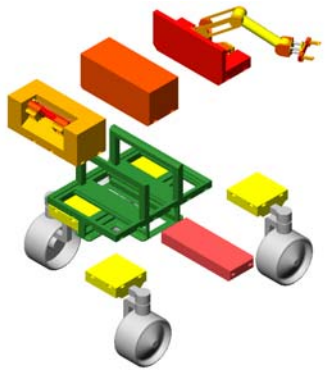

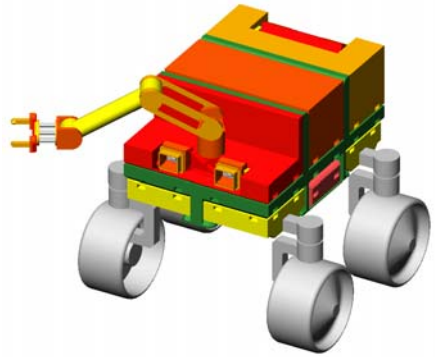

Mission Reliability Estimation for Repairable Robot Teams

First Int'l Workshop on Multi-Agent Robotic Systems
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Outline

- Motivation
- Background
- Problem Statement
- Representation
- Solution
- Example Results
- Recent Work
- Summary

Motivation

- Most mobile robots are unreliable.
- Small field robots have availability less than 50% (Carlson & Murphy, 2003)
- Those mobile robots that are highly reliable (e.g., NASA rovers) are very expensive.
- How can we increase the reliability of non-NASA mobile robots without the high cost?
- How can we design NASA rovers to be “just reliable enough”, rather than making them as reliable as possible?

Motivation

- In order to improve robot reliability we need:
  - To understand what reliability is, and in what ways robots are falling short.
  - To be able to predict reliability of robots and robot teams.
  - To compare different designs to determine which provide more reliability for less cost.

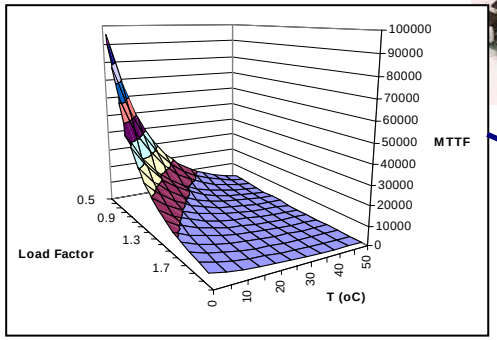
Background

- "To understand what reliability is, and in what ways robots are falling short.."
  - Reliability engineering is an old field. Why aren't we applying it to robots?
  - Carlson and Murphy (2003,2004) use reliability metrics for the analysis of robot failures and identify failures by subsystem.
  - Ebert and Stratton (2005) provide a list of common robot failures.

Background

- "To be able to predict reliability of robots and robot teams."
  - Bererton and Khosla (2002) use reliability concepts to predict performance of repairable and nonrepairable robot teams.
  - In prior work, we identify relevant models from reliability engineering, and demonstrate how they can be used to predict the probability that a robot will continue operating long enough to complete a mission task.

Background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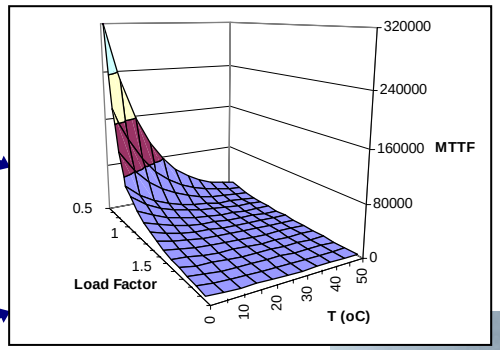
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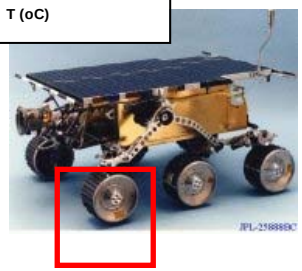

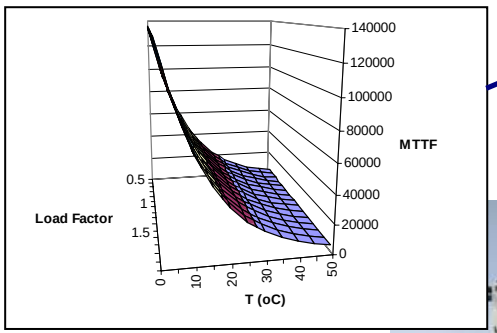
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Objective

- "To compare different designs to determine which provide more reliability for less cost."
  - In the current paper, we develop a method for predicting the probability of entire robot teams performing multiple tasks.

