JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 46, No. 5, September–October 2009

Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration

Matthew G. Richards,* Adam M. Ross,† Nirav B. Shah,‡ and Daniel E. Hastings§
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

DOI: 10.2514/1.41433

Survivability engineering is critical for minimizing the impact of disturbances to the operation of space systems. To improve the evaluation of survivability during conceptual design, metrics are proposed for the assessment of survivability as a dynamic, continuous, and path-dependent system property. Two of these metrics, time-weighted average utility loss and threshold availability, are then incorporated into a tradespace study on the survivability of future space tug vehicles to orbital debris. A value-based design approach, dynamic multi-attribute tradespace exploration, is taken to evaluate survivability based on the relationship between stochastic space tug utility trajectories and changing stakeholder expectations across nominal and disturbed environmental states. Results of the tradespace study show that moderate levels of bumper shielding and access to an on-orbit servicing infrastructure benefit space tugs with large exposed cross-sectional areas, whereas active collision avoidance only delivers value to extremely-risk-averse decision-makers. Time-weighted average utility loss and threshold availability are found to be discriminating metrics for navigating survivability tradespaces of thousands of design alternatives.

Nomenclature

A_T	=	threshold availability, %
CS	=	campaign-level survivability
P_H	=	probability of hit (susceptibility)
P_K	=	probability of kill
$P_{K\|E}$	=	probability of kill for multiple-shot engagement
$P_{K\|H}$	=	probability of kill given a hit (vulnerability)
$P_{K\|SS}$	=	probability of kill from a single shot
P_S	=	probability of survival
$P_{S\|E}$	=	probability of survival for multiple-shot engagement
TAT	=	time above critical value threshold, years
T_{dl}	=	time of design life, years
T_r	=	permitted recovery time, years
$U(t)$	=	utility delivery over time, multi-attribute utility trajectory
$U(\underline{x})$	=	multi-attribute utility function over attributes $\underline{x}$ at a point in time
U_e	=	emergency utility threshold (zero by definition), utilities are dimensionless
$\bar{U}_L$	=	time-weighted average utility loss from design utility, U_o
U_n	=	utility delivery during normal conditions
$\bar{U}_t$	=	time-weighted average utility
U_x	=	required utility threshold
$U^i(x^i)$	=	single-attribute utility function over attribute x^i
$V(t)$	=	value delivery over time
V_e	=	emergency value threshold
V_x	=	required value threshold
ΔV	=	change in velocity, m/s

Presented as Paper 7882 at the AIAA Space 2008, San Diego, CA, 9–11 September 2008; received 6 October 2008; revision received 31 March 2009; accepted for publication 7 April 2009.

*Ph.D. Graduate, Engineering Systems Division, Building NE38-550, 77 Massachusetts Avenue; mgr@alum.mit.edu. Member AIAA.

†Research Scientist, Systems Engineering Advancement Research Initiative. Member AIAA.

‡Research Assistant, Department of Aeronautics and Astronautics. Member AIAA.

§Professor of Aeronautics and Astronautics and Engineering Systems, Dean for Undergraduate Education. Fellow AIAA.

I. Introduction

SURVIVABILITY is the ability of a system to minimize the impact of a finite-duration environmental disturbance on value delivery [1]. Given the growth of military and commercial dependency on space systems [2,3], identified vulnerabilities in current systems [4], the proliferation of threats [5,6], and the weakening of the sanctuary view in military space policy [7,8], survivability is an increasingly important consideration during the design of space systems [9]. Counterintuitively, the risk-averse nature of the space industry, which manifested in the common satellite design elements of redundancy, proven technology, and long design lives [10], exacerbates space architecture fragility [11] by increasing the magnitude of potential downside losses and by reducing the speed at which space capabilities might be reconstituted. Although survivability is an emergent system property that arises from interactions among components and between space systems and their environments, conventional approaches to survivability engineering are often reductionist in nature (i.e., focused only on selected properties of subsystems or modules in isolation). Furthermore, existing survivability engineering methodologies are normally based on specific operating scenarios and presupposed disturbances rather than a general theory with indeterminate threats. As a result, current methods neither accommodate dynamic threat environments nor facilitate stakeholder communication for trading among system lifecycle cost, performance, and survivability [12].

To address these limitations, a set of metrics is introduced for the evaluation of satellite survivability in tradespace studies during conceptual design. The metrics are based on a characterization of survivability as the ability of a system to meet required levels of value delivery during nominal and perturbed environmental conditions. To demonstrate the survivability metrics, the survivability of a low-Earth-orbit (LEO) satellite to orbital debris is evaluated for systems incorporating various combinations of susceptibility reduction, vulnerability reduction, and resilience enhancement features. In particular, integrated cost, performance, and survivability trades are performed for an orbital transfer space tug vehicle operating in LEO for 10 years. Building on previous work [13], the impact of bumper shielding [14], collision avoidance [15], and on-orbit servicing [10] strategies on space tug encounters with orbital debris is examined.