A V-Diagram for the Design of Integrated Health Management for Unmanned Aerial Systems

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Abstract

Designing Integrated Vehicle Health Management (IVHM) for Unmanned Aerial Systems (UAS) is inherently complex. UAS are a system of systems (SoS) and IVHM is a product-service, thus the designer has to take into account many factors, such as: the design of the other systems of the UAS (e.g. engines, structure, communications), the split of functions between elements of the UAS, the intended operation/mission of the UAS, the cost verses benefit of monitoring a system/component/part, different techniques for monitoring the health of the UAS, optimizing the health of the fleet and not just the individual UAS, amongst others. The design of IVHM cannot sit alongside, or after, the design of UAS, but itself be integrated into the overall design to maximize IVHM's potential.

Many different methods exist to help design complex products and manage the process. One method used is the V-diagram which is based on three concepts: decomposition & definition; integration & testing; and verification & validation. This paper adapts the V-diagram so that it can be used for designing IVHM for UAS. The adapted v-diagram splits into different tracks for the different system elements of the UAS and responses to health states (decomposition and definition). These tracks are then combined into an overall IVHM provision for the UAS (integration and testing), which can be verified and validated. The stages of the adapted V-diagram can easily be aligned with the stages of the V-diagram being used to design the UAS bringing the design of the IVHM in step with the overall design process. The adapted V-diagram also allows the design IVHM for a UAS to be broken down in to smaller tasks which can be assigned to people/teams with the relevant competencies. The adapted V-diagram could also be used to design IVHM for other SoS and other vehicles or products

1. Introduction

Unmanned Aerial Systems (UAS) are Systems of Systems (SoS) where the pilot has been removed from the aircraft and been located in a Control Station (CS), usually on the ground. The CS and the Unmanned Aircraft (UA) are only two possible elements which makeup a UAS, others include: communication links, launch & recovery equipment, transportation – essentially anything which is needed for the UAS to fly and complete a mission.

The removal of the pilot from the aircraft allows greater variety of sizes and configurations for the UA, as they are not constrained by need to have space for humans or the equipment needed for their survival. However, removing the pilot from aircraft does come with its own set of problems. Perhaps one the key problems is that there can be a lack of situational awareness by the pilot, who gets the majority of their information about the aircraft from sensors onboard the UA via the communications link. To overcome this reduction in situational awareness and to aid the pilot various automated and autonomous responses are programmed into the UA. The responses could be could be small or large in scope – such as the UA conducting automated flight is the communication link to the CS is lost until it is reestablished. There is no typical UAS. Just as there is no typical UAS, there is no ideal IVHM solution for UAS as a whole (MacConnell, 2007).

1.1. IVHM Design

The design of any IVHM does not sit alone; it is part of the overall blend of systems and functions which will be part of the UAS. Because of this there must be an effort made to bring the design of the IVHM into the overall design of the UAS to allow health monitoring to move from a point solution to a problem which arises, to being part of the UAS from its conception. The design process of any one organization will vary form the next. Therefor it will be impractical to consider all the possibilities of how the design of IVHM for UAS will interact with the overall design.

IVHM can be considered a Product-Service System: a product (the physical items needed e.g. sensors, databases, networks) and service (the management of the health of the UAS and the fleet of UASs) integrated as one to deliver value (Baines et al, 2007; Grubic, Jennions, and Baines, 2009) to an asset through its life – shifting the responsibilities from the user to the supplier of the IVHM (which may or may not be the original manufacturer). Both the service and product for the IVHM need to be fully considered during the design.

The designer of IVHM for a UAS is still bound by the fundamental challenges of modern product development: they must attract and retain customers, be competitive in the market place, and satisfy the requirements of diverse global communities and governments (Liu and Boyle, 2009). Maintenance can often be overlooked during the design of a UAS (Drew et al, 2005), and this not helped by there being a lack of tools to address the design of maintenance (Price, Raghunathan, and Curran, 2007). There will need to be trade-offs in the design of the IVHM due to there being limited resources (e.g. power, cost) and constraints imposed on it by other aspects of the UAS design (e.g. weight, size).

1.2. The V-Diagram

The v-diagram (also known as the v-model) is one such way of designing complex systems. The general concept of the v-diagram can be seen in Figure 1, it consists of three parts: decomposition & definition; integration & testing; and verification & validation (Haskins 2007). The general concept has been adapted many times for use in both systems engineering and software engineering to design products, with each side of the v broken down into stages describing what needs to be done on. There is no standard v-diagram.

