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Title of Paper : System-Of-Systems Analysis Using Design of Experiments

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System-Of-Systems Analysis Using Design of Experiments

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Collaboration

- A collaborative proof of principle study was undertaken with input from both the S4 team at the Physical Science Laboratory at New Mexico State University and the SEED Center at the Naval Postgraduate School. The work was sponsored by the Survivability and Lethality Analysis Directorate (SLAD) of the Army Research Laboratory.
- Participants:
  - ARL/SLAD: Dr. Jeffrey A. Smith
  - PSL/S4: Dr. Jayashree Harikumar, Dr. Roger Hartley
  - NPS: Dr. Tom Lucas, Dr. Dashi Singham, Maj. Russ Edmiston

SEED: Simulation Experiments and Efficient Designs

S4[1]: System of Systems Survivability Simulation

Issue

SoSA requires M&S of people in battlefield situations; situations that inherently possess complex multidimensional input parameter spaces and corresponding output spaces. These complexities make it difficult for decision makers to have confidence in the conclusions drawn from the M&S.

Objectives

1. Develop a methodology to cover a large input space of parameters in a statistically adequate manner while keeping the number of simulation runs needed in a test suite to a minimum.
2. Evaluate the experiment design techniques proposed by the NPS SEED Center to explore the relationships between S4's input and output spaces.
3. Statistically examine the relationships between input and output spaces to enable assessments of the performance of the simulation.

SEED: Simulation Experiments and Efficient Designs
S4[1]: System of Systems Survivability Simulation

Latin Hypercube Sampling and SEED Center techniques

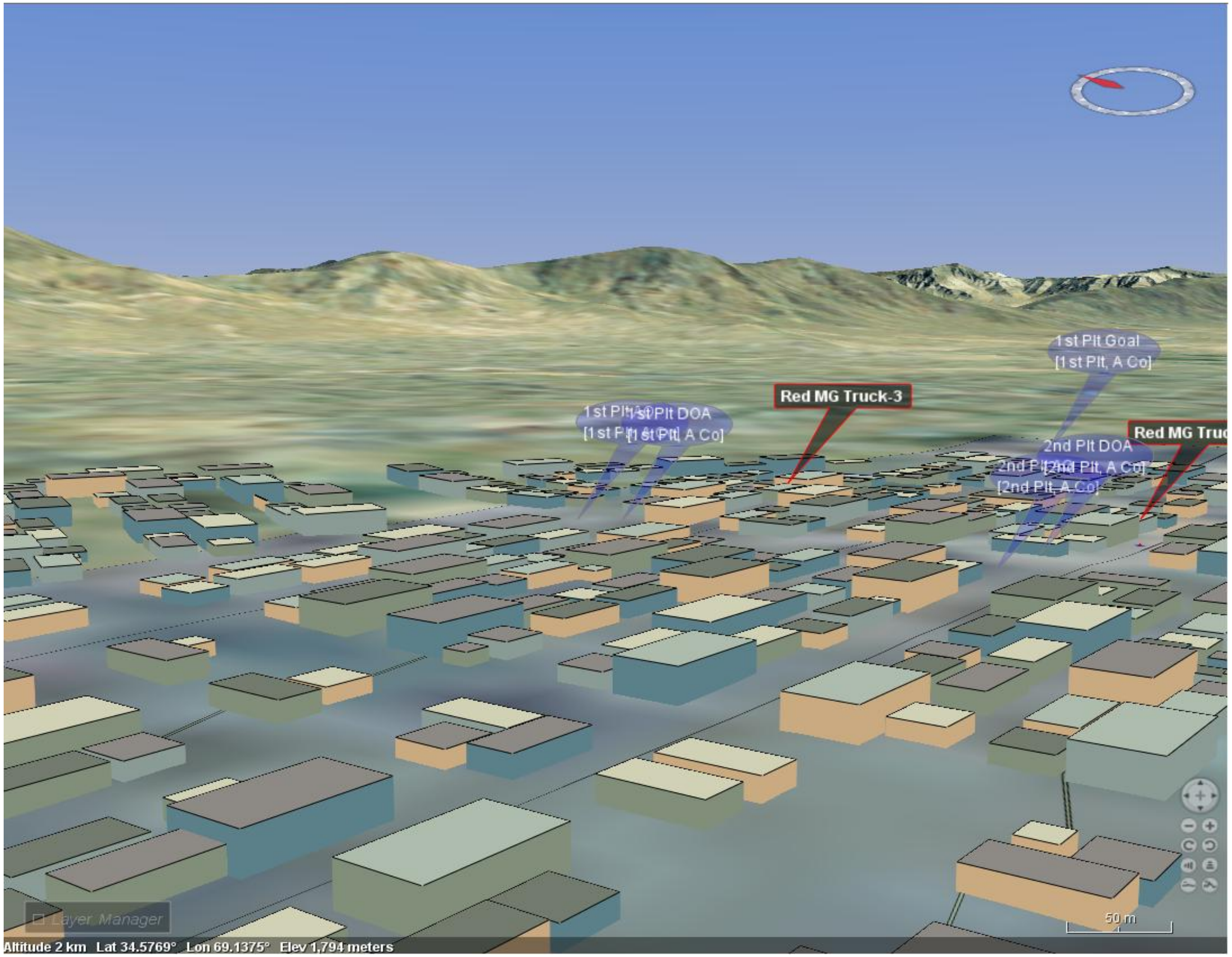
- S4 simulation has a **large input space** of **discrete**, **continuous**, **categorical** (rule based, tightly coupled) parameters.
- Exhaustive testing of this space for QA is impossible.
- **Latin Hypercube Sampling (LHS)** is a technique to uniformly sample an input space of factors and remain true to each factor's probability distribution of values. Ideally, LHS wants input factors to be orthogonal, but in practice it is often necessary to use non-orthogonal factors.
- SEED center has techniques to pair non-orthogonal input factors.
- They can also provide methods to pair input variables such that with fewer "tuples" of input factors (design points, DPs) one can explore the output space **(reduction in computing cost)**.

