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ADVANCED REQUIREMENTS INTEGRATION & EXPLORATION SYSTEM (ARIES) FOR ACQUISITION PROGRAMS

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ABSTRACT

Acquisition programs typically develop a set of system requirements early in their lifecycle, which then become the standard against which future designs are evaluated. It is critical that these requirements be set at appropriate levels. Requirement sets that are not simultaneously achievable are a relatively common problem in military acquisition programs and often are not recognized until significant investment has already been made – sometimes even leading to program cancellation. The Advanced Requirements Integration & Exploration System (ARIES) is designed to aid program stakeholders in understanding the requirements trade space for a system and facilitate the identification of an achievable set of requirements. This paper presents the ARIES methodology, describes the analytic capability, and discusses its application.

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1. INTRODUCTION

Developing an achievable set of requirements for complex military systems poses a significant challenge due to second- and third-order effects of subsystem interactions. For example, requesting a more stringent survivability requirement may entail additional system armor, whose extra weight thus reduces achievability of mobility requirements. This is an intuitive and well-known tradeoff, but this give-and-take becomes much more complex when large numbers of unique requirements (30 or more is not uncommon) are all interacting simultaneously. With many competing objectives, requirement sets often become unachievable, particularly when programmatic factors (such as acquisition cost and schedule) are considered. Developed by Sandia National Laboratories, in collaboration with the Combat Capabilities Development Command (CCDC) Ground Vehicle Systems Center (GVSC), Operational and Trade Space Analytics, the Advanced Requirements Integration &

Exploration System (ARIES) is a requirements trade space exploration methodology and decision support tool. The overarching goal of ARIES is to interactively inform the requirements development process by considering all performance and programmatic objectives (requirements) concurrently. This approach seeks to save time and money during defense acquisition efforts by enabling a deep understanding of relationships and potential conflicts between system requirements during their inception – identifying defensible, mutually compatible goals that satisfy multiple stakeholders.

In situations with many conflicting stakeholder requirements, negotiating compromise often requires understanding interdependencies and tradeoffs over an extremely large combinatorial trade space (10^{20} or more technology option combinations). Multi-objective optimization is a natural technique for exploring tradeoffs; however, existing approaches build "coalitions" of objectives, combining dozens of requirements into a relatively small number of measures to reduce trade space dimensionality (either explicitly via aggregation or implicitly). As a result, these approaches favor solutions that compromise across many objectives and can obfuscate tradeoffs amongst individual objectives. By contrast, ARIES uses a novel ultra-high-dimensional optimization to address this challenge, exploring the realm of the possible and preserving detailed individual requirement tradeoff information.

ARIES identifies Pareto optimal requirement sets (solutions) while considering technological, physical, and programmatic constraints for a system. Once ARIES has identified possible requirement values based on provided constraints, stakeholders are able to interactively explore relationships between requirements simultaneously to understand tradeoffs. The optimal requirements trade space can be visually and analytically explored using a broad set of interactive visualizations.

Sandia National Laboratories and CCDC GVSC have been collaborating over the past year to mature this capability and develop a framework to inform future requirements development efforts. Initial demonstration applications have focused on the Next Generation Combat Vehicles (NGCV) program.

2. PROCESS

The ARIES methodology is comprised of three primary activities: 1) problem definition/data gathering, 2) alternatives generation, and 3) results analysis/stakeholder negotiation. Figure 1 depicts the overall ARIES process and the remainder of this section covers details on the steps.

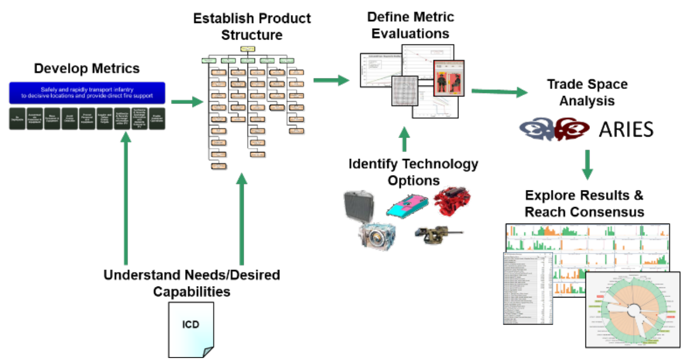

Figure 1: ARIES Methodology

2.1. Problem Definition

The first step to developing an ARIES model is to understand the needs and desired capabilities for the system of interest. Decision makers must have a basic notion of what the new system needs to achieve and why they are pursuing the acquisition program before ARIES can be applied. After initial application, the model can evolve over time as more information becomes known about the system, with data and assessments easily refined. ARIES is intended to be an iterative analytic process.

