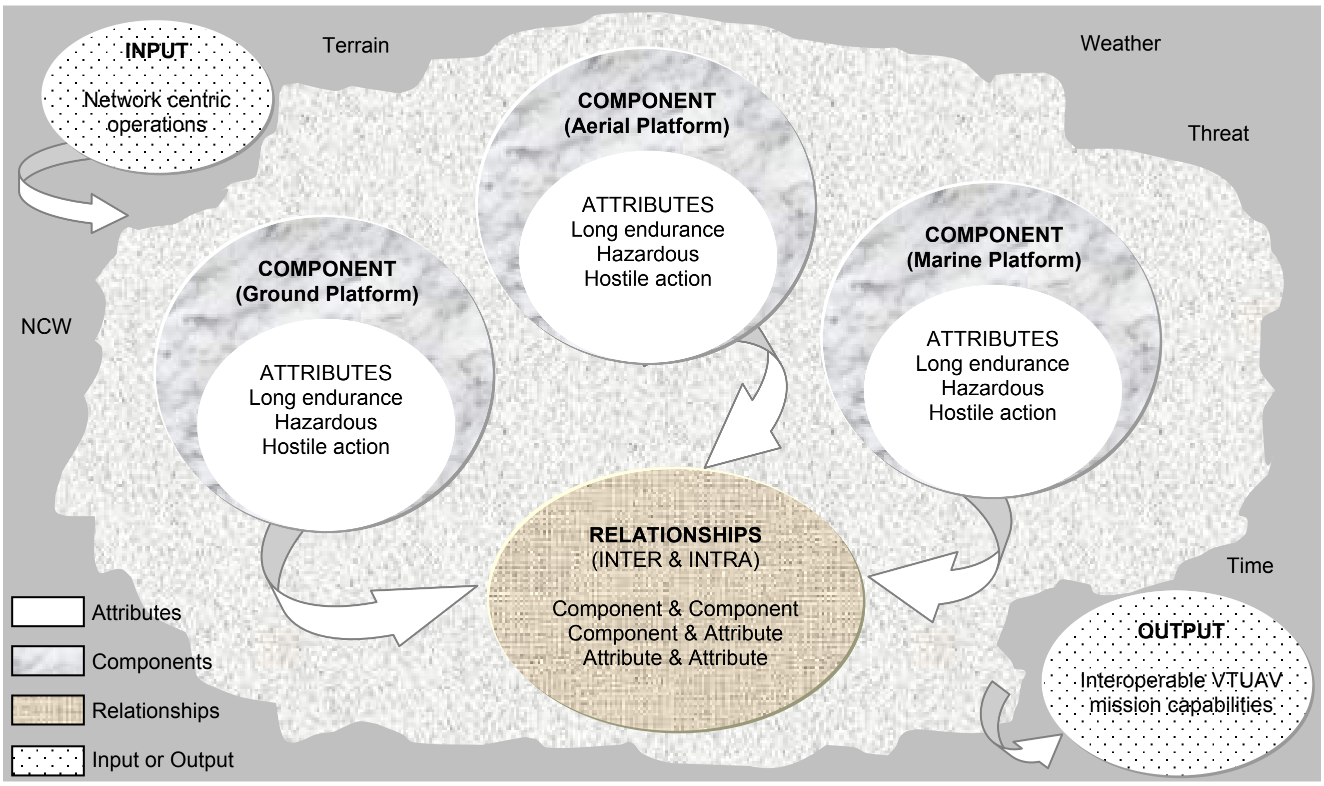

Fig. 3. System structure – Level 2

- Defensive Systems: Systems that provide active threat countermeasures;
- Weapons: Systems that provide the means of destroying (lethal) or incapacitating/ disabling (non-lethal) selected targets; and
- Data Links: Systems that provide two way communications between the iVTUAV and a control station.