Problem Statement

- Mission: A group of robots must traverse together for some number of days, and they must all be alive at the end.
- Problem: For this mission, compare the performance of repairable robot (RR) and nonrepairable robot (NR) teams.

Considerations

- If the reliability of the individual robots is the same, it seems obvious that the RR team will have greater probability of completing the mission.
- However, the cost of developing and implementing repairability is non-trivial. If we use NR, we can apply those funds to increase the reliability of the robots.
- If cost is equalized in this way, it is not obvious which team will have the greater probability of mission completion.

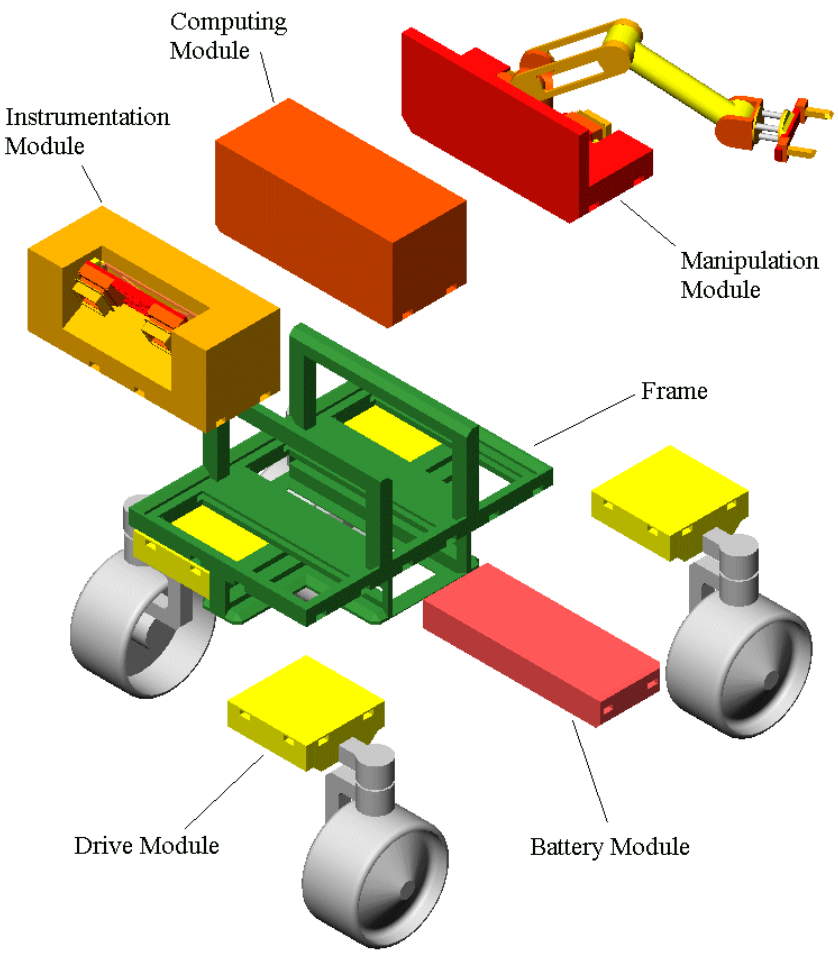
Considerations

- There are other equalizers to consider as well. For instance, more reliable components tend to be larger. For a NASA rover, volume is highly constrained. In a given payload volume we can therefore send a larger number of low-reliability robots. What is the break-even point in this tradeoff?
- How does the preference for lower reliability RR vs. higher reliability NR change if time is critical?
- How do changes in mission parameters affect the preference?

Modularity

- All robots are considered to be composed of multiple hardware modules.
- For RR, there are some number of spare modules available which can replace failed modules. Module replacement is carried out by a robot other than the failed robot, i.e. “cooperative repair.”

