A Generic Operational Simulation for Early Design Civil Unmanned Aerial Vehicles

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***Abstract*—Contemporary aerospace programmes often suffer from large cost overruns, delivery delays and inferior product quality. This is caused in part by poor predictive quality of the early design phase processes with regards to the operational environment of a product. This paper develops the idea of a generic operational simulation that can help designers to rigorously analyse and test their early product concepts. The simulation focusses on civil Unmanned Air Vehicle products and missions to keep the scope of work tractable. The research agenda is introduced along with ideas, initial results and future work. Designers specify details about their product, its environment and anticipated operational procedures. The simulation returns information that can help to estimate the value of the product using the value-driven design approach. Information will include recurring and non-recurring mission cost items. The research aim is to show that an operational simulation can improve early design concepts, thereby reducing delays and cost overruns. Moreover, a trade-off between mission fidelity and model generality is sought along with a generic ontology of civil Unmanned Air Vehicle missions and guidelines about capturing operational information.**

***Index Terms*—Aerospace testing; Remotely operated vehicles; Relational databases; Maintenance; Computational modeling; Object oriented modeling; Computer simulation; Discrete time systems; Unmanned aerial vehicles;**

I. Introduction

This paper introduces and explores the concept of an operational simulation for improving the early design process of aerospace products. The work aims to sketch out a road map to obtain a PhD. Section II establishes the current problems in early design and defines important concepts. Section III specifies the four main research questions to be answered by the project. Subsequently, initial results obtained so far are presented in section IV. Lastly, section V represents the main part of this paper, introducing the necessary steps towards answering the research questions.

II. Background

This section reviews the most important problems of the early design phase of aerospace products. Subsequently, it introduces the concept of Value-driven Design (VDD) and how it can help to alleviate these problems. Lastly, the concept of an operational simulation is introduced together with a more narrow definition applicable for this research.

A. Early design phase problems

Aerospace products are designed according to customer demand. Customers specify the required product and manufacturers focus their effort to meet expectations. During the early design phase, precise information about the final product and its environment is unknown [1]. Much work is based on expert opinion and subjective engineering judgement rather than rigorous, systematic and disciplined analysis [2]. However, wide-ranging decisions taking into account performance, environmental, legal, disposal and operational aspects must be agreed in a very short period of time. Early design phase decisions are generally acknowledged to determine the success of aerospace products to a great extend [3]. Therefore, improvements to the early design phase procedures can potentially improve aerospace products.

The current design process is guided by fixed, static specification documents that cannot account for the dynamic and complex nature of the product environment. This leads to unsatisfactory understanding of the product domain, which can be a primary cause for product failure [4]. The current processes do not account for the full life-cycle of a product, fail to evaluate operational costs properly and do not focus on the value a product generates [5]. Moreover, specification documents cannot capture all eventualities and details of the operational environment of the product. Partly due to these shortcomings, contemporary aerospace products regularly suffer from huge cost overruns, delivery delays and quality problems. It is becoming essential to found early design decisions upon tangible, tractable and rigorous decisions to create competitive products.

One important aspect currently skipped during early product design decision making is the operational environment the product will work in. As designers focus to meet customer expectations, they neglect to investigate how successful a product design will be in specific operational environments. Simulating the operational environment and the product interactions early on can help improve the current situation.

Another major problem occurring in early product design is the disregard for non-recurring costs in cost estimates [5]. However, non-recurring costs such as payload integration,

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transportation to the operational environment, support personnel costs and the influence of the design usually form a large part of total life-cycle costs. For example, about two thirds of the total cost of contemporary scientific Unmanned Air Vehicle (UAV) missions are non-recurring cost items [6]. An operational simulation can help to estimate these costs and improve the quality of cost estimates significantly.

B. Value-driven design

VDD emerged as a new approach to designing aerospace products that tries to reduce the problems of current design processes [7]. It aims to find the optimal design and not just any design that satisfies customer specifications. This is achieved by introducing a value function that incorporates life-cycle performance, product and operational information. The value function returns the product's value and allows intuitive comparison of different designs. The aim is to optimize a product for the value it delivers, possibly violating customer specifications for a better design and higher value [8]. The value function returns transparent and consistent scores to individual designs. Thereby, it replaces the traditional customer requirements like maximum weight or cost.

An optimized design can only be as good as the value function in use. The quality of the value function depends in part on the quality of the operational knowledge. In order to improve the operational knowledge during the early design process, an operational simulation can be helpful. By simulating operations, performance and environmental processes, novel insights can be gained into the product concept. Moreover, product performance can now be compared not only to different product designs but also to various operational scenarios.

