DISCRETE-EVENT SIMULATION MODELING FOR AIR FORCE REUSABLE MILITARY LAUNCH VEHICLE EVALUATION[1,2]

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ABSTRACT

The Air Force uses a family of expendable launch vehicles to meet its spacelift needs. Unfortunately, this method is not responsive: months of preparation are typically required and launch costs are high. Consequently, the Air Force seeks a reusable military launch vehicle (RMLV) that can be launched inexpensively and quickly regenerated between flights. Air Force Research Laboratory personnel desire a tool to help evaluate candidate designs and perform tradeoff studies necessary to acquire an RMLV that will achieve Air Force goals. Our research objective is to develop and validate discrete-event simulation models that can assess candidate RMLV maintenance and prelaunch concepts. This paper illustrates our progress and plans.

INTRODUCTION

The Department of Defense relies heavily on capabilities provided by space assets, so much so that a disruption of those capabilities would have grave implications. So far military use of space has not been significantly challenged, but this could change in the future. One Russian senior military official advocated the development of Russian antisatellite weapons in a recent assessment of U. S. military capability [1:1]. It is likely that U. S. space assets will become increasingly vulnerable as other nations improve their space access capabilities.

The Air Force now uses a family of expendable launch vehicles (ELV) to meet its spacelift needs. Unfortunately, this method of space access is far from responsive. An ELV commonly requires months of preparation before launch. Furthermore, each launch is extremely expensive--for example, a Titan IVB ELV launch costs between $350 and $450 million [2:496]. In an effort to reduce launch costs, the

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Air Force is pursuing the development of reusable military launch vehicles (RMLV), hoping that a fleet of reusable launch vehicles will significantly reduce launch cost because the vehicle would be refurbished after its mission and used again. Candidate vehicle designs have a reusable first stage and expendable second stage. This particular vehicle concept has been termed the Hybrid Launch Vehicle (HLV) [3:1]. The HLV's recurring flight cost goal is to reduce launch costs to 1/6 of current ELV levels [3:4].

The space shuttle is the only existing operational orbital reusable launch vehicle. Original design concepts in the mid-1970's called for approximately 40 launches per year from Cape Canaveral and 20 per year from Vandenberg Air Force Base. However, shuttle sorties have never achieved this performance, demonstrating only seven to eight flights per year at its peak in the mid-1990's. Shuttle regeneration requires an average of 126 calendar days [4:29]. Therefore, while the shuttle is a significant technological achievement and has contributed enormously to space access, it cannot be categorized as responsive spacelift.

Although NASA and the Air Force have collaborated on reusable launch vehicle (RLV) designs in the past, the two organizations have different missions and thus different space launch needs. Because of this, each is pursuing its own future space launch system. The Air Force is pursuing an unmanned, "all weather" system with a regeneration time of 24 to 48 hours that can quickly respond to war-time contingencies. In contrast, NASA seeks to replace the shuttle with a manned vehicle with less stringent weather-related launch requirements. This new space vehicle will be used for manned lunar missions and eventually manned missions to Mars. To this end, NASA is focusing its resources on development of the Crew Exploration Vehicle (CEV) [5], with manned missions beginning in 2012.

The Air Force is considering several uses for its future HLV space launch capability, including satellite replacement, surveillance, and rapid global strike [6]. Current plans call for a HLV subscale demonstrator that will undergo ground and flight tests by 2010. The actual operational vehicle, or HLV Operational Spacelift (HLV OS), is scheduled to begin operations by 2018.

Previous Launch Vehicle Simulation Research

Researchers have long used simulation models to analyze launch vehicle ground operations. However, most of these models were built in conjunction with NASA and focus exclusively on shuttle operations or are heavily influenced by shuttle data. While these models are extremely useful for analyzing shuttle operations, our research seeks to build a model that goes beyond the shuttle mindset and is more useful for analyzing potential RMLV operations.