Modularity


Computing Module
Instrumentation Module
Manipulation Module
Frame
Drive Module
Battery Module

per WBS element

Modular Design Synthesis Using NASA'S Hierarchical System Terminology

SYSTEM

SEGMENT

ELEMENT

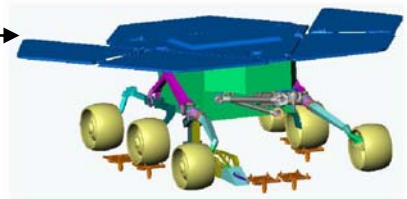
ROVER

ROBOTIC ARM

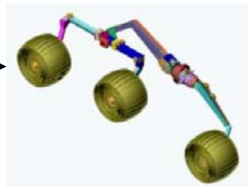
PAYLOAD

SUBSYSTEM

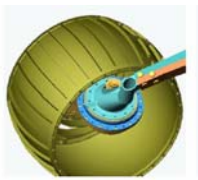
MOBILITY

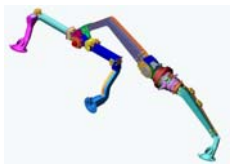


ASSEMBLY



SUBASSEMBLY





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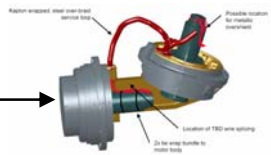
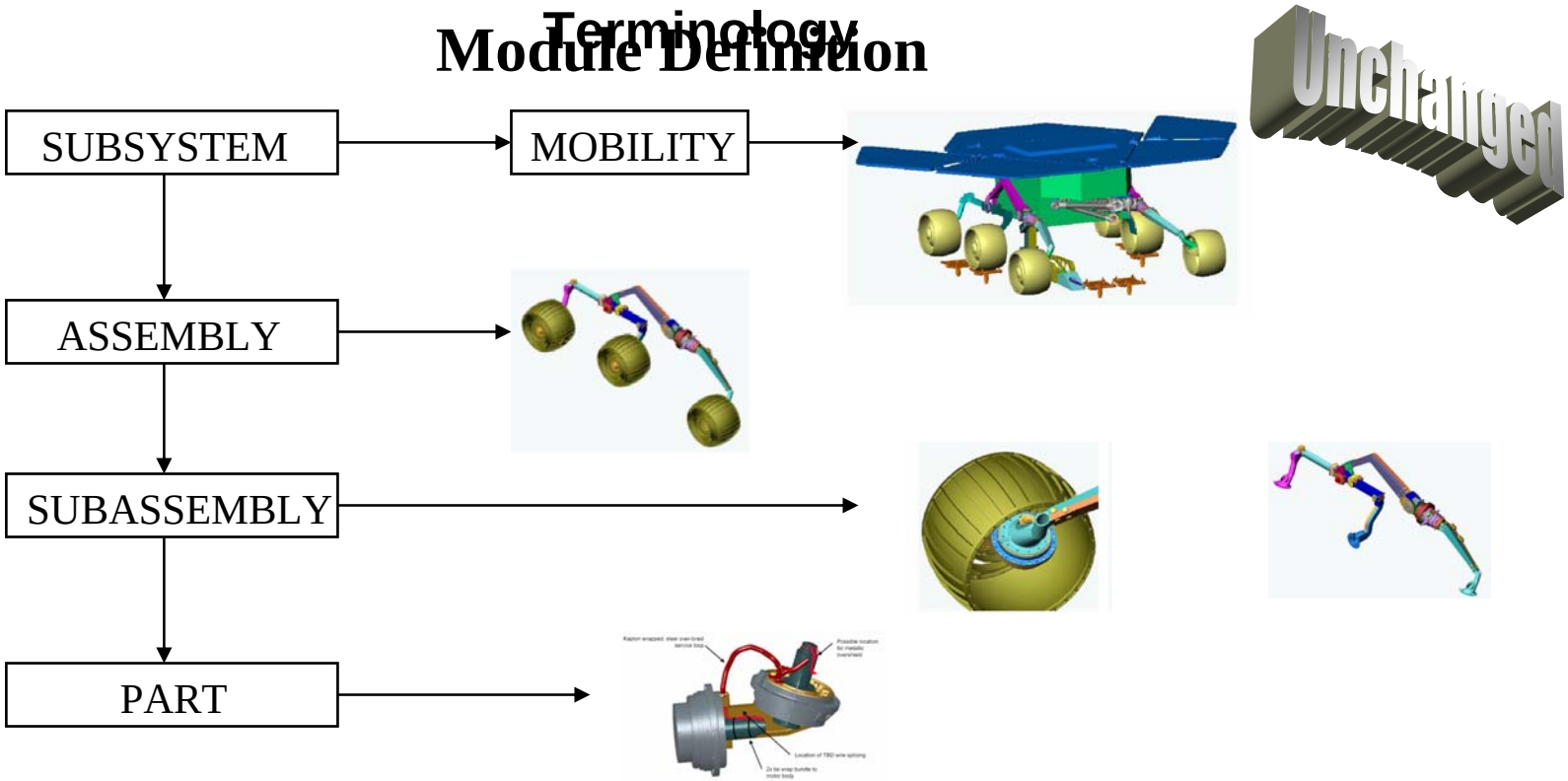


