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Measuring the Uncertainty Impacts During the Systems Engineering Lifecycle

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Abstract

- Uncertainty is a large part of the Systems Engineering (SE) development process. Particularly absent is the quantification of uncertainty of the threat, operating environment, and friendly force factors at each step of this lifecycle.
- This paper will explore a methodology to quantify the amount of uncertainty and the interdependencies of the uncertainty factors during the development.
- Included for consideration are internal and external factors and their contribution to the overall system uncertainty.

Outline

- Introduction
- Literature Review
- Uncertainty Calculation Methodology
- Illustrative Example
- Conclusion / Future Work

Introduction

- We are motivated to quantify the uncertainty inherent with the numerous inputs that affect a system development cycle
- Review of the current literature indicates a general lack of quantification of the total uncertainty and how component uncertainty factors are related to each other
- This uncertainty can be defined as:
  - Threat capability
  - Operating environment
  - Developed system's technical performance, tactical implementation, and program acquisition
- If uncertainty was not considered, requirements analysts, concept developers, and testers are in danger of starting development of a system that is not prepared to handle the representative threats or operate in a representative environment

Literature Review

- Hastings and McManus develop a framework to understand uncertainty during project development, identifying a lack of knowledge about the system, and lack of system definition
- Flage and Aven research the level of uncertainty intervals as being dependent on where one is in the systems development lifecycle
- Averyt et al. seek to identify the available system tradespace from earlier lifecycle stages
- Boehm introduces a “cone of uncertainty” concept that reflects a gradually decreasing level of uncertainty as the system concept matures

A formalized means to identify and evaluate the causality between system uncertainty factors, but the literature focuses only on a single primary source of uncertainty, and does not indicate such a means between different uncertainty factors

Uncertainty Calculation Methodology

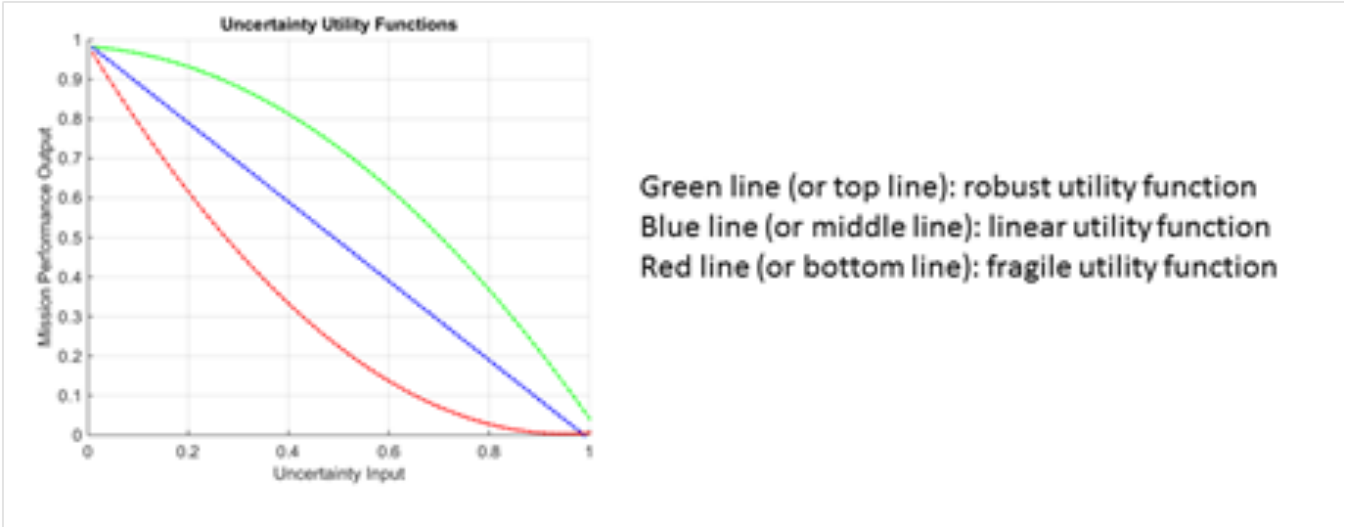
- Step 1: Identification of the Uncertainty Areas
- Step 2: Development of the Uncertainty Utility Function
- Step 3: Describe the Uncertainty Interdependency
- Step 4: Collection of the Uncertainty Inputs (Scenarios)
- Step 5: Perform Overall Mission Uncertainty Analysis

Step 1: Identification of the Uncertainty Areas

- Identify the different uncertainty areas that will influence the mission execution of the system under consideration:
- Internal – system technical performance, or operator tactics, techniques, and procedures (TTP)
- External – threat
- External – operational environment