Collaboration timeline

Dates	Major Milestones
October 2010	1st meeting to discuss possible collaboration
November 2010	S4 training for Dr. Singham and Maj. Edmiston
December 2010	S4 scenario provided to Maj. Edmiston
January 2011	Initial Design of Experiment (DOE) specified
February 2011	Design of experiments conducted
March 2011	First scenario analysis completed
June 2011	Formal presentation of results by Maj. Edmiston
June 2011	Final deliverables to ARL

- An agent-based battlefield simulation.
- Limited to Battalion(-) and below force structure (in the order of 100 agents).
- Major areas of modeling emphasis:
  - Sensing (human, EO, IR)
  - Mobility (terrain, movement)
  - Engagement (weapons, damage)
  - Communications (radios, networks)
  - Decision making (C2, COAs, operational planning)
- Used to aid analysts (SLAD, AEC) to provide a mission context for the use of devices and/or platforms.

A screenshot using Sage (a S4 visualization tool)



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Summary of results (Bottom line up front)

- SEED center proposed a **NOLH design that could not be used** as is and had to be “custom” modified to a **NONBMD design** (specifics in later slides).
- NONBMD was tested with a input sample space of 11 communication factors, on 3 scenario variants, using communication failures and their impact on mission success as output variables.
- To test 11 communication factors using their high, mid, and low values across 3 scenarios would require **531,441** simulation runs. With the new technique, **2160** runs were adequate to cover the input-output space of possibilities (specifics on DP selection and analysis given in later slides).
- Data analysis of the small sample study indicates that the **design may be extended** to cover a larger space of inputs, and may be used in structured evaluation of S4 modules in a generic (non study) context.

NOLH: Nearly Orthogonal Latin Hypercube
NONBMD: Nearly Orthogonal Nearly Balanced Mixed Design

Design of experiment: Guiding questions

- S4 simulation consists of software components that model sensors, terrain, ballistics effects, engagements, decision making processes (DMP), communications and networks.
- Flow of information is critical to the S4 DMPs, so the proof of principle study was designed around communication factors.
- The impact of these factors on the simulation output was measured predominantly in terms of operational delay.

Three guiding questions were used to address the objectives quantitatively.

1. Which input factors have the most influence on the *model's* output?
2. How sensitive are the model's DMPs to the success or failure of communications?
3. Is the model output a result of the equipment capabilities being analyzed or a product of the *communication environment* modeled?

