NASA Exploration Systems Enterprise
Request for Information
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Self-constructing / Self-reconfiguring Modular Construction Systems

A White Paper
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1.0 Candidate Technology

Plug-in Creations has developed two robotic self-constructing / self-reconfiguring modular structural systems for orbital and planetary surface structures. Each of the systems can be stored in a compact form for shipping, and deployed into self-leveling rigid structures (Hang & Howe, 2003). The systems are robotic Cubolding (Figure 1), and self-assembling Trigons (Figure 2).

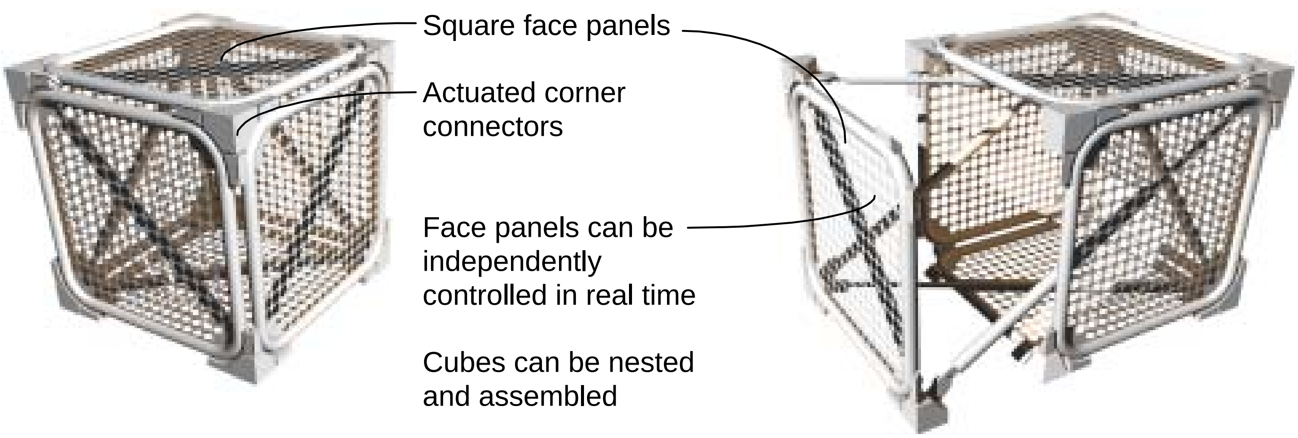

Figure 1: Cubolding system

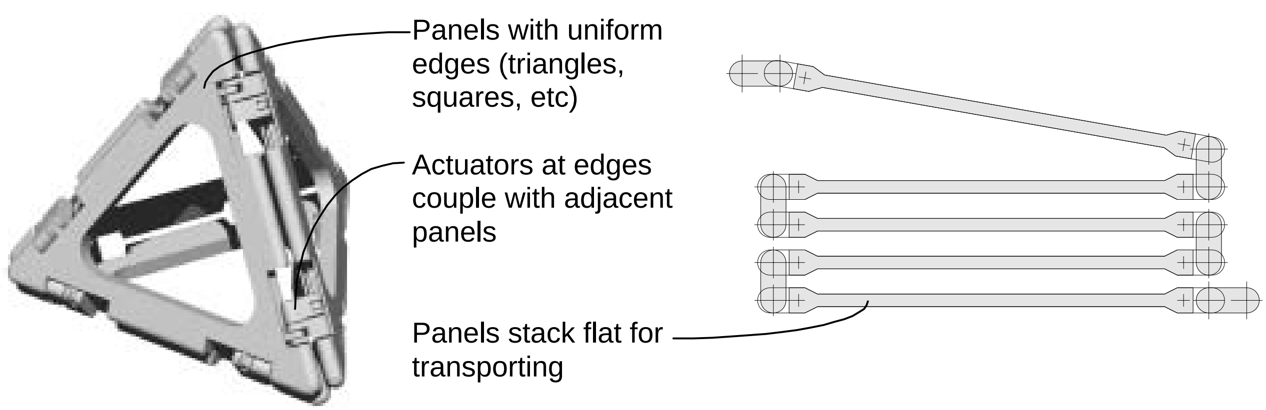

Figure 2: Trigon system

Since both systems are self-constructing / self-reconfiguring, it is possible to define a target structure geometry, and add new modules anywhere in the system, where they will climb already constructed portions to their target positions. However, at this stage the Cubolding system and Trigon system are two independent concepts and are not designed to interface with each other.

2.0 Applications

Two self-constructing / self-reconfiguring “intelligent modular systems” can be used to assemble a variety of orbital or planetary surface structure configurations, according to Kit-of-parts Theory (Howe, 2002). The two systems are discussed in depth:

2.1 Cubolding system: The Cubolding system is a general-use block system that can be used for creating bridges, walls, level platforms, and enclosures. The robotic Cubolding unit consists of six square panels fastened together by two power triangles of actuators. The power triangles are configured in such a way that temporary release of any one square panel from its neighbors will allow the actuators to push it away from the body of the cube. The square panels can individually be pushed away orthogonally, or diagonally on command (Figure 3).