Step 2: Development of the Uncertainty Utility Function

- Quantify the relationship between the input (uncertainty, whether that comes from an internal or external source), and the resultant output on system / subsystem performance
- Draws from utility theory, in which the input and output scale are normalized



Green line (or top line): robust utility function
Blue line (or middle line): linear utility function
Red line (or bottom line): fragile utility function

Step 3: Describe the Uncertainty Interdependency

- Describe the interdependencies of the uncertainty utility functions, and how one utility function may influence another
- Identify how some uncertainties contribute to other uncertainties, some which have one way or two way directionality

Step 4: Collection of the Uncertainty Inputs (Scenarios)

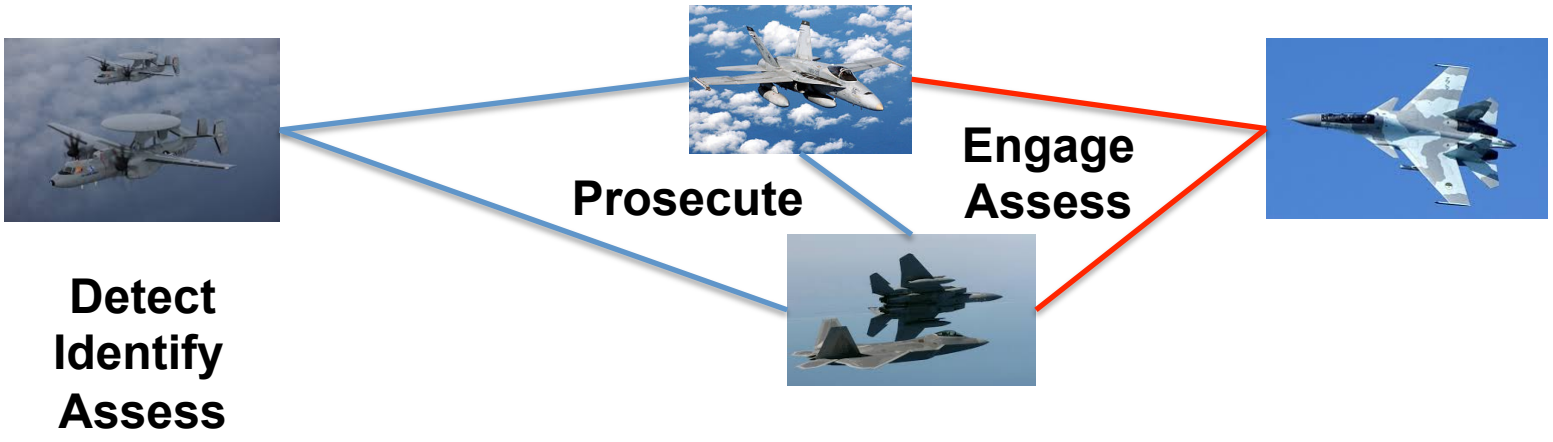
- Collect the different uncertainties that would affect the system, categorized into scenarios or use cases
- Represent near-term, mid-term, and far-term threat or environment projections
- Quantify the difference in mission performance based on the changes in uncertainties

Step 5: Perform Overall Mission Uncertainty Analysis

- Conduct the mission analysis based on the scenario inputs:
- Evaluate the scenarios will initial uncertainty levels
- Use the utility functions to produce an output to mission performance, and are linked to other dependent subsystems
- Evaluate the mission metrics based on the uncertainty factors and levels

Illustrative Example

- The five step methodology is explored with an illustrative example. The example seeks to develop an airborne platform capability that will attempt to detect, identify, prosecute, and engage threat airborne targets.



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Step 1: Problem Definition

- Divide the problem into three uncertainty types:
  - What the threat (red) can do
  - The operational environment
  - The friendly (blue) forces structure and tactics
- There are five phases of mission execution
- Search and detect the threat, identify the threat's intentions, decide what actions to take, engage the threat, and assess the next step

Step 1: Uncertainty Levels

What the threat can do

Phase	Component	Uncertainty type	Uncertainty input	Inputs (low uncertainty)	Inputs (high uncertainty)
Search / Detection	Sensor	Threat	Target signature	Good intel	Bad intel
Identify	Identification	Threat	Target jamming	Good intel	Bad intel
Decision Making	Decision Making	Threat	Target Low Probability of Intercept (LPI) communications	Good intel	Bad intel
Engage	Weapon	Threat	Threat weapons	Good intel	Bad intel
Assess	Communications	Threat	Threat tactics	Good intel	Bad intel