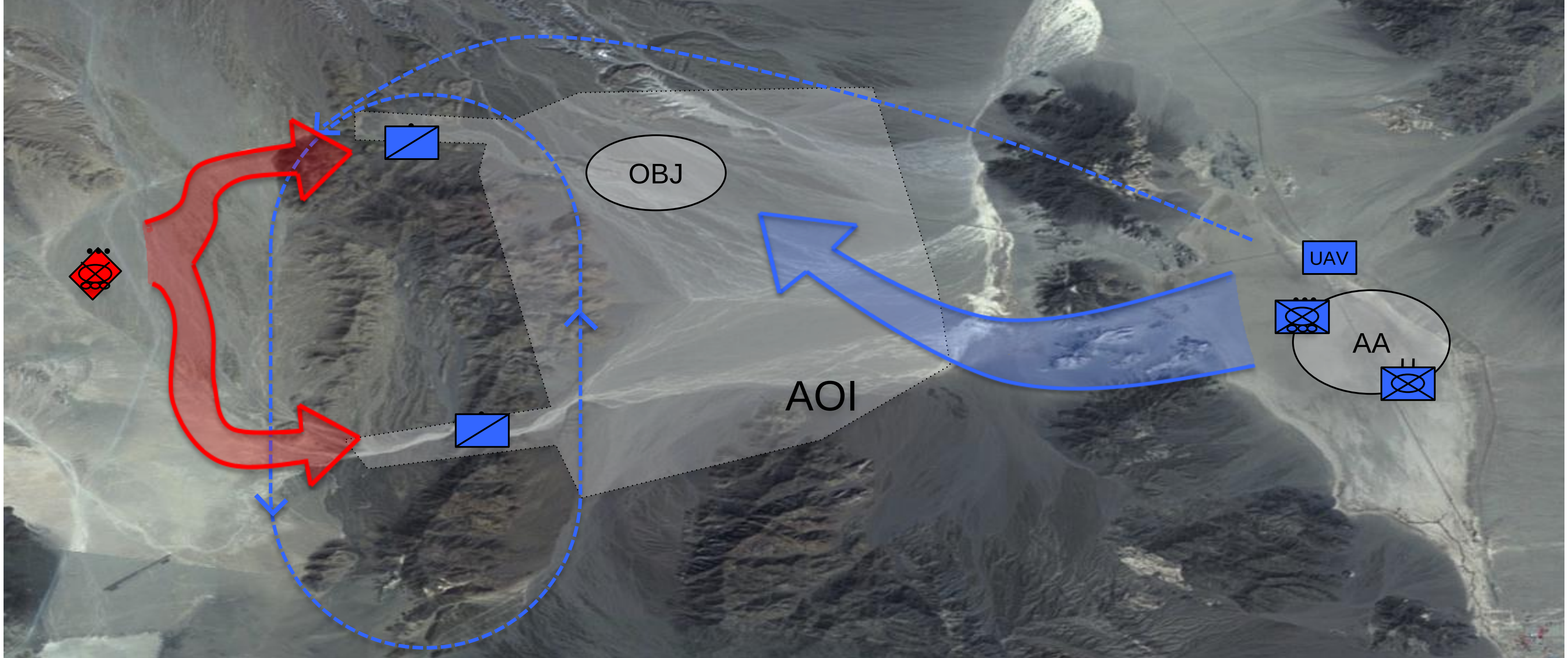
Design of experiment: Input parameters

Number and type of parameters		Communications parameters considered	Impacts	
			Voice	Data
1	Discrete	Max TCP Retries	☐	☑
2	Discrete	Bits in Data Unit	☐	☑
3	Discrete	Bits of Overhead	☐	☑
4	Continuous	Antenna Gain	☑	☑
5	Continuous	Link Refresh Meters	☑	☑
6	Continuous	Link Refresh Seconds	☑	☑
7	Continuous	TCP* Retransmit Interval	☐	☑
8,9	Categorical	Propagation Mode + P(Message Receipt)	☑	☑
10,11	Categorical	Available Bandwidth + Duration Mode	☐	☑

A categorical parameter comprises of 2 or more tightly coupled parameters

Design of experiment: Scenario

Sample scenario with EAST variant to emphasize analysis of communications parameters and their impact on DMPs.



- **1 scenario (3 variations in the start positions) for Blue**
- **21 Agents (16 BLUE, 5 RED)**
- **Communication heavy, no engagements**

Design of experiment: Communications networks

Network Name / LDR	Description	Members
BN / BN Cdr	Provide C2	CO Cdr, Recon Cdr
CO / CO Cdr	C2 to Maneuver PLT.	HMMWV 4
RECON / Recon Cdr	C2 to UAV, Scout Teams	UAV, Scouts 1-4, 2-4
Maneuver PLT / HMMWV-4	Platoon and Platform DMP	HMMWV -1, 2, 3
SCOUT Team-1 / Scout 1-4	Scout team leaders provide information collected by their teams to Recon Cdr	Scouts 1-1, 1-2, 1-3
SCOUT Team-2 / Scout 2-4		Scouts 2-1, 2-2, 2-3
INSURGENT / Insurgent Ldr	Provides C2 to entire RED force	Truck-1, Truck-3
TRUCK Team 1 / Truck-1	Platform DMP; Team leaders relay information collected by their team to Insurgent Ldr.	Truck-2
TRUCK Team 2 / Truck-3		Truck-4

Design of experiment: Design point (DP) selection

- NONBMD was used to define the design point (DP) or input tuples.
- NONBMD (Vieira Jr. and Sanchez, 2010) uses mixed integer program to
  - minimize the maximum off-diagonal pairwise correlation,
  - address the *imbalance* of the experiment caused by using mixed factor types of varying ranges.
- NONBMD limitations include
  - no catalogued design for “grab and use,”
  - has to be custom built to incorporate factor rules and ranges.
- Experiment choice was a NONBMD with 144 DP that had a maximum pairwise correlation of 1.4% (0.0 pairwise correlation is best.)