Modular Design Synthesis Using NASA'S Hierarchical System Terminology

Module Definition



- A module can be an ASSEMBLY, SUBASSEMBLY or PART.
- A particular mission design requirements will circumscribe what type of modules can be employed.

Representation

- The NR teams in this simple mission have only one type of task - *Transit*. It is repeated some number of times. If any robot fails during any *Transit*, then the mission fails.

- We also consider NR teams where there are an excess of robots, so for instance three robots start the mission, and only two need to survive.

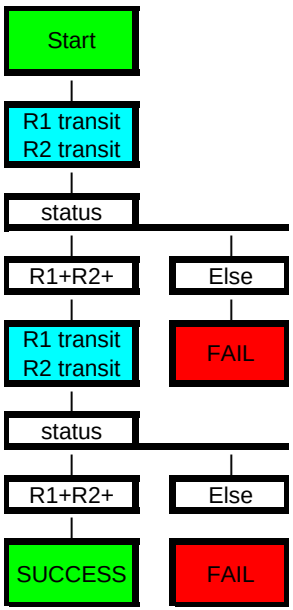
Representation

- The RR teams have two possible tasks - *Transit*, and *Repair*. If a robot fails during a *Transit* task, and there are spare modules available, then another robot must execute a *Repair*. If there are no spare modules left then the mission fails.

- We describe the possible mission+team configurations using the nomenclature (N,D,M) where N is the number of robots, D is the number of days to traverse, and M is the number of spare modules.