Operational environment

Phase	Component	Uncertainty type	Uncertainty input	Inputs (low uncertainty)	Inputs (high uncertainty)
Search / Detection	Sensor	Environment	Weather conditions to affect detection	Operating in known conditions	Unexpected conditions
Identify	Identification	Environment	Operational conditions to affect identification	Operating in known conditions	Unexpected conditions
Decision Making	Decision Making	Environment	Operational conditions to affect decision making	Operating in known conditions	Unexpected conditions
Engage	Weapon	Environment	Operational conditions to affect engagement	Operating in known conditions	Unexpected conditions
Assess	Communications	Environment	Weather conditions to affect communications	Operating in known conditions	Unexpected conditions

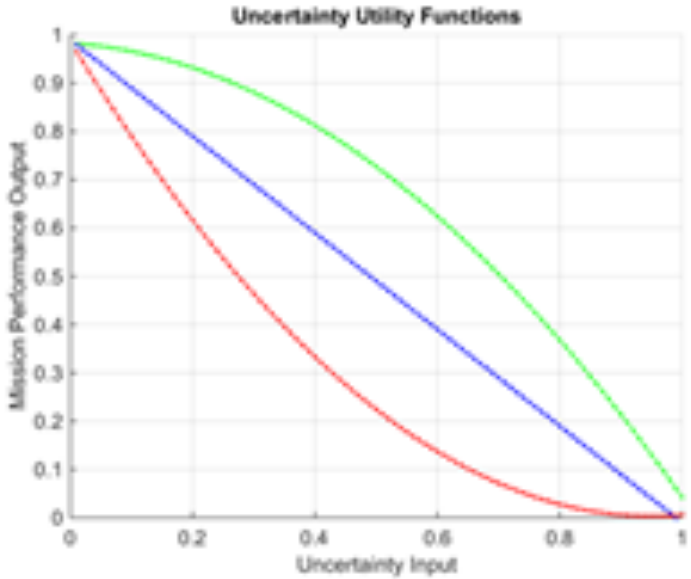
Friendly forces structure and tactics

Phase	Component	Uncertainty type	Uncertainty input	Inputs (low uncertainty)	Inputs (high uncertainty)
Search / Detection	Sensor	Blue	Acquisition changes	Fully funded	Less funded
Identify	Identification	Blue	Acquisition changes	Fully funded	Less funded
Decision Making	Decision Making	Blue	Tactics changes	Operating with known TTP	Operating with different TTP
Engage	Weapon	Blue	Acquisition changes	Fully funded	Less funded
Assess	Communications	Blue	Interoperability changes	Operating with known interoperability	Operating with unknown interoperability

Step 2: Uncertainty Utility Function

- For the purpose of this example, we will use the general utility function provided below

Better performance



Lower performance

Green line (or top line): robust utility function
Blue line (or middle line): linear utility function
Red line (or bottom line): fragile utility function

Less uncertainty (good)

More uncertainty (bad)

Step 3: Uncertainty Interdependency Table

- Initial mapping of the blue system capabilities to the groupings of uncertainty factors (threat, environment, blue)
- In each cell, there are four possibilities: no interaction, robust, linear, or fragile utility function types

	Uncertainty Dependencies									
Blue Capabilities	Target signature	Target jamming	Target LPI comms	Threat weapons	Threat tactics	Weather impacts	Operating environment constraints	Blue acquisition	Blue TTP	Blue interoperability
Sensor	1	2	0	1	1	2	2	2	2	0
Identification	2	1	2	3	3	2	2	2	3	3
Decision Making	2	3	0	2	3	0	2	1	2	1
Weapon	1	1	0	2	1	2	2	1	3	3
Communications	0	1	0	0	0	1	2	2	3	3
Key										
0: Not applicable										
1: Robust utility function										
2: Linear utility function										
3: Fragile utility function										

Step 3: Uncertainty Interdependency Table

- A notional view of the red and blue uncertainty factors interdependency for the air-to-air mission
- Read across from left to right to find the contributing inputs
  - 0 indicates no contribution / impact to the mission
  - 1 indicates there is a contributing input to the uncertainty factor