Categories of the COTS were designated as the components of the mission systems - Level 4 systems of the hierarchy. The mission systems technology categories are further investigated in detail to sub-categorise the functional characteristics for formulation of the next level of the hierarchy – Level 5. To illustrate, the sensor categories of the technology is subcategorised depending on the capabilities it offers – still/video image, electronic signals, nuclear, biological, chemical, and/or magnetic detection. In the design process, the slated mission requirements will govern the technologies to be considered for the design of the mission system.

The iVTUAV is one component of the NCW total system and in the network centric environment its slated mission requirements may be derived from other components of the system – manned/unmanned assets and its corresponding mission systems. Additive components, or mission systems, are at disposal of the iVTUAV for mission accomplishment – a concept of operations. Thus the issue is – which of theses components identified for formulation of the mission payload are be on-board the iVTUAV and which are on-call from other platforms.

The lower levels of the hierarchy (Level 4 & 5) for the unmanned ground vehicle (UGV) and unmanned marine vehicle (UMV) systems needs to be developed accordingly, with due consideration of inter and intra usage of the components for mission accomplishment. The pre-emptive and situational network centric mission requirements [4] state the need of mission systems from other platforms to achieve wider data fusion for enhanced situational awareness and mission effectiveness. Thus, the development of the Level 4 & 5 of the hierarchy is in-line with the concept-of-operations. The mission payload design of an iVTUAV, thus, needs to consider the mission systems on-board other unmanned assets to optimise its payload on-board and enhancement of its mission capability beyond its payload capability.

The Levels 4 & 5 of the iVTUAV system hierarchy with an additional segment for UGV and UMV mission systems are presented in Figure 4.

2.2.1 System Elements – Level 4

A total of six components of the mission systems have been identified by a categorisation process. The functional characteristics (attributes) of the components need to be slated in-line with the mission requirements of the iVTUAV. The detailed mission analysis for the identification of the attributes is as follows.

- <u>Navigation</u>: Navigational equipment is to provide the iVTUAV with positioning information to aid in its flight control. The accuracy depends on the technology. Precise positioning information is essential to aid the iVTUAV in collision avoidance with other airborne assets and obstacle detection & avoidance. It also assists with precise weapon guidance [2, 13]. Thus, the required attributes of the navigation systems are the following:
  - Flight control;
  - Survivability; and
  - Lethal precision.
- <u>Sensors</u>: Sensors provide multiple applications of tracking, locating, and identifying a source for situational awareness – imaging or signal/magnetic/ hazardous material detection. This data is transmitted or stored for analysis via control stations/C4I systems for dissemination to other assets for enhancing the tactical picture of the battlefield.