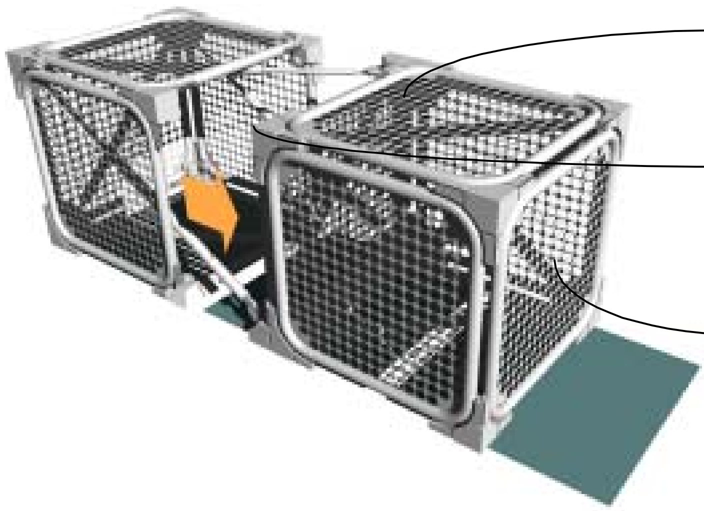

Figure 3: Relocating cube structure units

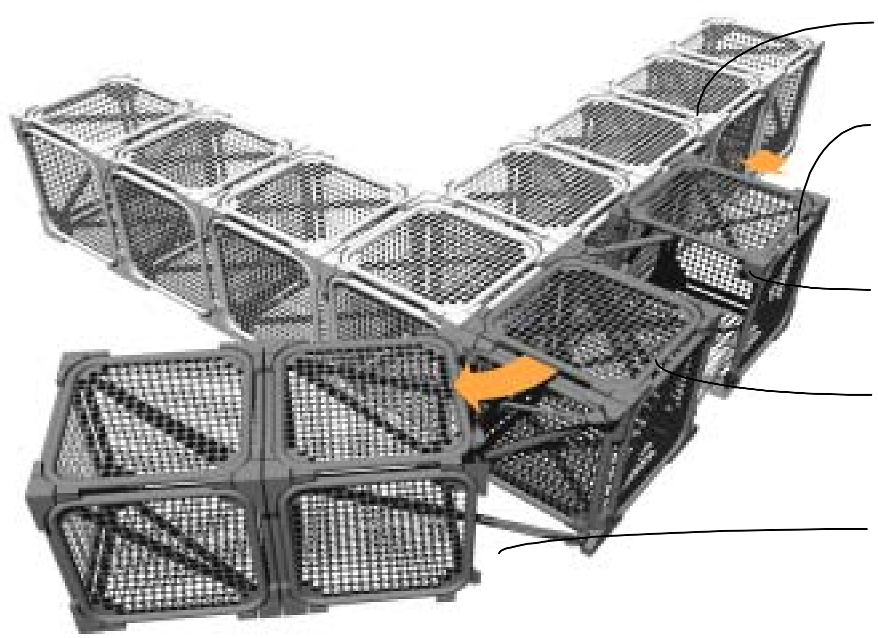

Figure 4: Cube scaffolding units can climb and turn corners

In addition, the cubes are able to clasp or unclasp other cubes that lie squarely adjacent to themselves. This function allows the power triangles to selectively push and pull various faces of the cubes and move along a previously assembled structure in an inchworm fashion. Two or more cubes can be attached to each other in groups for assembly, to provide anchorage for each other in turn (Figure 4).

The assembly groups can be continuously fed onto the structure at any point, whereupon they self-locate along the structure, climbing and turning corners to fill out any desired building configuration (Figure 4). The cubes can be broken down into their component square panels for compact transport. The Cubolding units use electric screw mechanisms for the linear prismatic actuator triangles which are particularly susceptible to wear and tear from dust and particles. In planetary surface constructions, the scaffolding units would need to be carefully designed to protect these mechanisms from wind-borne dust.

2.2 Trigon system: The self-constructing Trigons are similar to the robotic Cubolding units in that they have the capacity to climb previously assembled portions of the structure. The system consists of triangular or square panels that when assembled can create trusses and other structural elements (Figure 5). Computer controlled revolute actuators at the panel edges affect precision motion relative to the panel body, allowing it to swing end over end along the completed structure. As the free end is swung around and approaches the structure surface, the connectors are moved inward. Once the connectors enter the clasping area of the existing structure, an outward pressure is applied and a firm connection is established. At this point the previous fixed end can now release, and the end over end motion is repeated until the panel finds its own place in the uncompleted structure (Figure 6).