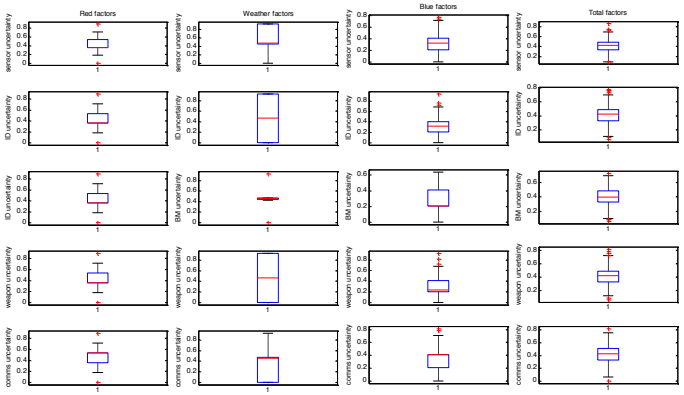
	Contributing Uncertainty (read across)				
Initial uncertainty (read down)	Target signature	Target jamming	Target LPI comms	Threat weapons	Threat tactics
Target signature	0	0	0	0	1
Target jamming	0	0	1	1	1
Target LPI comms	0	0	0	0	1
Threat weapons	1	1	0	0	1
Threat tactics	0	0	1	1	0
Key					
0: no contribution					
1: contribution					

	Contributing Uncertainty (read across)		
Initial uncertainty (read down)	Blue acquisition	Blue TTP	Blue interoperability
Blue acquisition	0	0	1
Blue TTP	0	0	1
Blue interoperability	1	1	0

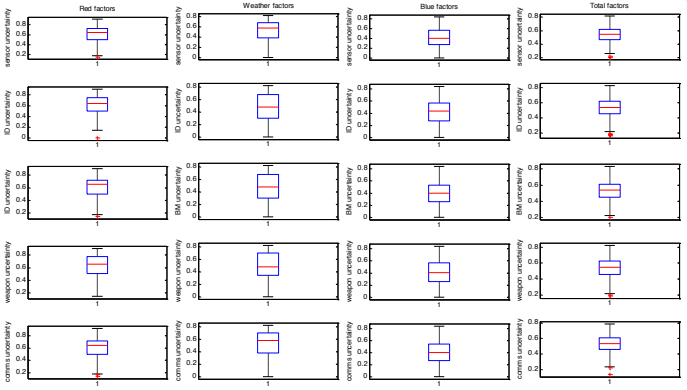
Step 4: Uncertainty Scenarios

- The first scenario is a **generally good understanding** of the threat and an accurate estimation of the uncertainty growth over time, which will be relatively small. The uncertainty levels for the threat, environment, and friendly factors will be limited to 0 (not applicable) and 1 (robust) utility function.
- The second scenario has an **average understanding** of the threat, but with a less accurate estimation of the uncertainty. The uncertainty levels for the threat, environment, and friendly factors can range from 0, 1, or 2 (linear) utility functions.
- The third scenario has a **poor understanding** of the threat, and a low estimation of the uncertainty. The uncertainty levels for the threat, environment, and friendly factors can range from 0, 1, 2, or 3 (fragile) utility functions.

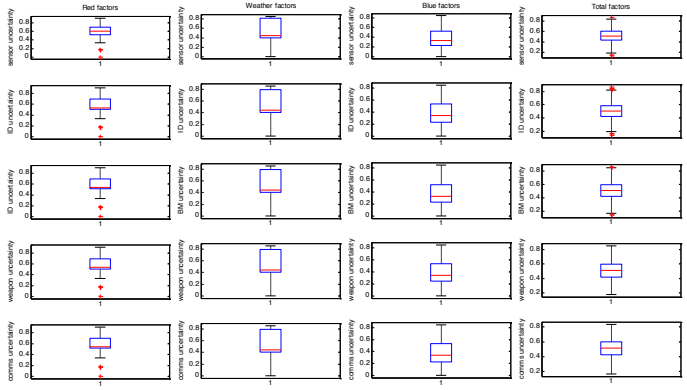
Step 5: Mission Uncertainty Analysis



Scenario 1 Analysis



Scenario 3 Analysis



Scenario 2 Analysis

The boxplot shows the mean (red line), the 1st and 3rd quartile (box), and data within the 1.5 Inter Quartile Range (IQR) of the upper and lower quartiles (whiskers) of the model output. Outliers outside the whiskers are labeled as red crosses.

The general trend of the uncertainty levels are increasing as we progress from scenario 1 (good understanding) to scenario 3 (poor understanding) of the threat, environment, and friendly force structure & tactics

Conclusions / Future Work

- This paper has developed a methodology in order to consider uncertainty in terms of three perspectives:
  - Uncertainty in the threat performance and employment
  - Uncertainty in the operational environment
  - Uncertainty in the friendly system interoperability and acquisition
- Through the process, we can calculate the relationships between the uncertainty factors, and view their interdependent effect on each other as their uncertainty levels change.
- Future work
  - Evaluate additional programs that have less quantifiable system performance measures (such as emergency management or asymmetric operations)
  - Evaluate system of systems configuration that may require multiple dependencies on multiple systems in order to accomplish the mission.