Shuttle Ops, a shuttle simulation model that accurately mirrors true shuttle regeneration capability, was developed in Arena software through a joint effort between NASA and the University of Central Florida [7: 754]. It was also used to model other scenarios such as mothballing a shuttle orbiter or closing shuttle facilities [7: 761]. Shuttle Ops was recently modified to create the Manifest Assessment Simulation Tool (MAST). MAST estimates probabilities of completing shuttle launches according to shuttle manifests [8:3]. A shuttle manifest is a schedule that outlines starting and completion times for major shuttle activities, such as orbiter maintenance, vehicle assembly, and launch pad operations. MAST has been used to demonstrate the low probability of achieving the planned number of shuttle launches before shuttle retirement in 2010 [8:25,26].

The Generic Simulation Environment for Modeling Future Launch Operations (GEMFLO) was developed in conjunction with NASA's Space Launch Initiative [9]. This initiative studied different RLV design alternatives as a replacement for the space shuttle. GEMFLO provides outputs such as estimates of vehicle flight rate per year and vehicle regeneration time. However, our research seeks to analyze launch operations in a military environment, while GEMFLO was designed to assess civil launch operations. Since Air Force requirements will dictate RMLV turnaround within a matter of hours, even processes that only take a matter of minutes, will be important to capture.

Finally, Rooney and Hartong developed an Arena-based simulation model that estimates maintenance task completion times for RMLVs. Like GEMFLO, their model also includes a Visual Basic GUI. The user inputs vehicle design parameters, such as amount of thermal protection system tile area and other resource and job sequencing information. The model feeds these inputs into Arena and estimates total turnaround time and turnaround time for specific vehicle subsystems [10:6,7]. This model does break processes down into an adequate level of detail, but processing time distributions are heavily influenced by shuttle historical data, which may or may not represent future RMLV operations. Their model does not include any prelaunch operations activities [10:7].

METHODOLOGY

Our research goal is to develop and validate discrete-event simulation models that can then assess candidate RMLV maintenance and prelaunch concepts. Air Force Research Laboratory's Air Vehicles Directorate personnel desire such a tool to help them evaluate designs and perform tradeoff studies necessary to acquire an RMLV that will achieve Air Force goals. Key RMLV assumptions provided by the sponsor are listed in Table 1.

Table 1. RMLV Assumptions and Goals.

Assumptions	Design goals
• Vertical launch, horizontal land configuration • Unmanned missions • Reusable first stage, expendable upper stage • 15 people maximum "touching" the RMLV post-mission • Likely propellant combinations: LOX/Methane or LOX/RP-1	• Regeneration within 24 hours • All-weather launch capability • "Aircraft-like" operations • No hypergolic fuels

We first developed conceptual flows of maintenance and prelaunch operations sequences based on the shuttle, Delta IV, Atlas V, Minuteman III, and Zenit 3SL launch processes and the shuttle and B-2 bomber regeneration cycles. The shuttle was chosen because it is the only operational RLV in the world. Atlas V and Delta IV were chosen because they are recent additions to the U.S. launch vehicle fleet and represent the most advanced technology and concept of prelaunch operations. The Zenit 3SL was chosen because it was originally designed for quick prelaunch operations. Finally, the B-2 represents the only heavy load-capable aircraft with the complexity and intermittent usage typical of a space vehicle. We then combined this information with our best estimates of what an RMLV prelaunch operations sequence will or will not include. We used an iterative approach by starting with a simple conceptual network of basic RMLV maintenance and prelaunch operations events and then adding more detail to those networks as more knowledge was gained.

We validated our conceptual flows by using a Delphi approach. Our Delphi panel was composed of 20 representatives from NASA, Air Force Research Laboratory, the Air Force Aeronautical Systems

Center, and Air Force Space Command. All participants possess a military grade of major or above or equivalent civilian grade. The panel of experts was chosen by us and approved by our sponsor. Our Delphi study proceeded as follows: first, a visual flow diagram of our maintenance and prelaunch networks was sent via email to the panel. Our models were coded in Arena simulation software, but the simulation's graphical models were not sent to the panel because their limited familiarity with the software would make the models difficult to interpret. Instead, a simplified representation of our models was created in Microsoft Visio software. This gave panel members an easy-to-read format while not sacrificing details that are important to the model's operation. Example diagrams are shown in Figures 1 and 2. Text was provided on each module as necessary to provide explanation or to refer the reader to a subsequent submodel for greater detail. After the panel members reviewed the models, they submitted comments and suggestions for improvement to us. We then compiled the responses and made changes to the models where there was consensus among the group members. For areas without consensus, we submitted the separate responses anonymously to the entire group along with the updated model. Responses from differing viewpoints facilitated a broader understanding of RMLV ground operations and allowed us to consider the full spectrum of launch vehicle processing possibilities. Three Delphi "rounds" were used to achieve overall consensus.