Metrics for evaluating key aspects of the system need to be defined with assumptions appropriate for its envisioned operating environment. These metrics can be assessed in several different ways, such as physics-based equations, surrogate equations developed from complex analytical models, lookup tables based on external assessments, or subjective valuations. In addition to the more typical performance measures, ARIES has the flexibility to include programmatic considerations (such as acquisition cost, operating and sustainment costs, and schedule risk) to ensure that requirement decisions are made with those factors in mind. The level of fidelity necessary for all the assessments depends on the questions to be addressed by the analysis.

An important underlying aspect of ARIES is that it ties the requirements trade space back to physical technology options to provide a more realistic assessment of requirement feasibility. Simply stated, combinations of subsystem technology options form complete system concepts whose evaluated metric values then serve as surrogates for possible requirements realizations. These technology options cover a gamut of possibilities including existing hardware ready to be integrated in the system today or developmental technologies that have remaining maturation time and an associated development risk. This risk can be captured as a separate measure in the model to demonstrate the tradeoff between requirement values and the risk associated with the technologies required to achieve those levels. By assessing requirement values based on the underlying subsystem technologies and accounting for physical compatibilities between these parts (as well as other design constraints, such as weight or power limits), ARIES captures the true relationships between which requirements levels can and cannot be mutually achieved.

Requirement assessments are driven directly by combinations of technology selections and their associated attributes. Gathering data for the technology options and metric assessments is generally the most time-consuming model development task – often requiring coordination amongst multiple agencies to engage the appropriate subject matter experts and obtain the necessary data. Eliciting ***desired*** threshold requirement levels from program stakeholders is also an important part of data gathering. These desired levels represent where stakeholders would want to set each requirement, independent of interactions with other requirements. These desired levels form an important reference point for the requirements negotiation process.

Program stakeholders and experts familiar with the system being analyzed should be involved in the metric definition, system decomposition, and identification of technology options. Their involvement ensures the model is representative of the appropriate trade space and considers important factors for the program of interest, as well as helping to develop trust in the model.

2.2. Alternatives Generation

ARIES utilizes a custom, newly-developed two-stage Genetic Algorithm (GA) to generate optimal candidate requirement sets that satisfy technological, design, and programmatic constraints defined for the system. The ARIES GA evolved from an existing multi-objective optimization [1] utilized by other capabilities developed at Sandia National Laboratories. The initial stage performs a single-objective optimization for each requirement in isolation to identify its best possible level of achievement. These solutions are then preserved both to form part of an initial population for the more challenging multi-dimensional optimization (stage two) and to appear in the final solution set that will inform the interactive trade space exploration. In this manner, each requirement is guaranteed to be treated equally; at least one solution with the best possible level of achievement in each requirement will be part of the final trade space.

The second stage is an ultra-high-dimensional GA that treats each requirement as an independent objective function and seeks to fill out the range of possible values for each requirement with a representative distribution of candidate solutions to capture the tradeoffs amongst all requirements. This second-stage GA is a highly tailored algorithm with many specialized functions including an extreme preservation mechanism (best values in each dimension must be propagated to subsequent generations) as well as a custom Space-Filling Nicher (SFN) and a Random Nicher to ensure the final population is most representative of the true trade space of requirements possibilities. The SFN utilizes Euclidean distance in normalized solution space to identify and select the most representative solutions to ensure the best coverage across the requirements trade space. The Random Nicher helps improve the speed of solution selection while attempting to represent the density of the solution distribution, naturally selecting more points from denser regions of the solution space. Additional details on the genesis of ARIES and development of the custom GA can be found in [2].

2.3. Results Analysis

Once a set of candidate requirement sets has been generated, the first step of the analysis process is to verify the solution quality in terms of covering the expanse of achievable values and adequately representing the distribution of potential values. In addition to analytic methods, meetings with subject matter experts familiar with the program and type of system being analyzed is a critical part of the process to ensure the set of solutions emerging from the optimization is appropriate. It is important to complete this review before holding a workshop with program stakeholders to ensure a reasonable and vetted set of results is being used to inform decisions and that questions about data sources and evaluation measures are resolved with program experts. Examination of the model results is an iterative process that should be repeated until the stakeholders are all satisfied with the quality of the results and the evaluation methods. Having knowledgeable program experts “bought in” to the underlying model and requirements trade space provides an important level of trust for the decision makers.

Once a good representation of the requirements trade space has been generated, analyses can begin. ARIES is somewhat unique in that it is explicitly designed be used in a real-time, interactive workshop format where program stakeholders, requirement developers, and functional experts come together to understand the tradeoffs in their requirements. Prior to this workshop, participants must first be “level set” and given an understanding of what each requirement means and how it is measured. Once this is accomplished, a facilitator then guides an exploration/negotiation process where participants ask questions and set requirement threshold levels to explore what desired possibilities can and cannot be met together. This interactive process continues until the participant interest areas have been adequately explored and consensus on a satisfactory set of requirement thresholds is reached.