C. Operational simulation

Operational simulations started to become widespread during the early 1990ies following growing animation capabilities and improved computing facilities. In the traditional sense, an operational simulation is used to support short-term planning and decisions within manufacturing scenarios. The models are highly detailed and realistic, feeding on real-time data to allow "live" decision making for operators [9]. The simulations can also be used to predict the near future to discern alternative decision scenarios. Today, operational simulations are predominantly used within transportation management and manufacturing: Railway timetabling is now conducted using operational simulations to verify scenarios and ensure operational stability [10]; operational simulations supported the development of hybrid cars by assessing the costs and benefits of batteries for various types of drivers [11].

In the context of this research, an operational simulation is defined as a non-analytical model recreating anticipated operations of a product during its service life. The model does not recreate existing missions. Instead, the aim is to embed the product into its future operational environment. Therefore, real-time data management and decision making are not aspects of the operational simulation presented here.

Fig. 1. The DECODE-UAV

This new approach to operational simulations is explained in more detail below.

III. Research questions

The aim of this research is to enable designers to create better products by improving the early design process. Products are tested within an operational simulation to observe how useful they are, how much value they produce and if important operational constraints exist. The research will investigate several key issues:

1) Can an operational simulation improve a product early on?
2) Is it possible to create a generic operational model to simulate different aerospace scenarios for various aerospace products? Where is the trade-off between adequate mission fidelity and sufficient model generality? What is adequate fidelity?
3) How can operational information be captured during the early design process?
4) What ontology can be used to unify various aerospace scenarios?

IV. Results so far

Some of these questions have been answered already while others remain open. This section presents the results obtained so far.

As a first step towards answering the research questions, a specific operational simulation has been created to support the design of a Search-and-Rescue (SAR) UAV for the DECODE-project (DEcision Environment for COmplex DEsigns) at the University of Southampton [12]. This UAV has been build based (among others) upon the results of the simulation and can be seen in Figure 1. The software of choice was AnyLogic [13], a Java-based simulation tool, which is able to combine Agent-based modelling with a discrete-event paradigm and visual algorithms.

The operational simulation is implemented into an iterative value-driven design work flow. Computer-aided Design (CAD), Computational Fluid Dynamics (CFD) and structural analysis tools supply product information such as weight, cruise speed and specific fuel consumption. Subsequently, 10 years of operations are simulated and operational parameters such as the total fuel used, the number of maintenance operations or the attrition of airframes are returned. This information

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Fig. 2. The simulation animation

is used to calculate a value for the product design in order to optimize it.

The simulation helped to improve the product by supporting the early design phase in two ways: (i) It was used “actively” by designers as an optimization tool within the operational environment and (ii) it was used “reactively” to inform about extensive product attributes such as maximum permissible cost. It was shown that it is possible to capture, understand and simulate operational information during the early design phase (research question 1). This was done through interviews, data acquisition and careful model building (see Figure 2).

However, the simulation turned out to be highly specific, restricting its use for SAR operations within a pre-defined area only. Moreover, the simulation fidelity was very high and subsequent simplification did not alter characteristic results. The knowledge and experience gained will be used to create a flexible and generic operational simulation incorporating an optimum level of fidelity (research questions 3 and 4).

V. Future work

This section details the steps necessary to answer the research questions. First, the scope of the simulation is specified followed by details on how to unify various mission scenarios. Subsequently, the model building phase is described followed by how the results will be obtained and help to answer the research questions.

A. Model scope

A first step towards a generic operational simulation is to define the scope of the model. A focus on civil UAV operations is imposed in order to keep the task manageable. This choice is based on practical considerations: The civil UAV sector is starting to grow as it has the potential to support and replace many “dull, dirty and dangerous missions” [5]. It is easy to validate simulation results against reality because civil UAV operations are small in scale compared to commercial or military operations. However, it is desirable to keep the simulation open for use in other domains such as commercial airliners. Despite regulatory and liability issues waiting to be resolved, the market forecasts for civil UAVs promise rapid expansion [14]. NASA [5] has identified a number of key operational areas suitable for viable and cost-effective use of UAVs. Figure 3 presents a selection of missions planned to be included into this research. The portfolio covers the majority of possible civil mission applications.