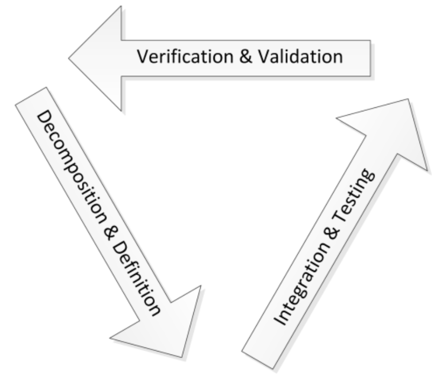

Figure 1. V-Diagram Concept

1.2.1. Decomposition & Definition

In this side of the v-diagram the design task is defined, by assessing customer needs and setting the high level requirements and goals. Once defined, the product can be decomposed into systems, subsystems, components, etc. Through the decomposition a link should be maintained to the higher level requirements.

1.2.2. Integration & Testing

In this side of the v-diagram the individual designs resulting from the decomposition and definition are combined and tested to see if they function as they should.

1.2.3. Verification & Validation

Although not strictly a side in the v-diagram, verification (whether the design meets the requirements established) and validation (whether the design meets the customers' needs) is an integral part to ensure that the product is of value.

2. ADAPTATION OF THE V-DIAGRAM

2.1. Integrted Vehicle Health Management for Unmanned Aerial Systems V-Diagram

The v-diagram adapted for designing IVHM for UAS is presented in Figure 2 and brief explanations of each stage is provided after. Two factors went into this adaptation. First, the fact that UAS are SoS and IVHM is both product and service have been taken into account. With the v-diagram splitting into different tracks at various points to represent this. However, the v-diagram presented here is generalized version which does not provide full detail for all the tracks. It focusses on the UA, which is common to all UAS. Other elements in the UAS will vary from one to the next as will the elements of IVHM external to the UAS. These additional tracks will be discussed at the point when they split from the UA-track.

Second, is to bring the IVHM design into line with the rest for the design for a particular UAS. As the v-diagram is a common tool used within systems engineering the adapted version should make the task easier for organizations to integrate it into their design process. Even if an organization does not use the v-diagram to govern its overall design process it may still be of use, but may need further adaptation to work within their design framework or philosophy.

1. Customer Proposition to IVHM

This stage looks at how the IVHM will add value to the UAS and befit the stakeholders; the stakeholders will be dependent on the business model. It looks to establish the amount and nature of IVHM to be included in the design.

2. UAS IVHM Concept of operations and Fleet IVHM

This stage looks to establish how IVHM will be used support the concept of operations of the UAS. It also will look at IVHM can be used to support the management of fleet of UAS.

3. Internal-External Split

This stage looks to split IVHM functions between being internal to the UAS and external to it.

a. IVHM Internal to the UAS

The products (e.g. sensors, code) and services (e.g. automated response to a leak) that are to be implemented internally to the UAS.

b. IVHM External to the UAS

The products and services that are to be implanted externally to the UAS and is expected to follow a different set of stages beyond this point (and they are out of the scope of the project). This will include (but not limited to) the infrastructure needed for IVHM – e.g. data warehouses.

4. UAS Element Split

This stage looks to split the IVHM functions between the elements of the UAS. The IVHM functions for an element may not necessary contained within it – e.g. prognostics for the UA could be implemented in the CS.

a. IVHM On-Board the UA

As the UA is focus of the project this element being looked into, and the flowing stages relate to it.

b. IVHM on Other UAS Element

Other elements are assumed to follow a similar process to the UA.

5. UA Functional Systems Decomposition

In this stage the functions and boundaries of the systems on-board the UA will be defined.

6. UA Health States & Responses

a. UA Key Function & Health Evaluation

In this stage the effects of the functions in the UAS will be assessed and how they relate to the health of the UA. Then the key functions which affect the health of the UA will be identified.

b. On-Board UA Responses to IVHM

This stage is in parallel with the Key Function & Health Evaluation stage and looks what the responses (service) implemented on-board the UA will be, based off the IVHM data and information produced (both on-board and off-board). Responses could be automatic/autonomous or require human action; this choice is dependent on many factors including autonomy of the UA, time criticality of a fault. It is assumed a different set of stages will follow on from this stage.

c. Off-Board Responses to IVHM

Off-board responses covers any responses to IVHM data and information produced off-board the UA. This will fall under two board categories. First, is responses relating to other elements of the UAS (e.g. a component/system on a specific UA is going to fail in x amount of time). Second, is responses relating to the fleet of UAS (e.g. a component/system is failing to perform as designed across the fleet).