Representation

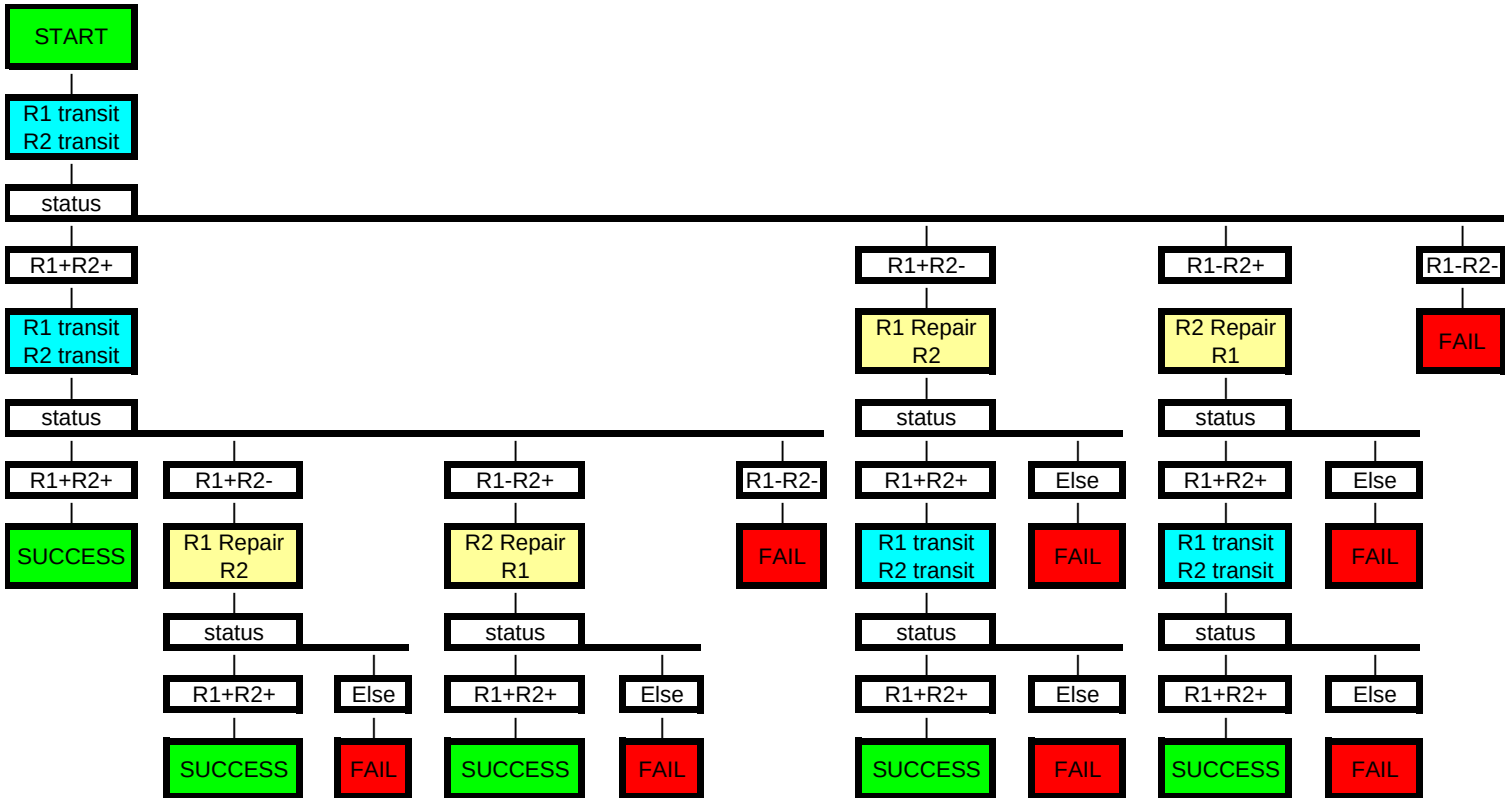
- The space of all possible task sequences can be represented in tree form.
- Example: Two NR traverse for two days (2,2,0):



Representation

- Repairability adds considerable complexity.
- Adding a single spare module increases the number of tasks considered from two to eight. Illustrated by the tree for (2,1,1) on next slide.

Representation



Solution

- The tree can be used to evaluate the probability of completing the mission, which is the sum of the probabilities of occurrence for all *Success* leaf nodes.
- The probability of occurrence for a leaf node is calculated by traversing the path from root to leaf and multiplying probabilities.

Solution

- Possible ways of dealing with combinatorial explosion:
  - Closed-form analytical solution.
  - Limit search space through mission constraints.
  - Heuristic pruning.
  - Stochastic sampling.

Solution

- Simplifications:
  - Failure is assumed to occur only at the end of a task.
  - We do not track different types of spare modules.
  - We do not consider differences in cost of repair.
  - We ignore simultaneous module failures, other than complete failure of the team.

Solution

- In this paper - closed-form analytical solution.
- Procedure - draw out tree by hand for a few cases, express the P(survival, mission) of each in terms of the P(survival, task) for the Transit and Repair tasks, then generalize the equations by observing patterns.
- Example:
  - $P(N,1,0)= T^{+}$ (N robots, one day, no spares)
  - $P(N,1,1)=T^{+} + T^{-}R^{+}$
  - T^{+} is P(all robots alive) T^{-} is P(exactly one robot dead)

Solution

- After much derivation and generalization, arrive at a general equation in terms of number of robots N, number of days D and number of spare modules M.