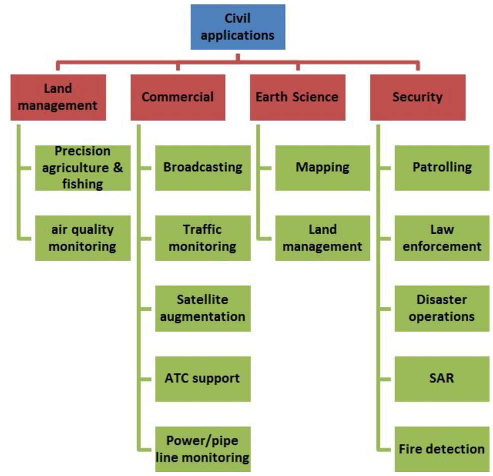

Fig. 3. Classification of civil UAV missions (adapted from [5])

B. Unify mission specifications

The next step will be to investigate mission characteristics and unify mission stages, requirements and definitions into a coherent ontology that can map any one mission into any other. This will enable designers to test-run products in pre-defined scenarios and also enable comparison of different missions. Thereby, a unique way to improve the early product design is found because one of the major barriers to successful market introduction is the capability to fly multiple types of missions [5].

One example of ontological unification are the various mission goals: Each one can be reduced into one of the following categories:

- to find something (casualties, animals, pollution)
- to cover a certain area (agriculture, patrolling)
- to stay at a fixed point (traffic, broadcasting)
- to follow a track (pipelines, borders)

Simplifications like this will be sought for other mission properties such as frequency, length, flight profiles (vertical and horizontal), typical weather, visibility and the number of UAVs involved.

The UAVs will be specified by parameters such as specific fuel consumption, range, endurance and fuel capacity. The on-board equipment characteristics will include the type of equipment (camera, sensor or radios), over-the-horizon communication requirements (what SatCom bandwidth, time of usage, amount of data) and on-board analysis equipment (image analysers, etc.), which reduce bandwidth. As with mission parameters, UAV parameters will be unified into one ontology.

All specifications will be accompanied by reliability estimates in order to increase trustworthiness into simulation results. Useful reliability figures will help users to estimate insurance costs as well. Moreover, all specifications can be entered using confidence intervals in order to reflect information uncertainty.

The operational simulation output will enable better cost estimation by including traceable and comprehensible operational information about UAV consumables, transit operations, maintenance, staff requirements, payload installation and SatCom requirements. However, some aspects will still require traditional cost estimates such as payload development, data analysis, documentation or mission planning.

C. Model building

Subsequently, the generic operational simulation will be constructed based on the developed ontology. Separating data and simulation logic is good modelling practice to support understanding of users and developers. As a first step, an external database will capture the ontology details. This ensures that more mission scenarios can be added to the simulation later on. User input will be possible through the external database, the ontology tool or directly in the runtime environment of the Java-application. Users can select a pre-defined typical mission as defined in the database. Alternatively, they vary specific mission characteristics to suit individual requirements. Subsequently, users enter UAV parameters and equipment details. Based on user requirements, the simulation will then run for one mission only, several missions, or simulate the whole product life-cycle. Output will be in simple text format for flexible data analysis.

Throughout model building, the mission scenarios will be validated and tested by real users such as the DECODE-team for SAR-missions.

D. Results

Once the model is built and validated, the research questions can be answered.

The work conducted so far already indicates that an operational simulation can improve a product early on in the design process [12]. This will be verified further using the advanced simulation model. A baseline case for an existing real UAV will be compared to a UAV optimized by the simulation for a range of mission scenarios.

The second research question will be answered while building and testing the model. It will be shown to what extend it is possible to create a generic operational model spanning a number of missions and a range of UAV-characteristics. The trade-off between model fidelity and generality will be discussed.

The extent of capturing operational information during the early design process will be defined by the input specifications required by the user. It will be discussed how much information is required by the user and how little information is sufficient to still produce useful results.

The ontology unifying various civil UAV missions will be explained.

VI. Conclusion

The lack of rigorous engineering analysis during the early design process leads to major problems with complex aerospace programmes. This research aims to improve the situation by introducing the concept of a generic operational simulation. This enables designers to test their product ideas and concepts in various operational scenarios in order to support cost and value analysis based on the environment the product will work in. Ongoing work has already shown the validity of this approach by optimizing the design of a civil Search-and-Rescue UAV developed at the University of Southampton. This work used a unique operational simulation specifically developed for Search-and-Rescue missions. The planned generic simulation will include the majority of possible civil UAV missions in order to give designers flexibility and the ability to compare designs and scenarios. It will be shown that an operational simulation can help finding the best initial concept based on rigorous analysis instead of engineering judgement and intuition. A trade-off between model fidelity and generality will be sought. A useful ontology for civil UAV missions will be developed along with best practices to capture operational information early in the design process.

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