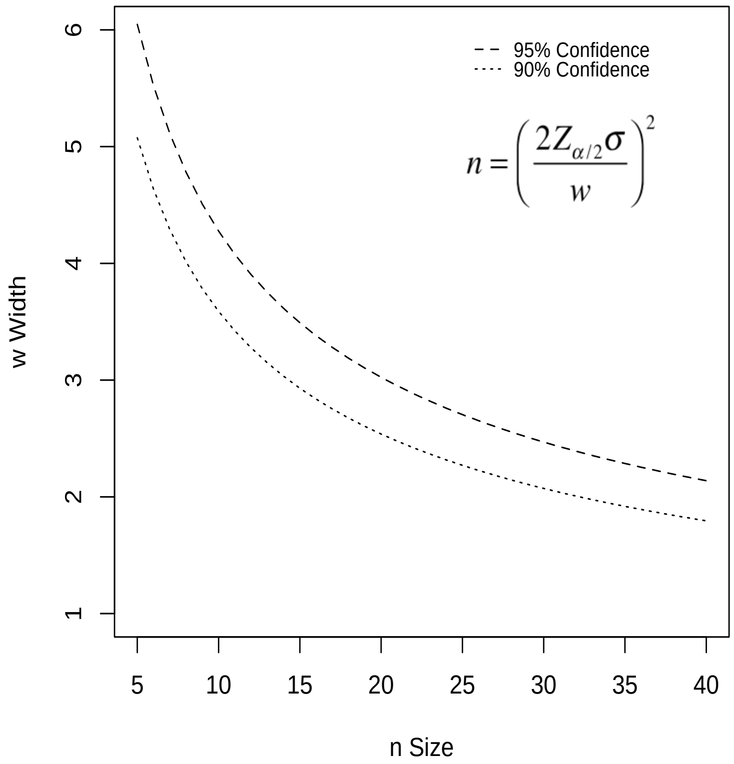
NONBMD: Nearly Orthogonal Nearly Balanced Mixed Design
DP: Design point (DP) is a unique combination of values of input variables

Design of experiment: Design Point (DP) replication

- Runs with the same input parameters but different seeds produce different results, which makes it necessary to replicate the DPs so that statistical inferences can be made.
- To address the impact of changing parameter values and random draws, a different seed was used for every run.
- To determine the number of replications, from 12 seed variance runs we computed the variance (σ=11.9) and used the power formula:

  $(n=(2\ Z_{\alpha/2}\ \sigma\ /\ w)^2)$

  (Maj. Edmiston 2011).



Data analysis

- We examined communication failures by type (4) and by agent (21) from 2160 runs (144 DP x 5 replications per run x 3 scenario variants).
- We used the operational impact of communication failure as the output to do the analysis. By operational impact, we mean, the time delay between the RED Insurgent teams' first being spotted in the area of interest (AOI) and the BLUE Maneuver Platoon's receiving a new mission information package (MIP).
- The assumption made was that communications do not affect physical movement and once RED begins moving to its AOI it should reach there approximately within the same amount of time.
- Failure Distributions (Maj. Edmiston 2011)
  - Mean of total failures ~84.9 (95% confidence interval [83.34, 86.46]).
  - 77 % failures because time to send message expired.
  - Agents with low failures were predominantly receivers of information.

Results of data analysis (Maj. Edmiston 2011)

- We examined parameters influence using regression models (2-way interactions) with communication failures as the response, and partition trees.
  - P(Message Receipt) and Max TCP Retries were the most influential factors. They showed influence across their entire range.
- Quality of the communications environment affected the decisions made by the DMPs.
  - In a “good” communications environment, a mission order was received ~6 minutes earlier than in the base case.
  - In a “poor” but effective environment, mission order was delayed by ~15 minutes compared to the base case.
- Communications environment played a critical role between equipment sending and receiving information.

Conclusions

NONBMD shows promise in handling a small sample space. More conclusions on the extendibility of this design can be made only after more testing of the design using a larger sample space.

References

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2. Cioppa Thomas M. and Lucas Thomas W. Efficient Nearly Orthogonal and Space-Filling Latin Hypercubes. Technometrics, pp. 45–55, February 2007.
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4. Maj. Russell Edmiston. An Exploration of the Communications Environment Within the System of Systems Survivability Simulation (S4), June 2011 (Thesis).