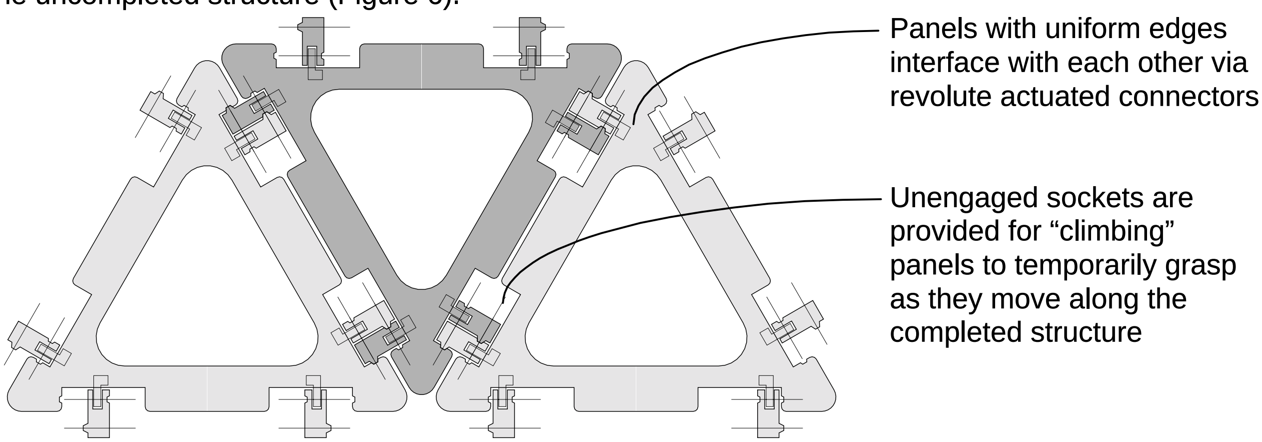

Figure 5: Trigon connection: engaging each other at edges

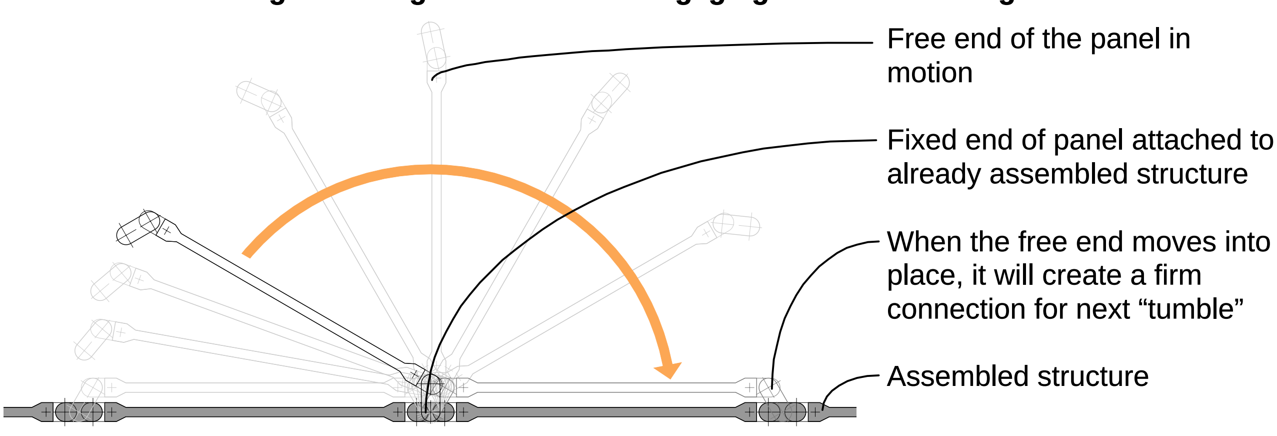

Figure 6: Trigon panels “tumble” along existing structure

An equilateral triangle primitive combined with a square primitive (Figure 7) can be used to create thousands of stable structural configurations (Figure 8). The flexibility of the Trigon system comes from the uniformity of the edge lengths, and the way connection via corners is avoided. This allows pairing or grouping of elements for self-mobility across structures created from a variety of primitives. Other primitives with uniform edge lengths can also be added.