3. OUTPUT VISUALIZATIONS

ARIES provides a variety of results views to explore the optimal requirement sets that are generated by the two-stage optimization discussed in Section 2.2. Many of the ARIES visualizations are intended to be used in a group setting, with program stakeholders and requirement developers taking turns interacting with the charts – facilitating collaborative communication amongst stakeholders and generating insights that lead to informed requirement decisions that consider practical constraints on the program.

3.1. Radar Chart

An example of the primary collaborative ARIES visualization is displayed in Figure 2, which shows a dynamic radar chart that enables stakeholders to slide one requirement at a time to a certain value and then immediately see the corresponding impacts on achievable values for each of the other requirements. Figure 3 shows an example of the same chart after filter sliders have been moved.

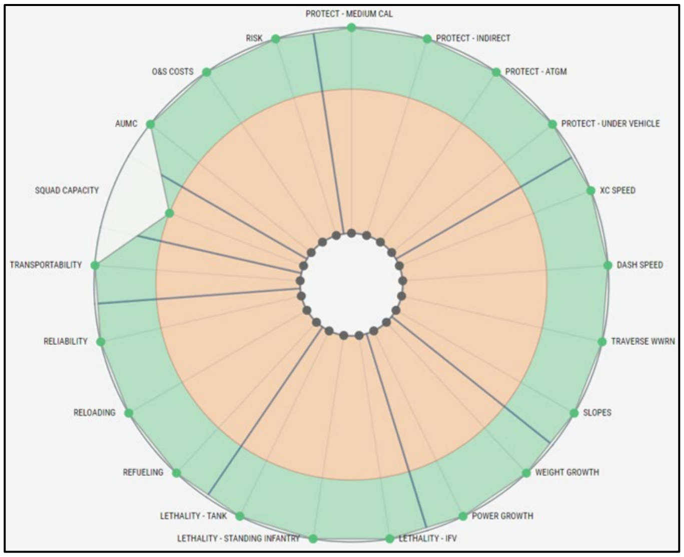

Figure 2: Dynamic Radar Chart to Interactively Explore Requirement Relationships (Before Filtering)

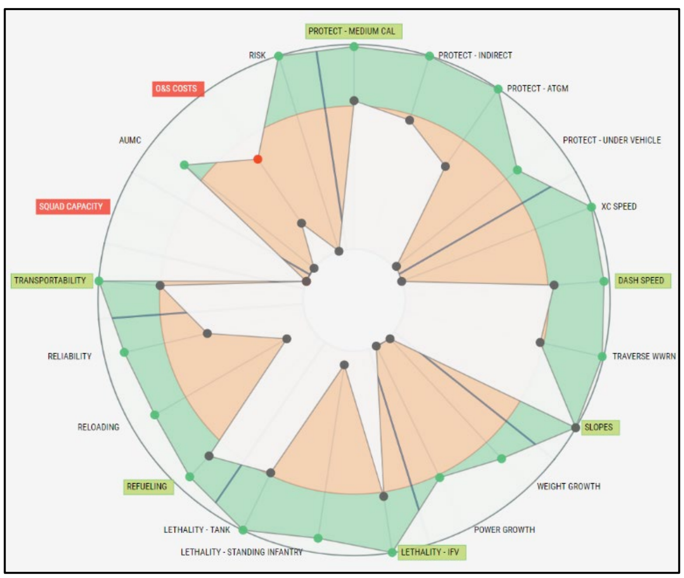

Figure 3: Dynamic Radar Chart to Interactively Explore Requirement Relationships (After Filtering)

The radar chart has one spoke (and corresponding filter slider) for each requirement, normalized from the worst (inner circle) observed requirement value in the set of optimal solutions to the best (outer circle) observed requirement value. Gray dots on the radar chart represent current slider positions, which correspond to the current best simultaneously achievable value for each requirement. Red and green dots represent the best remaining values possible in the set of optimal solutions for each requirement, with red representing that the value is below the user-specified desired value (where stakeholders would want to set a requirement threshold in an ideal world) and green representing that the value is at or above the desired value. Above and below the desired value is represented on the chart by the green and orange shaded regions, respectively. Additional information can be toggled on and off by the user (such as previous positions of sliders/best values before the most recent slider action; the current best, simultaneously achievable requirement values; and units for each measure).

3.2. Histograms

Figure 4 presents another way of viewing the requirements trade space. The grid contains a histogram of observed optimal solution values for each requirement examined.

