Game-theoretic Risk Assessment for Distributed Systems (GRADS)

Sponsor: DASD(SE)

By
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10th Annual SERC Sponsor Research Review
November 8, 2018
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Overview and Agenda

- Problem Statement
- Research Questions
- Foundations: Stag Hunt Game and Risk Dominance
- Research Plan: Application to NPOESS Scenario
- Conclusion and Future Work
Distributed System Architectures

Upside Potential

• Flexibility, robustness
• Mission effectiveness
• Resource efficiency

Downside Risk

• Interdependencies
• Complex behavior
• Cascading failures

System F6 Concept (DARPA)

TROPICS Mission Concept (NASA, Lincoln Labs)
Problem Statement

• Future complex engineered systems will have more distributed architectures with decentralized decision-making among multiple independent design actors.

• Two types of risk in collaborative projects:
  — Systemic risk: cost, schedule, and technology uncertainty
  — Collaborative risk: conflict and coordination failures

• Need improved methods to assess collaborative risk
  — Identify and avoid poor strategic dynamics early
  — Improve strategic decision-making to balance efficiency (feasibility), effectiveness (desirability), and stability (viability)
Research Questions

• How to assess collaborative risk in distributed systems?
  – Tradeoff between expected upside and possible downside
  – Collaborative risk linked to decision stability, not uncertainty
  – Evaluate an objective risk metric based on Selten’s (1995) Weighted Average Log Measure (WALM) of risk dominance

• How can a collaborative risk metric be operationalized to evaluate a realistic joint program proposal?
  – Develop scenario narrative following National Operational Polar-orbiting Environmental Satellite System (NPOESS) program
  – Assess collaborative risk for a joint project between Department of Defense (DoD) and National Atmospheric and Oceanic Administration (NOAA)
# Foundation: Stag Hunt Game

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- Cell entries measure actor payoff/utility/value
- Two pure Nash equilibria
  - Hare, Hare: risk-dominant equilibrium (minimize risk)
  - Stag, Stag: payoff-dominant equilibrium (maximize reward)

*Stag hunt* by Gaston Phoebus (Bibliotheque Nationale de France)
Stag Hunt Under Uncertainty

- $p > u$: choose stag option, $p < u$: choose hare option

- $u$: Normalized deviation loss, $u = \frac{(2-0)}{(2-0)+(5-4)} = \frac{2}{3}$
Risk Dominance Metric

- Proposed by Selten (1995) to meet a set of desirable axioms
  - Normative for rational actors
  - Purely objective (assumes $p = 0.5$)

- $n$-player general case:
  \[ R = \sum_{i=1}^{n} w_i(A) \ln \left( \frac{u_i}{1-u_i} \right) \]

- 2-player asymmetric case:
  \[ R = \frac{1}{2} \ln \left( \frac{u_1}{1-u_1} \right) + \frac{1}{2} \ln \left( \frac{u_2}{1-u_2} \right) \]

- 2-player symmetric case:
  \[ R = \ln \left( \frac{u}{1-u} \right) \]

\[ R = \ln \left( \frac{2/3}{1-2/3} \right) = \ln \left( \frac{2-0}{5-4} \right) = \ln 2 \]
Engineering requires two levels of design decisions:

- Strategy: long-term policy (collaboration or independence)
- Design: architecture to maximize value in strategic context

**Strategy space:**
\[ S = \{\text{Stag, Hare}\} \]

**Design space:**
\[ D = \{\text{Axe, Bow, Club, Dog, ...}\} \]

**Multi-actor value function:**
\[ V^{S_1,S_2}(d_1,d_2) : D^2 \times S^2 \rightarrow \mathbb{R}^2 \]

### Strategic Design Games

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- Dog is selected “design” to execute Stag “strategy”
- Bow is selected “design” to execute Hare “strategy”

Other designs could be tested
Ensuring Collaboration (1)

- Two general approaches to reduce collaborative risk:

1. **Increase upside potential**
   - Increase benefit of collaboration
   - Better design to hunt stag *together*
   - Maximize denominator of $R$

2. **Fundamental problem:**
   - *robust-yet-fragile* behaviors
   - Highly-optimized stag hunt design trades context-specific value for fragility
   - Example: coordination overhead, mutual dependence

$$R = \ln \left( \frac{2 - 0}{5 - 4} \right) = \ln 2$$
Ensuring Collaboration (2)

• Two general approaches to reduce collaborative risk:

2. **Decrease downside risk**
   - Reduce penalty of coordination failure
   - Better design to hunt stag *alone*
   - Minimize denominator of $R$

• Reflects principle of *stable intermediate forms*
   - Reduce coordination overhead
   - Establish independent source of value regardless of coordination outcome

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$$R = \ln \left( \frac{2 - 0}{5 - 4} \right) = \ln 2$$
Application Case Scenario

• Study how concepts of collaborative risk dominance can be applied to a realistic systems design problem

• Retrospective study of National Polar-orbiting Operational Environmental Satellite System (NPOESS)
  — Proposed joint program between the U.S. Department of Defense (DoD) and U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)
  — Incorporate instruments developed under the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) program
  — Motivated by resource efficiency (cost savings)
NPOESS Background

Polar-orbiting Operational Environmental Satellite (POES)
 Defense Meteorological Satellite Program (DMSP)
 Earth Observing System (EOS)

Joint Polar Satellite System (JPSS)
 Defense Weather Satellite System (DWSS)
 Weather System Follow-on (WSF)

National Polar-orbiting Operational Environmental Satellite System (NPOESS)

## NPOESS Strategic Design Game

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• Model alternative architectures/designs:
  — 2 baseline independent systems: DMSP, POES
  — 1 successful collaborative system: NPOESS
  — 2 “coordination failure” systems: DWSS/WSF, JPSS

• Simulate key performance attributes: measurements, revisit period, data latency, data volume, cost

• Model actor preferences (multi-actor value)
  — Subjective preferences and weights for each attribute
  — Aggregate preferences for each design alternative
  — Inherently subjective, many simplifying assumptions
Anticipated Results (Idealized)

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$: Unit of Cost  
#: Unit of Value  

Preference
Caveats and Limitations

• NPOESS program experienced substantial *systemic risk*, specifically cost growth studied by others
  — Goal is *not* to provide retrospective analysis or “hotwash”
  — Leverage large volume of information availability and academic/government reports
  — Purposefully simplify context and scenario for tractability

• This study focuses solely on *collaborative risk*
  — Use context of NPOESS to evaluate the usefulness of the proposed collaborative risk assessment methodology
  — Communicate and validate results of an analysis process
Conclusion and Future Work

• Two types of risk in collaborative projects:
  — **Systemic risk**: cost, schedule, and technology uncertainty
  — **Collaborative risk**: conflict and coordination failures

• Investigate Selten’s risk dominance measure to assess collaborative risk from a game-theoretic perspective

• Demonstrate with application case based on NPOESS
  — Define design space under collaborative/independent scenarios
  — Model performance attributes for each design
  — Model value preferences for each actor
  — Assess risk dominance for strategic design game
Acknowledgements

• This material is based on work supported, in whole or in part, by the U.S. Department of Defense through the Systems Engineering Research Center (SERC) under Contract No. HQ0034-13-D-0004.

• Thanks to the graduate students working with me:
  — Ambrosio Valencia-Romero, Ph.D. Student Systems Engineering
  — Matthew Sabatini, M.E. Student in Space Systems Engineering
  — Henry Lee, M.E. Student in Space Systems Engineering

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