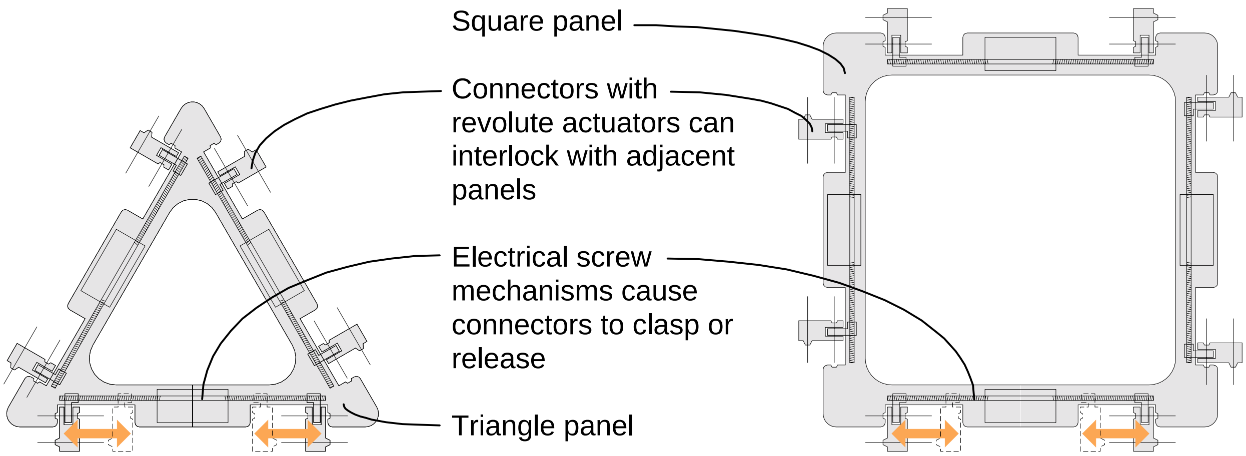

Figure 7: Triangles and squares interface with each other

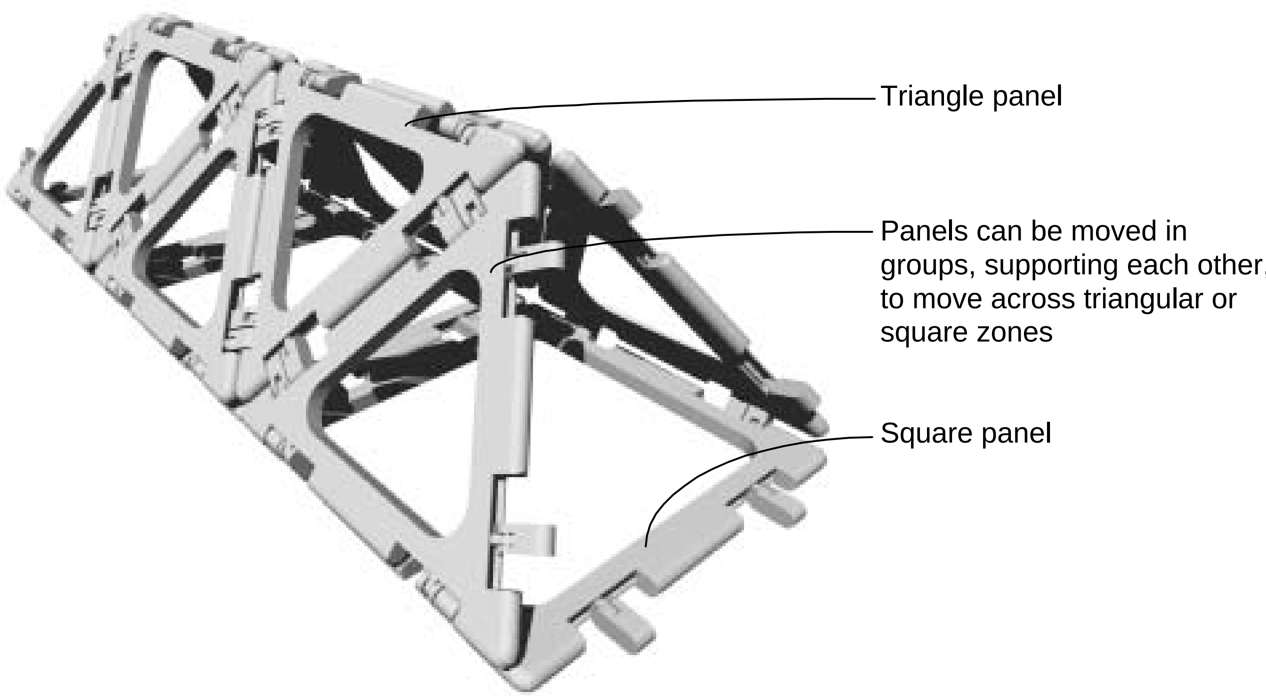

Figure 8: Trigon truss structures

A large variety of geometries for trusses, towers, enclosed volumes, and domes can be constructed with equilateral triangles and squares. Using the stacking ability, the Trigon panels can be pre-assembled into a variety of pre-determined structures and flattened out (with a few key edges temporarily separated). Advanced planning for folding can allow these flattened structures to be stacked into a compact space, and “unfurled” at the time of deployment (Figure 9).