$$P(N,D,M) = \left(T^{+}\right)^{D} + \sum_{j=1}^{M}\left[{}^{D}C_{j} \cdot \left(T^{+}\right)^{D-j} \cdot \left(T^{-}R^{+}\right) \cdot \sum_{i=0}^{M-j}\left(R^{-}\right)^{i} \right]$$

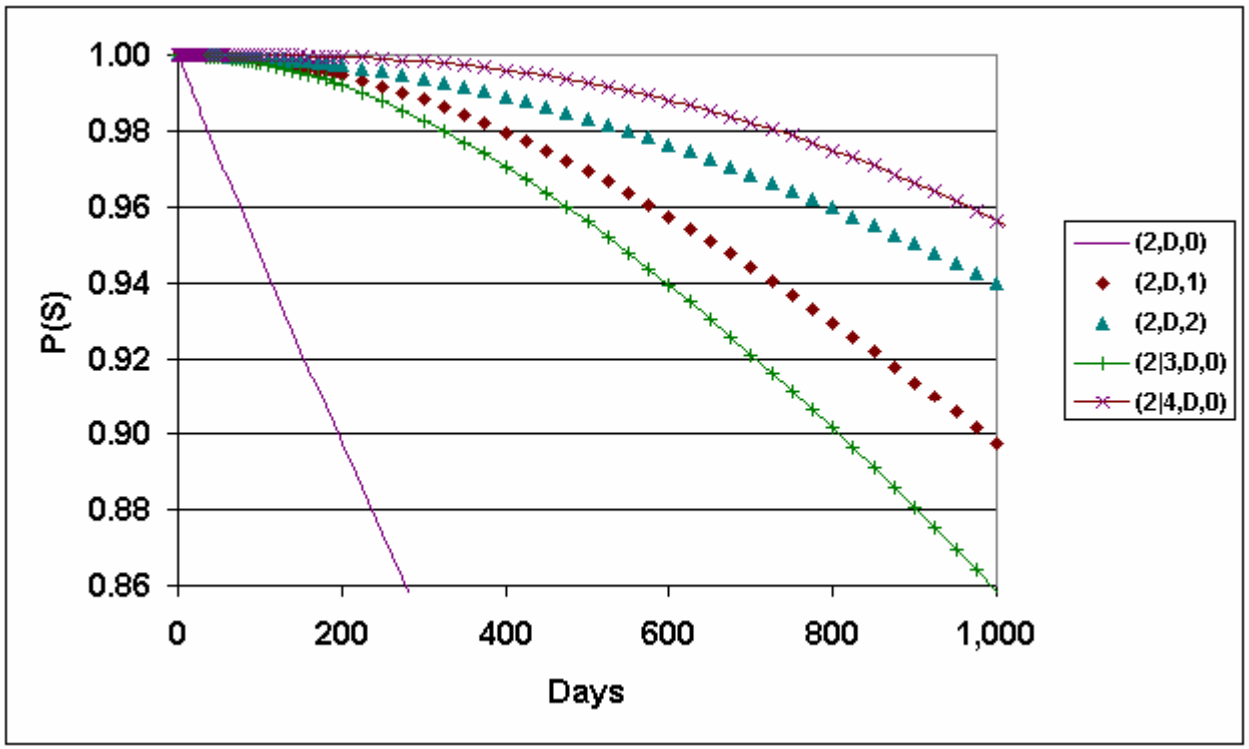
Where ${}^{D}C_{j}$ is the number of combinations of j in D.

Example Application

- Two robots to be alive after a traverse of D days.
- All robots are identical and composed of three modules: propulsion, manipulation, sensing/power.
- MTTF for each module is given, along with number of hours each module is used for the *Transit* and *Repair* tasks.
- Compare different team configurations (2 NR, 3 NR, 2RR) for base case.
- Compare configurations again with reduced reliability for the basic task (*Transit*.)

