Architectures and Algorithms for Self-Healing Autonomous Spacecraft

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Phase I Objectives

• Profile missions requiring revolutionary
  – survivability
  – performance

• Characterize avionics and software

• Survey appropriate technologies

• Advance state-of-the-art for mission-critical architectures and algorithms
Unlike the three R’s (Rockets, Rovers, Robots) reconfiguration lacks visibility … except for 2 minutes of fame in Terminator 2
Interstellar Missions Require Revolutionary Survivability and Performance

You are here

Alpha Centauri
A: G2 V (Lum. 1.77)
Prob. habitable planet: 0.054
B: K0 V (Lum. 0.55)
Prob. habitable planet: 0.057
# Profile of Interstellar Missions

<table>
<thead>
<tr>
<th>Jet Propulsion Laboratory Interstellar Probe</th>
<th>Johns Hopkins University McNutt IPM</th>
<th>The Right Stuff of Tahoe Santa Maria</th>
</tr>
</thead>
<tbody>
<tr>
<td>nose of heliosphere</td>
<td>beyond nose of heliosphere</td>
<td>Alpha Centauri</td>
</tr>
<tr>
<td>200 AU</td>
<td>1000 AU</td>
<td>278256 AU</td>
</tr>
<tr>
<td>ecliptic trajectory with solar swingby</td>
<td>ecliptic trajectory with Jovian / solar swingby</td>
<td>out of ecliptic, direct</td>
</tr>
<tr>
<td>solar sail</td>
<td>Orion class nuclear</td>
<td>nuclear, $I_{sp} &gt; 10^5$ sec</td>
</tr>
<tr>
<td>launch: 2010</td>
<td>50 years</td>
<td>launch: 2-Aug-2022</td>
</tr>
<tr>
<td>15 years</td>
<td>50 years</td>
<td>200–500 years</td>
</tr>
<tr>
<td>100 kg payload</td>
<td>50 kg payload</td>
<td>1000 kg payload</td>
</tr>
<tr>
<td>20 watts</td>
<td>15 watts</td>
<td>100 watts</td>
</tr>
<tr>
<td>25 bits per second</td>
<td>20 bits per second</td>
<td>100 bits per second</td>
</tr>
</tbody>
</table>
Flight System Mass Less Sail, kg

Sail Performance Trade: Tf, S/C Mass, Perihelion with Sail Technology

- Circular Sail
- Sail Jettisoned at 5 AU

- Sail Radius = 300 m
  Perihelion = 0.20 AU
  Areal Density = 0.75 g/m²

- Sail Radius = 300 m
  Perihelion = 0.20 AU
  Areal Density = 1 g/m²

- Sail Radius = 197.5 m
  Perihelion = 0.25 AU
  Areal Density = 1 g/m²

Flight Time (Tf) to 200 AU, yrs

Adapted from JPL viewgraph

04/29/99
Santa Maria
Initial Mass versus Flight Time

Time of Flight (years)

Initial Mass (kg)

- Antimatter/Flyby
- Antimatter/Rendezvous
- Fusion/Flyby
- Fusion/Rendezvous
Contemporary Performance Ceiling

$10^{12}$ operations per second, > 100 kilograms
(Brookhaven, Sandia supercomputers)
Contemporary Fault Tolerance

Titan 4A explosion 40 seconds after launch, 12-Aug-1998. Cause: faulty wiring
Contemporary Fault Tolerance

- X2000 avionics and software: 1 fault
- STS Missions: 2 faults in active payload
- Needed: tolerance to a proportional number of
  - latent design faults
  - transient faults, single or burst
  - permanent faults, regardless of source
Architectures for Interstellar Avionics

- Unmanned robots
- Will support software that can adapt on its own
- $10^{15}$ operations per second per kilogram
- Tolerate constant proportion of faulty components
- Uniform elements maintain healthy connectivity
- Design hinges upon dependable tools that embody a dependable theory about dependability
Revolutionary Reliability Requires Radical Rigor

- Standard approaches to avionics (e.g., n-module redundancy with voters) will not work
- *Ad hoc* approaches to software will leave the number and severity of faults unpredictably high
- Function and performance of hardware architecture should be dictated by applications software
- A major application will be assuring the health of the onboard software
Appropriate Technologies: Mathematical Advances Enable Software That Really Works

• **Provably correct programs**
  - E.g., work by Angela B. Shiflet (Wofford College), Martin Feather (JPL), Frank Schneider (JPL), Mike Lowry (ARC)

• **Tracking and analysis of soft failures and faults**
  - E.g., work by Allen Nikora (JPL), Larry LaForge (The Right Stuff of Tahoe), Norman Schneidewind (Naval Postgraduate School), John C. Munson (University of Idaho), Taghi Khoshgaftaar (Florida Atlantic University)
Appropriate Technologies:
Mathematical Advances Enable
Hardware That Really Works

Necessary and sufficient: logarithmic redundancy

• **Mutual test and diagnosis**
  – Edward Scheinerman (Johns Hopkins), Doug Blough (University of California, Irvine), Larry LaForge (The Right Stuff of Tahoe), Andrez Pelc (University of Quebec)

• **Reconfiguration architectures and algorithms**
  – Shuki Bruck (CalTech), Larry LaForge (The Right Stuff of Tahoe), John Hayes (University of Michigan), Charles Leiserson (MIT)
A Technology Roadmap (Rather, a *Starchart*) Identifies Inappropriate As Well As Appropriate Innovations

Not quite ready for a 200 year mission, $10^4$ Mrad(Si):

- Contemporary flight processors
  *(e.g. those aboard Mars Pathfinder, Deep Space 1)*

Will take more than 40 years to be ready:

- Chemical computers (Hewlett Packard, will take more than 40 years to mature)
- Nano-robots that mechanically repair avionics (MIT)
Example: Technology Combined With Our Contributions

Classical hypercubes are not what we should be building. Clique-based cubes are what we should be building.

**Theorem 33.** Denote by $\rho_{\text{Thm 6}}^{-}$ the lower bound on the radius of any quorum.

If $\rho_{m, j, d}^{-} = \log_j (n/m) + \lfloor m/2 \rfloor$ and $\rho_{m, j, d}^{+} = 1 + \log_j (n/m) + \lfloor m/2 \rfloor$ are the minimum resp. maximum radius of quorums of $K_{m, j}^d$, then

$$\left[d + \left\lfloor \frac{m}{2} \right\rfloor \right] \frac{\ln (j-2) + \ln d}{\ln m + d \ln j} \leq \frac{\rho_{m, j, d}^{-}}{\rho_{\text{Thm 6}}} \leq \frac{\rho_{m, j, d}^{+}}{\rho_{\text{Thm 6}}} \leq \left[d + \left\lfloor \frac{m}{2} \right\rfloor + 1 \right] \frac{\ln j + \ln d}{\ln m + d \ln j - 1.4}$$
Research Tools Incorporate Mathematical Advances in Diagnosis and Configuration
The *Integration* of Advanced Modeling, Tools, and Technologies Will Enable Self-Healing Architectures and Algorithms for Autonomous Spacecraft