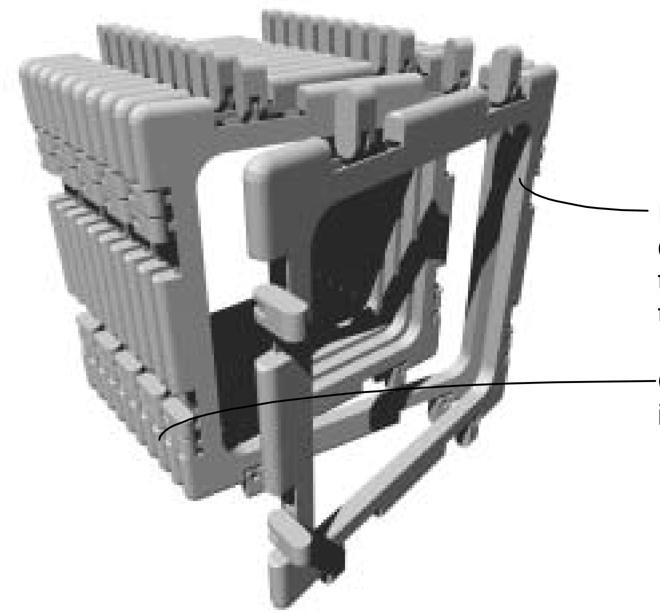

Figure 9: Stackable trigon panels

2.3 Appropriate environments: The Cubolding system could be applied to planetary surface construction projects in a variety of partial Earth gravity environments. The Cubolding system would also be appropriate for use in terrestrial applications.

The Trigon system could be applied to orbital and planetary surface construction projects, in a variety of partial Earth gravity environments, and in terrestrial situations. An additional application that has been proposed is to use the Trigon system as a reconfigurable outer skin having the function of thermal insulation, radiation & impact protection, and structural support for very thin inflatable pressure membrane (Lai & Howe, 2003).

3.0 Relevance to H&RT Strategic Technical Challenges (STCs)

NASA space architects have given a recommended roadmap for technology and development of planetary habitats (Cohen & Kennedy, 1997). The roadmap divides planetary surface construction into three classes, coinciding with a phased schedule for habitation:

- Class I: Pre-integrated hard shell modules ready to use immediately upon delivery.
- Class II: Prefabricated kit-of-parts that is surface assembled after delivery.
- Class III: In-Situ Resource Utilization (ISRU) derived structure with integrated Earth components.

Class I structures are prepared and tested on Earth, and are designed to be fully self-contained habitats that can be delivered to the surface of other planets. In an initial mission to put human explorers on Mars, a Class I habitat would provide the bare minimum habitable facilities when continued support from Earth is not possible.

The Class II structures call for a pre-manufactured kit-of-parts system that has flexible capacity for demountability and reuse. Class II structures can be used to expand the facilities established by the initial Class I habitat, and can allow for the assembly of additional structures either before the crew arrives, or after their occupancy of the pre-integrated habitat.

The purpose of Class III structures is to allow for the construction of additional facilities that would support a larger population, and to develop the capacity for the local production of building materials and structures without the need for resupply from Earth.

To facilitate the development of technology required to implement the three phases, Cohen and Kennedy stress the need to explore robust robotic system concepts that can be used to assist in the construction process, or perform the tasks autonomously. Among other things, the roadmap stresses the need for adapting structural components for robotic assembly, and determining appropriate levels of modularity, assembly, and component packaging. The roadmap also sets the development of experimental construction systems in parallel with components as an important milestone. The Cubolding and Trigon systems fall within the Class II category of prefabricated kit-of-parts concepts. The two systems also provide an automated means for their own assembly (Howe & Howe, 2000).

4.0 Figures of Merit

Performance characteristics of the self-constructing / self-reconfiguring modular construction systems can be evaluated individually based on target geometric configurations and hardware performance.