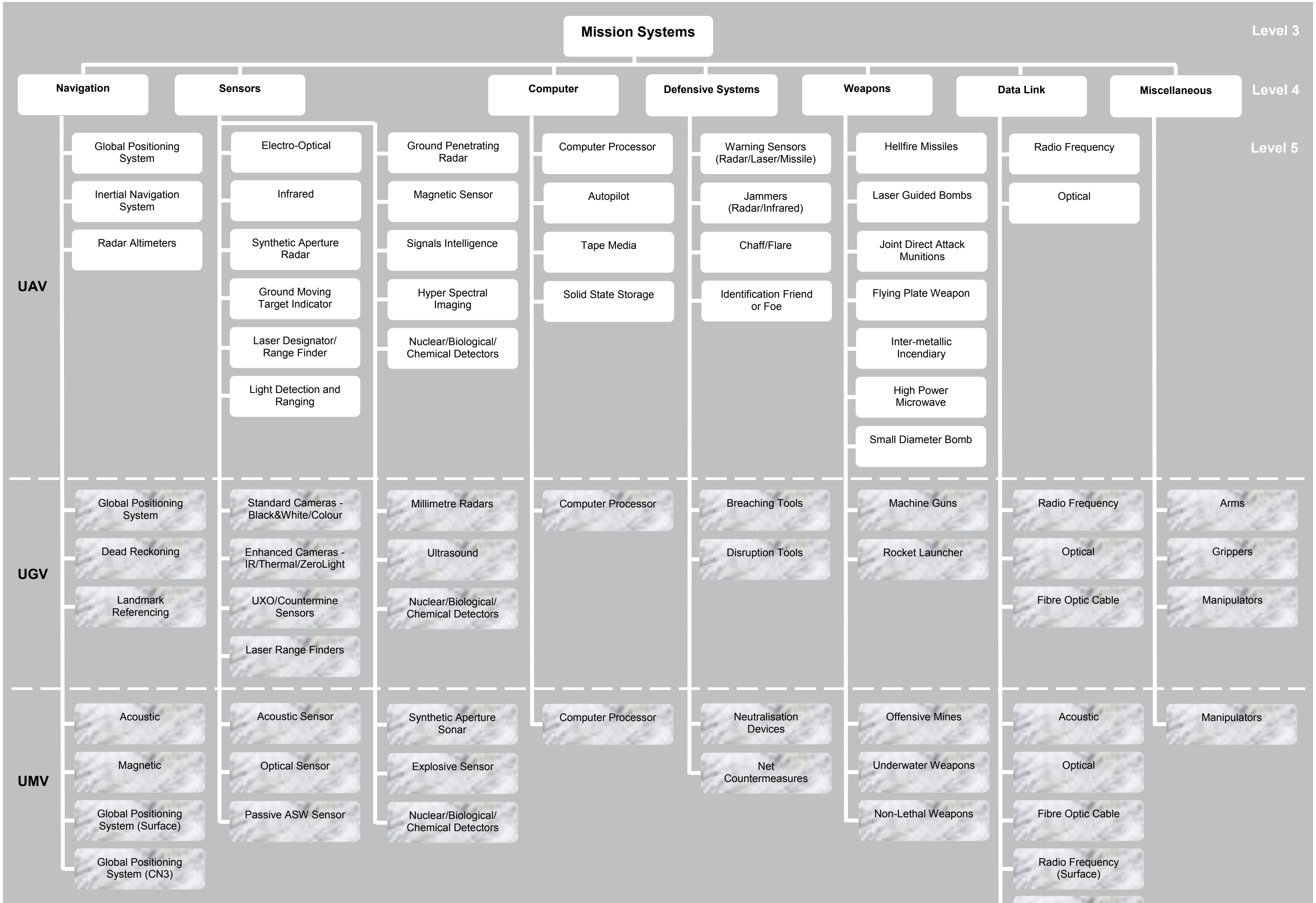

Fig. 4. System hierarchy with UGV and UMV segments – Level 4 and 5

Bandwidth requirements increase with the increase in information to be transmitted. Sensors also provide observational information, to assist in obstacle detection and avoidance, and threat detection for targeting the weapons [2]. The required attributes of the sensors are as follows:

- Observation & detection;
- Communication;
- Survivability; and
- Lethal precision