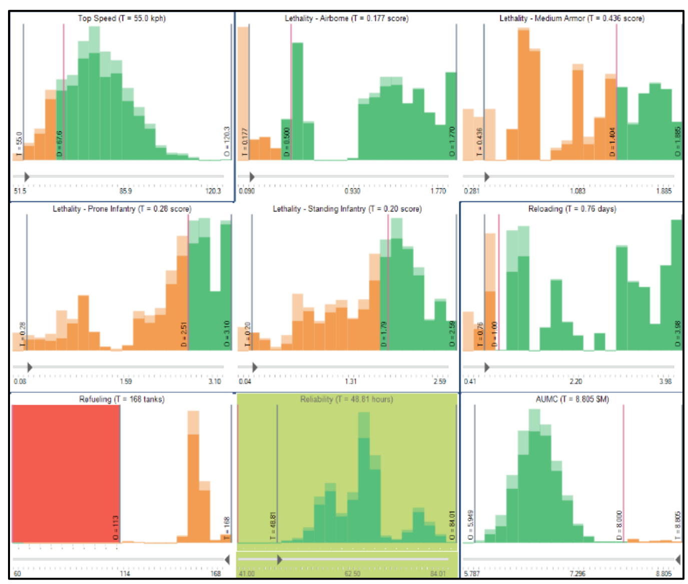

Figure 4: Histograms Showing Distribution of Potential Requirement Values

Each histogram has a slider at the bottom that enables filtering the candidate requirement sets to show only those that meet a specified value. As candidate solutions are filtered out, the bar height drains, giving a visual indication of what has changed from the initial distributions. Histograms also display a vertical red line, labeled D, to represent the reference desired threshold value that was elicited from stakeholders ahead of time. Vertical black lines are shown to represent the bounds of remaining viable solutions as filters have been applied. The vertical line labeled T (worst remaining value for that requirement in the optimal solution set) on each histogram represents the value at which the threshold requirements could be set, and all be simultaneously achievable given the constraints and assumptions that have been applied. The vertical line labeled O (best remaining value for that requirement) represents a possible value for the objective level of that requirement, but these are not all simultaneously achievable.

A red region on the histogram indicates that given the constraints already applied, no remaining optimal solutions meet the desired threshold level for that requirement. This red region draws the user's attention to the associated requirement so that the deficit can be discussed and addressed if necessary. Conversely, a histogram that has turned completely green indicates that all remaining solutions meet the desired level for that requirement and therefore does not require attention at the moment.

Colors in the histograms have similar meanings as in the radar chart and changes in each view are synchronized with the other view to facilitate switching between them as necessary. The histograms contain more detailed information regarding the distribution of potential requirement values within the trade space, which can be beneficial for answering questions, but can also be overwhelming when going through the results with a large group of people.

4. APPLICATIONS

Existing applications in the ground vehicle area have focused on the NGCV program. An initial demonstration model was created for the Robotic Combat Vehicle – Medium in late 2019 and shown to the NGCV Cross Functional Team (CFT) and Project Manager (PM) Maneuver Combat Systems (MCS). As a follow-on to that initial demonstration, the ARIES team has been collaborating with the NGCV CFT and PM MCS to begin developing an ARIES model to explore the requirements trade space for the Optionally Manned Fighting Vehicle program.

5. SUMMARY

ARIES provides acquisition programs with an analytic capability to explore the requirements trade space and interactively understand relationships between requirements in real-time. The goal of ARIES is to support definition of an achievable set of requirements early in a program to avoid incompatible, unachievable thresholds that can jeopardize program success.

ARIES is a relatively new analytic capability that has matured from a research prototype to a functional analytic capability over the last year. Since it is a new capability, there are new learnings each time it is applied in a real world scenario. Interactive sessions with stakeholders have helped identify opportunities to refine the result visualizations and supporting functionality to provide better insights.

One particularly interesting way to grow the capability that has been identified is through the incorporation of automated analytics to help facilitators answer stakeholder questions. Common questions that have arisen in initial workshops centered around why the requirement relationships are the way they are, what is constraining the achievable requirement levels, and why did certain values change with the last filter action that was taken. These questions can be answered currently by examining the details of the underlying model, but methods for automatically extracting information or providing cues to the facilitator are being explored to speed up the process and make the live, interactive workshops smoother and even more informative.

6. REFERENCES

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[2] A.I. Dessanti, J.H. Gauthier, S.M. Henry, M.J. Hoffman, "Ultra-High Dimensional Optimization and Interactive Requirements Negotiation for New Acquisition Programs", SAND2019-2286C, Sandia National Laboratories, Albuquerque, NM, 2019.

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