7. Function KPI Identification

In this stage the key performance indicators (KPIs) for the key functions identified in the previous stage will be identified as well as the possible way for them to be to be monitored.

8. Implementation

This stage is the detailed design and testing of the hardware and software needed to fulfill the functionality identified in the previous step.

9. Function KPI Monitoring Verification

This stage verifies that they KPIs identified in stage seven are being monitored by the IVHM built in the implementation stage (stage eight).

10. Health Evaluation & Responses Verification

This stage verifiers that the KPIs being monitored can be used to establish a health state for the key UA functions and that each health state will have an appropriate response to it, either on-board the UA, elsewhere in the UAS, or external to the UAS (fleet IVHM, ordering a part, etc.).

11. UA Functional Systems Health Verification

This stage verifies that all conceived health states for the functional systems are covered.

12. UAS SoS IVHM Validation

This stage validates that the IVHM as designed for the UAS meets its needs. This is to ensure that that the IVHM as designed supports the operation of the UAS.

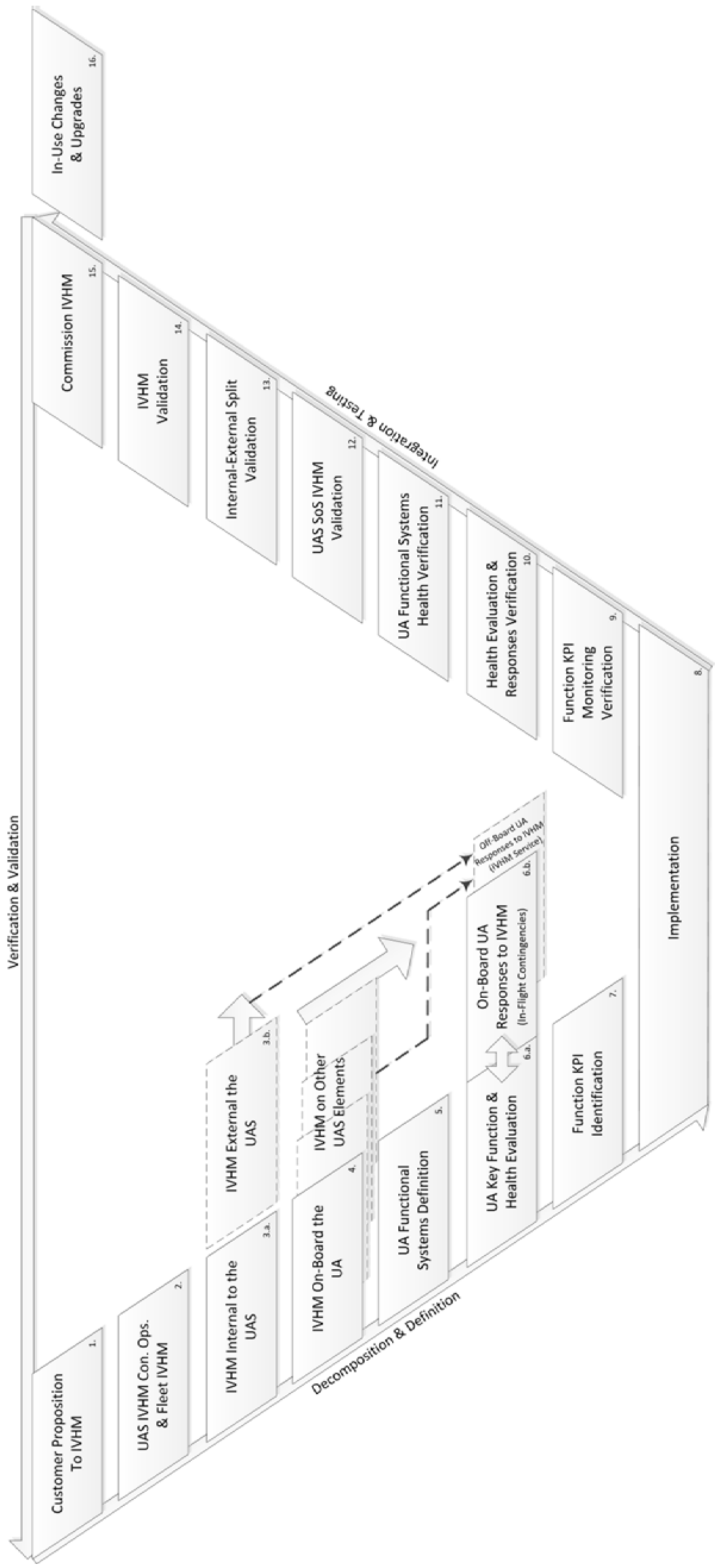

Figure 2. UAS-IVHM V-Diagram

13. Internal-External Split Validation

This stage validates the division of the IVHM functions into those internal and external to the UAS. It should validate the allocation of IVHM functions to the internal and external categories.

