Applying Systems Engineering Methodologies to the Micro and Nanoscale Realm

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“Systems engineering will become a key enabler for the successful commercialization of multi-functional, micro and nano technologies. Systems engineering delivers methodologies, processes, and tools to enable the efficient integration and exploitation of these disruptive technologies.”

Yves LaCerte of Rockwell Collins addressed the International Council on Systems Engineering (INCOSE) 2008
… to visualize how a nanofactory system works, it helps to consider a conventional factory system. The technical questions you raise reach beyond chemistry to systems engineering.

Problems of control, transport, error rates, and component failure have answers involving computers, conveyors, noise margins, and failure-tolerant redundancy.”
FIRE, PREVENT IT?
I HAVE TO INVENT IT.

When Capabilities don’t meet Requirements
Features of future systems are:

- **Increasingly complex**, involving quantum mechanics, quantum chemistry, solid state physics, materials science, and chemistry principles, especially when considering micro and nano scaling;
- **Highly integrated** systems of increasing complexity which use a range of technologies for the improvement of the overall system;
- **Networked, energy-autonomous**, miniaturized, and **reliable** for space, defense, medical, civil, and commercial applications;
- Operating within larger systems in which they are embedded;
- Interfacing with each other, with the larger system, the environment, and humans; and
- Ease of use and integration of mechanical, optical, biological functions.

Criteria to Identify a Complex System (Ottino)

- What they do - they display emergence and
- How they may or may not be analyzed - classical systems engineering approaches of decomposing/analyzing subparts do not necessarily yield clues of their behavior as a whole.

## Machine Age vs Systems Age Approaches

<table>
<thead>
<tr>
<th>Machine Age Thinking</th>
<th>System Age Thinking</th>
<th>Machine Age Analysis</th>
<th>Systems Age Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procedure</td>
<td>Process</td>
<td>Analysis focuses on structure; it reveals how things work</td>
<td>Synthesis focuses on function; it reveals why things operate as they do</td>
</tr>
<tr>
<td>Decompose that which is to be explained</td>
<td>Identify a containing system of which the thing to be explained is part</td>
<td>Analysis yields knowledge</td>
<td>Synthesis yields understanding</td>
</tr>
<tr>
<td>Explain the behavior or properties of the contained parts separately</td>
<td>Explain the behavior of the propertied containing the whole</td>
<td>Analysis enables description</td>
<td>Synthesis enables explanation</td>
</tr>
<tr>
<td>Aggregate these explanations into an explanation of the whole (additive)</td>
<td>Explain the behavior of the thing in terms of its roles and functions within its containing whole</td>
<td>Analysis looks into things</td>
<td>Synthesis looks out of things</td>
</tr>
</tbody>
</table>
First attempts as producing microchips through top down methodology.

Nano child’s play.
To the Third Generation

First Generation - Passive nanostructures
• Achieved circa 2001
• Example: bulk structures

Second Generation - Active nanostructures
• Achieved circa 2005
• Example: targeted drugs

Third Generation - Systems of nanosystems
• Was expected circa 2010
• Example: bioassemblies

Fourth Generation – Molecular nanosystems
• Forecasted circa 2015
• Example: molecular devices by design
“Would you like the Bottom up or Top down section?”
Heterogeneous molecular nanosystems. Molecules as engineered structures and architectures yield fundamentally new functions. New syntheses and assembling techniques, such as bioassembling; nanonetworking and multiscale architectures emerge.
Successful Technology Transition

• The establishment of “Skunk Works-like” environment — these groups are committed, multidisciplinary teams led by champions who inspire and motivate their teams toward specific goals;

• Team determination to make the technology succeed—which may include making the technology profitable and demonstrating to customers that they need the technology;

• The use of expanded mechanisms of open and free communication—especially involving the ability to communicate an awareness of problems that will affect process goals; and

• The willingness of the champion to take personal risk—such leadership results in the willingness of the organization to take risks at the enterprise level.
When top down meets bottom up construction techniques.
JHU/APL is Familiar With High Pressure Challenges

- Ventured high technology development since its conception
- Developed disruptive technologies with innovative management philosophies
- Designed & launched 68 satellites and 150+ space instruments

**NEAR 1996 - 2001**

- First launch of NASA’s Discovery Small Satellite Program
- Cost $104M
- Developed in 27 months using a distributed architecture design
- Studied Eros asteroid from several close orbits before landing on its surface