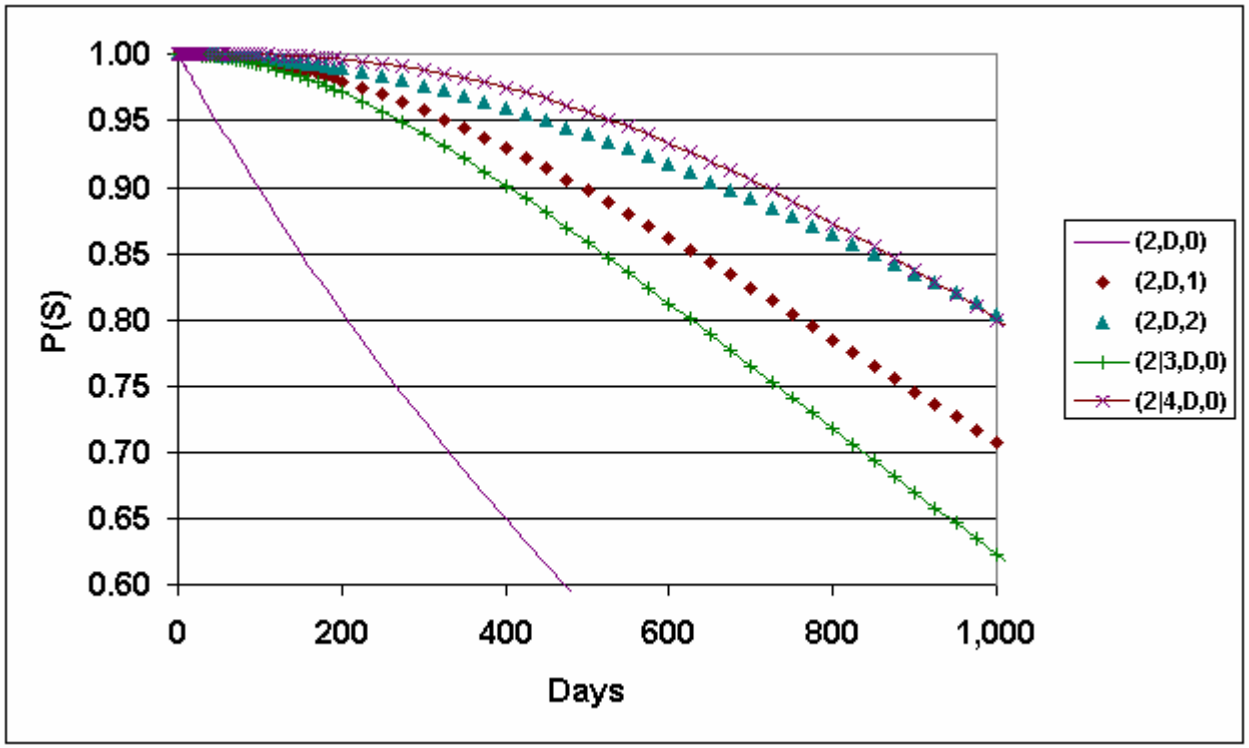
Example Application

Mission success for different team configurations.



Example Application

- Mission success with lower *Transit* reliability.



Example Application

- Reliability of all teams is lower when the basic task is less reliable. However the RR team has a smaller drop in reliability.
- Indicates that repairability is more valuable when basic mission (i.e., modules and tasks) has lower reliability.

Recent Work

- Deriving equations for the probabilities is only feasible for very simple problems.
- Use stochastic sampling instead.
- Elimination of earlier simplifications:
  - We now track different types of spare modules.
  - We now deal with simultaneous module failures.
- This new method with results for a more complex mission published in recent ISAIRAS paper.

Summary

- First general method for analytically predicting the probability of robot teams.
- Makes use of long-established models from reliability engineering.
- While the method in this paper has broad applicability, the amount of human labor involved makes it impractical for any but the simplest missions. Follow-on work has increased usefulness by using stochastic sampling instead of analytical derivations.

For More Information

- S. Stancliff, J. Dolan, and A. Trebi-Ollennu. “Towards a Predictive Model of Robot Reliability," CMU Technical Report CMU-RI-TR-??, August, 2005.
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References

- J. Carlson and R. Murphy. "Reliability analysis of mobile robots," in *Proc. ICRA*, 2003.
- J. Carlson, R. Murphy, and A. Nelson, "Follow-up analysis of mobile robot failures," in *Proc. ICRA*, 2004.
- K. Ebert, and B. Stratton, "Supporting the joint warfighter by development, training and fielding of man-portable UGVs," in *SPIE Proc. 5804: UGV Technology*, March, 2005.