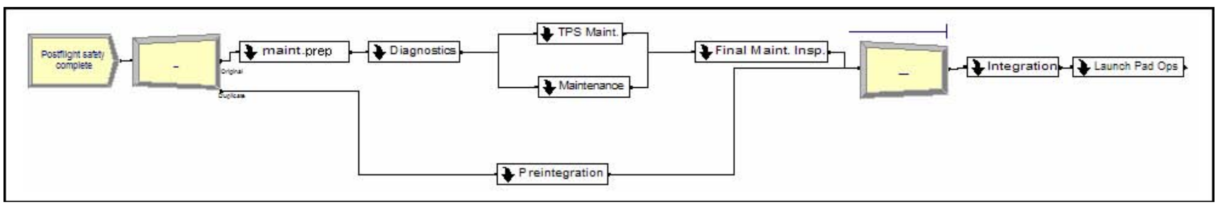

Figure 1. Top-level diagram view

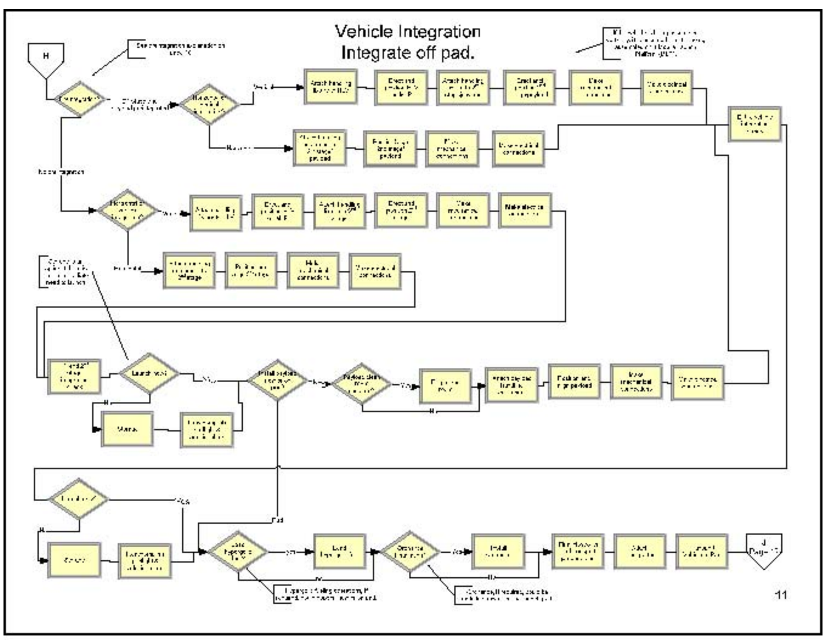

Figure 2. Sample network, vehicle integration functional flow

The final model required approximately 200 Arena modules and 1800 lines of code. The associated network diagram spans thirteen 8.5"x 11" pages-- the diagram in Figure 2 is typical. The model was designed to accommodate numerous design alternatives, such as horizontal versus vertical integration, hypergolic versus nonhypergolic fuels, and so on. To avoid the burden of requiring the user to update the Arena model's source code before simulating a particular alternative, we are currently developing the graphical user interfaces needed to simplify model/user interaction. Our final actions will be to perform some additional model verification by investigating the model's response to changes in selected input parameters, and to use the models to perform an exploratory analysis of the tradeoffs associated with allocating overall schedule time to individual regeneration tasks. Further research will optimize regeneration task times with respect to expected cost and technical risk.

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