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REVIEW ARTICLE (INVITED)

System of systems oriented flight vehicle conceptual design: Perspectives and progresses

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Abstract In order to obtain optimized flight vehicle concepts which meet system of systems (SoS) operation requirements, designers have to pay high attention to the impact of SoS at conceptual design stage since operation environment goes increasingly complex. Based on this tendency, perspectives and progresses of SoS oriented flight vehicle conceptual design, which is abbreviate as SoSed design, are reviewed in this paper. Such basic concepts of SoS as definition, characteristics, differences between systems engineering and SoS engineering, as well as SoSed design process are introduced, then SoS engineering process model for research and development of flight vehicles and SoSed design wheel model for conceptual design are proposed. Related literature is classified and analyzed in accordance with four major elements including requirements, design concept, design analysis, and trade studies and optimization: typical SoS architectures, description and quantization of indexes are introduced; Application of inverse design in designing concept is analyzed; Modeling and simulation (M&S)-based methods and their applications in SoSed effectiveness evaluation are highlighted; According to SoSed trade studies and optimization related research, the importance of such points as decision-making and using multidisciplinary design optimization for reference are emphasized. Finally, the value of SoSed design is concluded, and five directions which are worthy of attention in this field are presented.
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1. Introduction

The development of modern high-performance flight vehicles, including military aircraft, civil transport aircraft, helicopters and etc., is an extremely complex, lengthy and costly process. It makes flight vehicle conceptual designers face many challenges, since conceptual design always plays a vital role in development. In fact, conceptual designers' tasks have far beyond the definition of "design" proposed in Raymer's classical conceptual design book,[1] i.e., "creating the geometric

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description of a thing to be built''. One of the arising challenges which conceptual designers have to handle is ensuring their design concepts meet more and more requirements in the context of system of systems (or System-of-systems, SoS),[2,3] such as a net-centric operation scenario[4] to military aircraft and a network described in next generation air transportation system (NextGen)[5] to airliners. This kind of design activity is denoted as ''system of systems oriented flight vehicle conceptual design'' by the authors, and ''SoSed design'' is used as abbreviation.

A distinct trait between SoSed design and traditional conceptual design lies in the transition from emphasizing measure of performance (MoP) to measure of effectiveness (MoE) and capability.[6] MoP is used to evaluate how well a system performs a task, but it is not sufficient when operational context is taken into account. For example, flight 1000 km at 10000 m is a statement of a fighter aircraft's performance, but the same aircraft has different effectiveness at completing a mission if the 1000 km distance is over water or over a hostile area.[7] As defined in Ref.[8], MoE is ''a criterion used to assess changes in system behavior, capability, or operational environment that is tied to measure the attainment of an end state, achievement of an objective, or creation of an effect''. Although the research and applications of MoE related topics have a quite long history, just as the creation of multidisciplinary design optimization (MDO) results from increasing number and coupling of disciplines, the increasing complexity of operation environment makes designers inevitably use SoS prospective to extend conceptual design's scope and use the related new theories and methods to solve problems that did not exist before. In short, the duty of conceptual designers keeps the same but the world has changed.

Nowadays, SoS related research has covered both fundamental theories and applications in many fields, such as policy-making, defense, air transport, medical and health management,[9] etc. and research focus of different fields varies significantly. In aerospace, SoS has covered almost every category of flight vehicle, including commercial aircraft,[10] manned military aircraft,[11] unmanned aero vehicle,[12] missile,[13] spacecraft[14] and launch vehicles,[15] etc. Fig. 1 gives two typical SoS examples in aerospace community, i.e., U.S. coast guard integrated deepwater system[16] and air transportation network.[17] The arising SoS cases make researchers working on each branch of flight vehicles design not neglect potential impact of SoSed design.

Although there has been some overview on SoS,[18–20] it is rare to make an summary on up to date flight vehicles' SoSed design. Since military missions and civil transportations tend to become more and more complex, the authors believe that SoSed design would be one of the promising hot points to aerospace community after MDO, while the main purpose of this paper is to show a general picture of perspectives and progresses of SoSed design, discuss its impact and give systematic reference, as well as inspire further exploration in this area.

2. Basic concepts of SoS

2.1. Brief history of SoS

The initial mention of SoS in public journal can be traced to 1956, when Boulding[21] imagined SoS as a ''gestalt'' in theoretical construction creating a ''spectrum of theories'' greater than the sum of its parts. In 1971, Ackoff[22] considered SoS as a ''unified or integrated set'' of systems concepts. He proposed that ''the systems approach to problems focuses on systems taken as a whole, not on their parts taken separately''. In 1984, Jackson and Keys[23] suggested using the ''SoS methodologies'' as interrelationship between different systems-based problem-solving methodologies in the field of operation research. It was not until 1989, with the Strategic Defense Initiative, that we find the first use of the term ''system-of-systems'' to describe an engineered technology system.[24]

As shown in Fig. 2, Ref.[18] gives a summary of typical development of SoS from 1990s to 2008, which shows that academic research in SoS was much earlier than industry and government applications. SoS was firstly introduced to military research by Admiral W.A. Owens in 1995, and it has been widely investigated since then. Maier[25] was considered to be one of the most influential contributors to the study of the SoS field and proposed for the first time to use the characterization approach to distinguish ''monolithic'' systems from SoS. In 2008, the first two books dedicated to SoS were introduced by Jamshidi[9,26] and it can be expected that more work will be available in future.

Nowadays there are some specialized research organizations on SoS, such as the Office of the Secretary of Defense (OSD),[27] Group of Global Earth Observation,[28,29] and the International Council on Systems Engineering (INCOSE).[30] There are also some typical research groups in universities, such as the System-of-Systems Signature Area Group of Purdue University,[3] Aerospace Systems Design Laboratory of Virginia Tech,[31] National Centers for System of Systems Engineering in Old Dominion University,[32] Centre for Autonomous Systems of Royal Institute of Technology,[33] and Command Control Communication Computer Intelligence Surveillance Reconnaissance (C4ISR) Laboratory of National University of Defense Technology.[34] Some specialized international conferences like the IEEE international conference on system of systems engineering[35] have also been launched, and some SoS related sessions are available in traditional aerospace conferences like aerospace sciences meeting,[36] AIAA/ISSMO multidisciplinary analysis and optimization conference,[37] and AIAA modeling and simulation technologies conference.[38]

2.2. Definitions of SoS

There was no universally accepted definition of SoS, different researchers have given different descriptions, and the follows list some typical ones:

Definition 1. SoS is a collection of task-oriented or dedicated systems that pool their resources and capabilities together to create a new, more complex system which offers more functionality and performance than simply the sum of the constituent systems.[39]

Definition 2. In relation to joint war-fighting, SoS is concerned with interoperability and synergism of command, control, computers, communications, and information (C4I) and intelligence, surveillance, and reconnaissance (ISR) systems.[40]

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