**MESSENGER 2004 - Ongoing**

- First mission to orbit Mercury
- Strict schedule requirements in order to meet fixed launch date
- 2011 Completed flybys of Earth, Venus, and Mercury before insertion
- Complex design and mission to withstand large temperature difference while studying Mercury
DAVID TAKES DOWN GOLIATH USING A NANO SAT.
### What is a Small Satellite? Taxonomy

<table>
<thead>
<tr>
<th>Category</th>
<th>Mass Range</th>
<th>Satellites</th>
<th>System Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large OpSats</strong></td>
<td>5000 kg</td>
<td>IRS P6, Yaogan-2, Cosmo-Skymed 1</td>
<td>Mature &amp; “Exquisite” Systems</td>
</tr>
<tr>
<td><strong>Small/Mini Sats</strong></td>
<td>1000 kg</td>
<td>QuickBird-2, KOMPSAT-2, SAR-Lupe 1-5, FormoSat-2</td>
<td>Demo &amp; Emerging Systems</td>
</tr>
<tr>
<td><strong>Micro Sats</strong></td>
<td>200 kg</td>
<td>Beijing-1, TopSat, Lapan-Tubsat, RapidEye 1-5, MOST</td>
<td>Science &amp; Technology Class</td>
</tr>
<tr>
<td><strong>Nano Sats</strong></td>
<td>50 kg</td>
<td>Tiungsat-1, FASTRAC, ThreeCornerSat ST-5</td>
<td>“Experiment” &amp; “University Class”</td>
</tr>
<tr>
<td><strong>Cube Sats</strong></td>
<td>3U</td>
<td>GeneSat CP4, QuakeSat, CanX-2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1U</td>
<td>CanX-2</td>
<td></td>
</tr>
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</table>
JHUAPL — Innovative, Cost-Effective End-to-End Space Missions

- 68 Spacecraft
- Over 150 Sensors and Payloads
- Short time to space
  - Tight requirements process
  - Disciplined development
  - Unparalleled cost/schedule performance
- 150 science grants in progress continuously
- Trusted-agent studies in support of NASA, NOAA, & DoD

**Complexity: No. of Sensors and Mission Type**

- Earth Orbiting
- Solar Orbiting
- Interplanetary

**Recent Examples:**
- 68 Spacecraft
- Over 150 Sensors and Payloads
- Short time to space
- Tight requirements process
- Disciplined development
- Unparalleled cost/schedule performance
- 150 science grants in progress continuously
- Trusted-agent studies in support of NASA, NOAA, & DoD
IF ONLY DOWNSIZING WAS THIS EASY
Military Mission Challenges

- **Responsive Launch**
  - Short design, integration, and testing phases
  - Launch and in operation before mission is over
  - Lower launch cost

- **Coverage**
  - More than 50 CubeSats would be required to achieve continuous/near continuous coverage from LEO
    - Constellation
    - Train Formation
  - Need larger effective field of view
  - Fast and efficient data transmission to the ground

- **Assured Access**
  - Give full control of satellite to commander at any time
  - Ground radio and control system must be manageable and easy to use
Limitations

- **Size constraints**
  - Subsystem requirements are limited by volume
  - Limited area for solar cells
  - Limited amount of power to operate all subsystems
  - Limited room for redundancy in case of component malfunction/failure

- **Attitude control systems**
  - Torque coils and momentum wheels
  - Not as responsive - reducing power generation
  - No propulsion to assist movement

- **Communication**
  - Low power radio – low data rate transmission
  - Radio antenna must fit within size constraint
  - GPS receiver

- **Thermal Control**
  - Meet the temperature ranges required for subsystems

- **COTS**
  - Components often use parts not designed for space environment
Trade Space

(-) Reduced Science or Mission Goals
- Reduced goals due to
  1) Lack of collaboration from same or similar instrument
  2) Lack of multi-spectral information
  3) Decreased number of observations yield reduced reliability in outcomes
  4) Reduced life expectancy
  5) Downlink bandwidth and power constrained
  6) If collaboration is needed between space vehicles the complexity increases

Multi sensor compatibility issues
1) Mechanical such as vibration
2) Electrical (EMI/EMC)
3) Optical field of view
4) Thermal

(+ ) Reduction of Engineering Issues
Engineering optimization through
1) Reduced number of interfaces
2) Opportunity to provide full support to single payload

Trade Space

Reduction of Programmatic Issues
Programmatic concerns lessened
1) Cost and schedule savings (including cost of and time to launch)
2) Reduced programmatic interfaces
3) Increased single sensor functionality and performance