- Computer: Computing capability on-board is required to enhance sensor data processing, and autonomous behaviour. Autonomy, in the form of autopilot and algorithms, provides various degrees of autonomous behaviour from simple stability adjustments to complicated adaptive behaviour. This reduces the vulnerability of the iVTUAV and maintains its effectiveness during non-deliberate communication loss or deliberate jamming. In conjunction with on-board sensor data processing, it also reduces the requirement of large communication bandwidth. The storage devices provide post-mission analysis of data. The required attributes of a computing system on-board the iVTUAV are the following:
  - Flight control;
  - Data processing/storage;
  - Communication; and
  - Survivability.
- Defensive Systems: Defensive mission systems provide active threat countermeasures and include warning sensors (radar, laser, and missile), jammers (radar and infrared), and chaff and flare dispensers. Identification Friend or Foe (IFF) assists in collision avoidance [10]. The required attributes of defensive systems are as follows:
  - Observation & detection; and
  - Threat countermeasures.
- Weapons: Weapons provide the means of destroying (lethal) or incapacitating/ disabling (non-lethal) selected targets. Weapons may be installed internally or externally. Technology advancement has resulted in miniaturisation of the lethal warheads. Rules - of - Engagement considerations require final weapon control and authorisation to reside off-board the iVTUAV [2]. The required attributes of weapons are as follows:
  - Lethality.
- Data Link: Data link systems include the air terminal and antennas. Data links provide two way communications between the iVTUAV and a control station. An up-link allows the control station to control the iVTUAV as well as its payload, while a down-link provides iVTUAV status and sensor data transmissions. The rate of data transmissions governs the communication bandwidth. A continuous link and dissemination of data to all networked assets in a NCW battlefield provides enhanced situational awareness, provides higher degrees of synchronisation, and rapid decision making. This enhances survivability and lethality [2, 14]. A continuous data link is also necessary for Rules-of-Engagement considerations which mandate a man-in-the-loop to analyse and authorise an iVTUAVs weapons release [2]. Thus, the required attributes of the data link systems are the following::
  - Flight control;
  - Communication;
  - Survivability; and
  - Lethal precision.

2.2.2 System Structure – Level 4

Similar to previous levels, the inputs, outputs, and relationships needs to be identified to develop the system structure. The environment was adequately analysed at previous levels - time, weather, threat, terrain, and NCW (Sec 2.1.4). The input is the iVTUAV mission requirements and the output is iVTUAV mission payload. The relationships remain inter and intra – component and component, component and attribute, and attributes and attribute.

The system structure based on the identified system elements and the environment is presented in Figure 5.

3 Results and Discussion

The investigations on payload issues of iVTUAV resulted in the development of the system hierarchy and system structure. This provided an in-sight of the system components and its functional characteristics, including the operational environment. It further provided the foundation to identify the mission systems for the design of an optimised payload – one that meets the slated mission requirements from systems on-board, and enhances the mission capabilities through on-call systems from off-board. The various levels of the systems hierarchy and the components and attributes at these levels are discussed below.

Hierarchy Level 1 to 3

The system hierarchy of an iVTUAV was considered as part of a NCW system – total system, which comprised of the unmanned and manned components. The unmanned component was categorised as aerial, ground, and marine platforms. The iVTUAV formed part of the aerial platform and comprised of the vehicle and the mission systems. The system structure at Level 1 (Figure 2) thus included the manned and unmanned as components, with detailed attributes governed by the required functional characteristics. The crew/pilot on-board/off-board stipulated the attributes.

The system structure at Level 2 (Figure 3) included the aerial, ground, and marine platforms as the components, with the mission requirements of long endurance, hazardous exposure, and hostile action as the attributes.