14. IVHM Validation

This stage the whole IVHM as designed is validated against both the IVHM needs from UAS concept of operations and the needs of the fleet.

15. Commission IVHM

After all the verification and validation stages have been passed then the IVHM have proved that it meets the needs of the customer and can be commissioned into service.

16. In-Use Changes & Upgrades

This stage deals with changes that need to be made to the IVHM due to a better understanding of how both the UAS and the IVHM for it operate in service. This stage also has connections the in-use changes and upgrades of other systems and elements within the UAS. The first way it connects is that IVHM data and information could instigate a change elsewhere – e.g. a problem component is identified and redesign or replaced with an alternative. The second is that a change in a different system or element will instigate a change in the IVHM – e.g. change in the engine used on the UA.

3. DISCUSSION

The v-diagram is only one possible tool which can be used to design products and services and the adapted version is one possible version that could be used for designing IVHM for a fleet of UAS.

The UAS-IVHM v-diagram presented in this paper is a generic representation of the process, with no particular UAS (or UAS fleet) in mind, and follows only the UA full to avoid unnecessary complication. Due vast diversity that there is in the size, shapes, and configurations of UA, rest of the UAS enabling their flight (e.g. CS), the nature of the relationship between the operate of the UAS (or fleet), the provider of the IVHM service/maintainer, and the original equipment manufacturer, and the design process of used means that it can only be used as a guide.

The v-diagram is an established tool which is used in many companies and already has many adaptations for use with overall product design. The UAS-IVHM v-diagram is been created with the intention that it can be integrated with v-diagrams.

Table 1. Comparison of UAS IVHM V-Diagram Stage to Other V-Diagrams

<table>
<tr><th colspan="2">UAS IVHM V-Diagram</th><th colspan="3">Other V-Diagrams for the Overall Design Process</th></tr>
<tr><th>Stage</th><th></th><th>Sydenham, 2004</th><th>Grady, 2007</th><th>Defense Acquisition University, 2015</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">Customer Proposition to IVHM</td><td rowspan="3">Define Requirements</td><td>Customer Need</td><td rowspan="2">Stakeholder Requirements Definition</td></tr>
<tr><td>System Requirements</td></tr>
<tr><td>2</td><td>UAS IVHM Concept of operations and Fleet IVHM</td><td>End Item Requirements</td><td>Requirements Analysis</td></tr>
<tr><td>3</td><td>Internal-External Split</td><td rowspan="5">Allocate Subsystem Functions</td><td rowspan="3">Subsystem Requirements</td><td rowspan="5">Architecture Design</td></tr>
<tr><td>4</td><td>UAS Element Split</td></tr>
<tr><td>5</td><td>UA Fictional systems Decomposition</td></tr>
<tr><td>6</td><td>UA Health States & Responses</td><td rowspan="2">Component Requirements</td></tr>
<tr><td>7</td><td>Function KPI Identification</td></tr>
<tr><td>8</td><td>Implementation</td><td>(No Direct Comparison)</td><td>Design</td><td>Implementation</td></tr>
<tr><td>9</td><td>Function KPI Monitoring Verification</td><td rowspan="2">Prove Component Parts Work</td><td rowspan="2">Component Test</td><td rowspan="3">Verification</td></tr>
<tr><td>10</td><td>Health Evaluation & Responses Verification</td></tr>
<tr><td>11</td><td>UA Functional Systems Health Verification</td><td rowspan="3">Prove Subsystems Work</td><td rowspan="3">Subsystem Test</td></tr>
<tr><td>12</td><td>UAS SoS IVHM Validation</td><td rowspan="2">Validation</td></tr>
<tr><td>13</td><td>Internal-External Split Validation</td></tr>
<tr><td rowspan="2">14</td><td rowspan="2">IVHM Validation</td><td rowspan="3">Complete System Operation Proven</td><td>End Item Test</td><td rowspan="2"></td></tr>
<tr><td>System Test</td></tr>
<tr><td>15</td><td>Commission IVHM</td><td>Product</td><td>Transition</td></tr>
<tr><td>16</td><td>In-Use Changes & Upgrades</td><td>(No Direct Comparison)</td><td>(No Direct Comparison)</td><td>(No Direct Comparison)</td></tr>
</table>