Reduced Complexity
MMBD Fully Qualified Satellite

- Completed Rigorous Testing
  - Thermal Balance
  - Thermal Cycle
  - Mechanical Vibration
  - EMI/EMC
MMBD Challenges

- **Small Spacecraft with a mission**
  - Demonstrate operational military value in 3U form-factor

- **Advanced Concept Technology Demonstration**
  - Develop two ready-to-launch spacecraft
  - ‘Super-high-tech’ development - high level of uncertainty
  - Non-proven concept hardware development
  - No COTS parts qualify

- **Program Management**
  - In-house end-to-end development and support
  - Severe cost and schedule constraints
  - Incite accelerated innovation
  - Carry non-fixed requirements forward
Manifesto for Agile Software Development Published in 2001

- **Individuals and interaction** over processes and tools
- **Working products** over comprehensive documentation
- **Customer collaboration** over contact negotiation
- **Responding to change** over following a plan

http://agilemanifesto.org/
Management Approach

AGILE MANIFESTO

- Individuals and interactions
- Working software
- Customer collaboration
- Responding to change

- Process and tools
- Comprehensive documentation
- Contract negotiation
- Following a plan
Organizational Structure
– promote interactions between individuals

- **Traditional**
  - Approval of tasks often requires many reviews and signatures
  - A method of risk mitigation
  - Appropriate for managing programs with large numbers of members or multiple groups

- **MMBD**
  - Effective in saving time and money
  - Shorter path between managers, engineers, and technicians
  - Faster decision making and approval

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Effective Team - collaborative interface

The Agile Sponsor - Client
- Close working relationship
- Willing to be flexible
- Attend all major reviews
  - Face-to-face meetings
  - Status reviews
- Accessible to all team members
- Aware of all issues
- Provided feedback and direction
- Immediate response to questions - avoiding cost of idle time

Program Manager
- Need to execute decisions rapidly
- High-rank official
- Ability to pull in needed experts or push out not needed personnel

Team Leads
- Responsible for subsystem
- Small, close-knit, self-organizing team
- Highly experienced and able to work in high pressure situations
- Multi-talented, cross functional, interdisciplinary
- Empowerment/authority/responsibility to implement ideas and decisions
- Attention is mainly focused on this aggressive program
- Affiliated from beginning to end of program

Experts – Outside Help
- Brought on and off program for single tasks
- Reputed expert
Co-Location
– promote interactions between individuals

- Open Team Area
  - All deputies in one large room
  - Greatly increases inter-disciplinary knowledge
  - Reduces the number of formal meetings
  - Increases discussions and collaboration
  - Innovative force multiplier

- Spacecraft Development Area
  - Easily accessible from Garden
  - All instruments, tools, and materials needed for end-to-end development
Development Timeline
- emphasis on working system

Traditional:

- Requirements & Concepts
- Design & Development
- Implement & Integration
- Test & Evaluation
- Deployment
- Operations

TIME SCALE

MMBD:

- Requirements & Concepts
- Design & Development
- Implementation & Integration
- Test & Evaluation
- Operations

Non-linear approach
- Emphasis of completing project – not phases
- Execute multiple development phases simultaneously
- Address issues as they come up by priority

Agile Hardware Enablers
- Designs adaptive and flexible to changes
- Quick iterative testing for validation - fit checks, subsystem integration, test runs
- Test boards and subsystems as they are built
Fluidic Scheduling and Tasking  
- respond to change

- Rolling Wave Planning
  - Managed uncertainty
  - Non-linear planning
  - Day-to-day renewed focus based on problems with the highest priority
  - ‘look for trouble’ mentality
  - Sustained project momentum by solving issues as they arise

- SCRUM
  - Organized daily changing task priorities
  - Located at focal point of the meeting room
  - Mapped out most current issues and who/what was being ‘held up’ until it was solved
  - Created urgency and responsibility
1. Use small empowered team with direct link to embedded sponsor.
2. Make each lead have authority and responsibility. Project Manager needs to be figure of authority.
3. Leverage outside help from experts on a ‘as needed’ basis.
4. Co-locate the team for daily review of tasks, issues, cost, and schedule.
5. Use interactive reviews and select reviewers that can contribute and provide input in order to have an effective design review.
6. Tailor processes to the requirements of the project; document the most important work.
7. Analyze and test as early as possible to mitigate issues.
Team