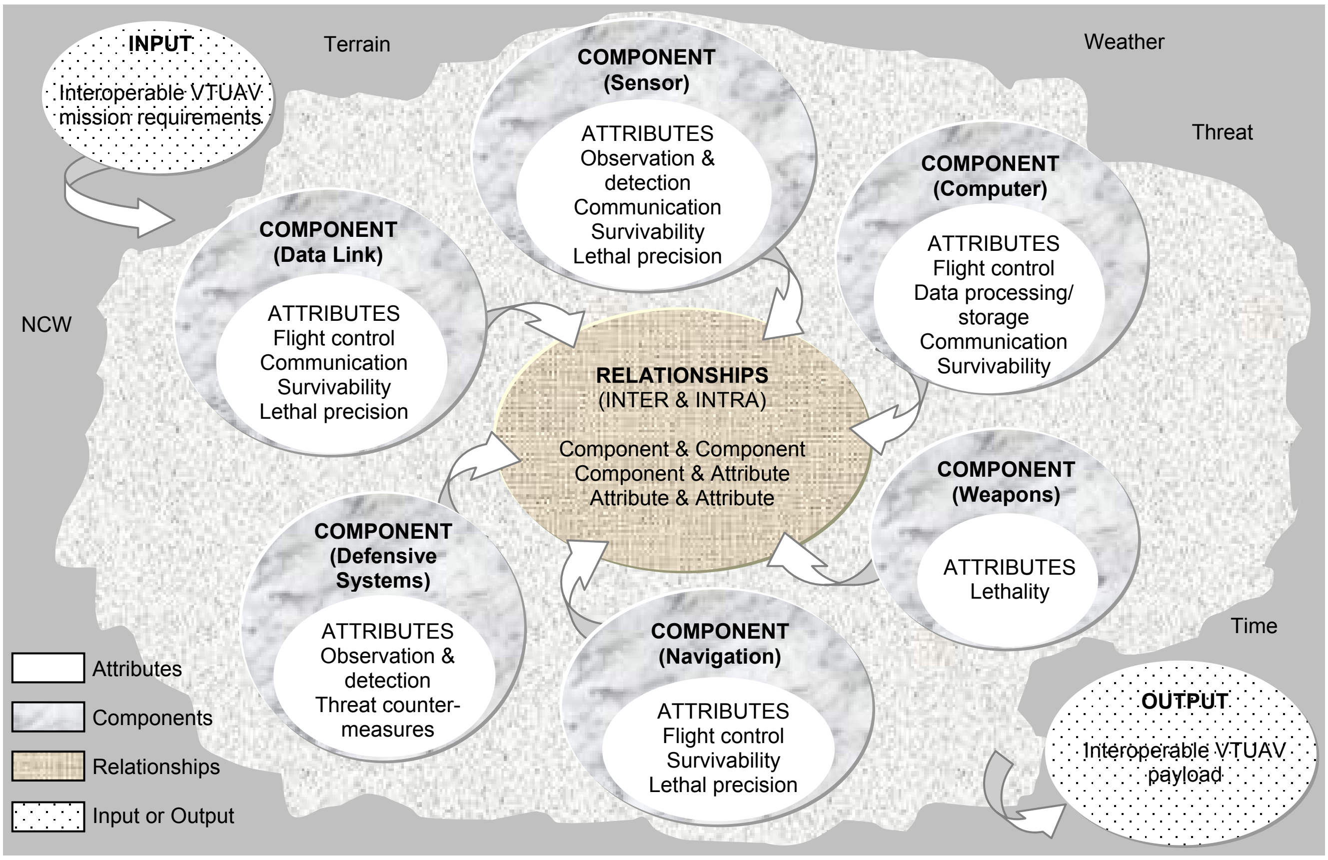

Fig. 5. System structure – Level 4

Hierarchy Level 3 to 5

The Level 4 and 5 of the hierarchy consisted of the mission system sub-components. The mission systems were categorised as navigation, sensors, computer, defensive systems, weapons, and data link at Level 4. These were further subcategorised at Level 5 for the design of the mission payload. The functional characteristics of these systems provided the mission capability to the payload.

The network centric perspective created an additional UGV and UMV segment at the hierarchy levels 4 and 5 (Figure 4) to address pre-emptive and situational network centric mission requirements [4]. This was to address the data fusion and functional redundancy requirements.

The system structure at Level 4 (Figure 5) identified a total of six components and their functional attributes were derived from the mission capability they provide to meet the stipulated mission requirements of the iVTUAV.

4 Concluding Remarks

The adoption of a system approach to investigate the payload design in an interoperability context of VTUAV provided the means to systematically develop the system hierarchy. It further resulted in structuring the system at various levels of the hierarchy to identify the system elements.

The last level of the hierarchy presented a format to further investigate other platform payloads from an interoperability perspective of the VTUAV. Further research needs to identify the critical systems of the payload that needs to be on-board the iVTUAV and those that are viable to be on-board other platforms.

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