Table 1 compared the stages of the UAS-IVHM v-diagram with three difference adaptations of the v-diagram depicting the overall design process: two generic v-diagrams from text books (Sydenham, 2004; Grady 2007) and the third the US Department of Defense's 2014 adaptation (Defense Acquisition University 2015). There are differences between these three different adaptations, both in terminology and stages, but the UAS-IVHM adaptation can be mapped roughly to all of them. However, this is just a cursory comparison, consideration will need to be taken when mapping the stages of the UAS-IVHM v-diagram of their own v-diagram in use in their organization. It is also shown that there is no direct comparison for stage sixteen (In-Use Changes & Upgrades) in all three cases. This stage is key for efficient and effective IVHM – lessons will be learnt during the operation and maintenance of the UAS fleet which can be used to improve the IVHM. However, the concept of in use changes and upgrades can be seen in other v-diagram adaptations, such as one used by the US Department of Transpiration (United States Department of Transportation 2013).

3.1. Splits in the V-Diagram

Most notable feature of the UAS-IVHM v-diagram is the splits – at stages three, four, and six. These splits in the design task allow the right people, with the right skills and experience, to be assigned to the different parts of the design problem – i.e. the division of labor. Further division of some stages could also be included in the UAS-IVHM v-diagram. Such as stage eight (Implementation) which could be divided, but into how many different tasks (and the nature of them) would be dependent on the UAS it is being designed for the outcomes of the previous stages.

Stage three (the Internal-External Split) recognizes the differences between product-service of the IVHM and the support structure need to fulfil the service part of the IVHM external to the UAS. This ensure during the design the systems (e.g. fault forwarding, automated part/work orders are produced) and infrastructure (e.g. data warehouses, communications links) needed external to the UAS is considered and designed.

Stage four (UAS Element Split) again reflects the guiding nature of the UAS-IVHM v-diagram and the variety of UASs. Each UAS is difference, and thus will need different aspects of IVHM on difference elements – there is no ideal IVHM for UAS (MacConnell, 2007). The designer should still be considering the UAS a SoS at this point splitting into the different IVHM functions between the difference elements. This allows them to consider placing some IVHM features for one element on another. Such as prognostics for the UA on the CS, which will have less power and weigh constraints opposed to it being implemented on the UA – again this will be subject to the benefits of any trade-offs in the design of a particular UAS. The stages in the different tracts crated for each element are to be similar to for the UA, as described above.

Stage six (UA Health States & Responses) is different from the splits in the previous stages as it does not create new tracts but has two interlinked parts and links to the IVHM external to the UAS. There will need to be a like between the different health states identified and the appropriate responses and their location within the overall IVHM, whether it is on- or off-board the UA, or internal or external to the UAS.

However, these splits in the design process could compromise the 'integrated' nature of the IVHM. Breaking down the design task into smaller sections in this way could cause the design teams tasked with each part to lose sight of the whole picture. It is therefore important that the whole design is properly manage, with someone overseeing the whole process, during all stages of the UAS-IVHM v-diagram. This should help ensure that there are less (ideally no) major issues when conducting the integration and testing, and the validation and verification. There should be keeping of why decisions have been made (e.g. cost, test/simulation results) and how they support the IVHM design overall (e.g. ensuring lower level requirements are linked to a higher level one).

3.2. Tasks of Each Stage

Being a generic representation of the design process the v-diagram does not prescribe what the exact tasks of each stage should be, nor how they should be done. Each design will be different, as will the organization designing the IVHM or UAS.

4. CONCLUSION

The UAS-IVHM v-diagram presented in this paper provides a useful framework for designing IVHM for UAS. The UAS-IVHM v-diagram breaks down the design of the IVHM into different tracks. As the UAS-IVHM v-diagram is adapted from an established tool can be integrated in the overall design of the UAS with greater ease that a totally new framework.

However, the diagram as presented in this paper is a generic version and will need further development if it were to be used to design IVHM for a specific UAS. Also, in order to determine whether the UAS-IVHM v-diagram is useful to the designer of an IVHM it will need to be compared with the current method(s) use within various organizations and also used during the design of IVHM for a UAS.

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NOMENCLATURE

UAS	Unmanned Aerial System
IVHM	Integrated Vehicle Health Management
SoS	System of Systems
CS	Control Station
UA	Unmanned Aircraft
KPI	Key Performance Indicators

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