<u>4.1 Cubolding Performance Metrics:</u> It is proposed that the Cubolding system technology maturity can be measured by the following qualitative capability characteristics:

- Lifting capacity of each cube unit. Cubolding units can only climb existing structure in groups, where the various units in a group “inchworm” across the surface. For this reason, single cube units are required to lift multiple other members of the group. Also, it is possible that cube unit faces and interiors can be fitted out with other equipment, used for material handling and transportation, and have a variety of materials installed on their faces, which could vary the weight and mass of each unit.
- Power consumption of each cube unit. The variety of drivers and actuators employed within the power triangles and corner connectors may have a predictable rate of power consumption, however it may also be possible to fit individual cube units with additional implements and tools that have their own draw of power.
- Speed of construction / assembly. Given a variety of target structure geometries, the balance between speed and accuracy can be evaluated to find optimum construction times.
- Protection against foreign particles and radiation. Since multiple drives and actuators are required for each cube unit to remain an effective construction element, the degree to which the units are protected during operation and idleness will be critical.
- Hardware performance. Statistical analysis of sensors, drivers, actuators, etc will be critical.

<u>4.2 Trigon Performance Metrics:</u> It is proposed that the Trigon system technology maturity can be measured by the following qualitative capability characteristics:

- Lifting capacity of each triangular or square panel. Trigon panels can climb individually if they are moving across structure made up of the same geometry as the climbing panel (triangles on triangle structure, squares on square structure), but must be paired with additional “carrier” panels if there is mixed geometry. In addition, it is possible to fit each panel with additional equipment, implements, and tools that have additional weight and mass.
- Power consumption of each Trigon panel. The variety of drivers and actuators employed within each panel will have a predictable power load, but additional fitted equipment, implements, and tools may have additional power draw.
- Speed of construction / assembly: The balance between erection speed and accuracy can be evaluated to find optimum construction times.

- Protection against foreign particles and radiation: The degree to which Trigon panels and connectors can be protected from dust, radiation, and other foreign influences will need to be evaluated.
- Target geometries. Though a great number of trusses, volumes, domes, etc can be created using a combination of triangular and square panels, some geometries may be difficult or impossible to achieve using climbing panels (there are some configurations that will not allow panels to bridge across or insert themselves). The performance on a variety of structural geometries will need to be evaluated.
- Hardware performance. Statistical analysis of sensors, drivers, actuators, etc will be critical.

5.0 Current State of the Art: Technology Readiness Level (TRL)

Both the Cubolding and Trigon systems are currently at TRL 3 readiness level. Both systems have been modeled computationally and performance measured via computer analysis. Also, a variety of structural target geometries have been conceived and computationally tested with both systems. However, the analysis has been limited to the functionality of individual components in respect to the overall geometry, and limited coordination between groups of components. System-wide performance via object-oriented performance and programming has not been evaluated.

6.0 Assessment of Research and Development Degree of Difficulty

The research and development for the both the Cubolding and Trigon systems is progressing toward the following targets and milestones:

- Manufacture of functional scale components for configurational simulations. R&D3-I
- Fully functional individual element validation in laboratory environment, R&D3-I
- Object-oriented behavioral programming, R&D3-I
- System-wide performance simulations, R&D3-II
- System-wide performance in relevant environment, R&D3-III

7.0 Exit Criteria

Research and development for either of the Cubolding or Trigon systems may be aborted if it becomes apparent that target geometries cannot reliably be achieved, or poor hardware performance creates insurmountable difficulties. Termination may also be considered if it is found that components cannot be protected from dust, foreign particles, or radiation without an unreasonable amount of insulation or shielding.

8.0 Other Relevant Programs

Research on the Cubolding and Trigon systems is currently being conducted by Plug-in Creations Architecture, LLC as part of investigations into Kit-of-parts Theory and component-based building systems for harsh and extreme environments. Plug-in Creations is collaborating with NASA Ames Research Center on the development of self-sustaining robotic ecologies in the form of a "Robosphere" robotic human exploration support infrastructure (Colombano, 2003).

9.0 References

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10.0 Contact information

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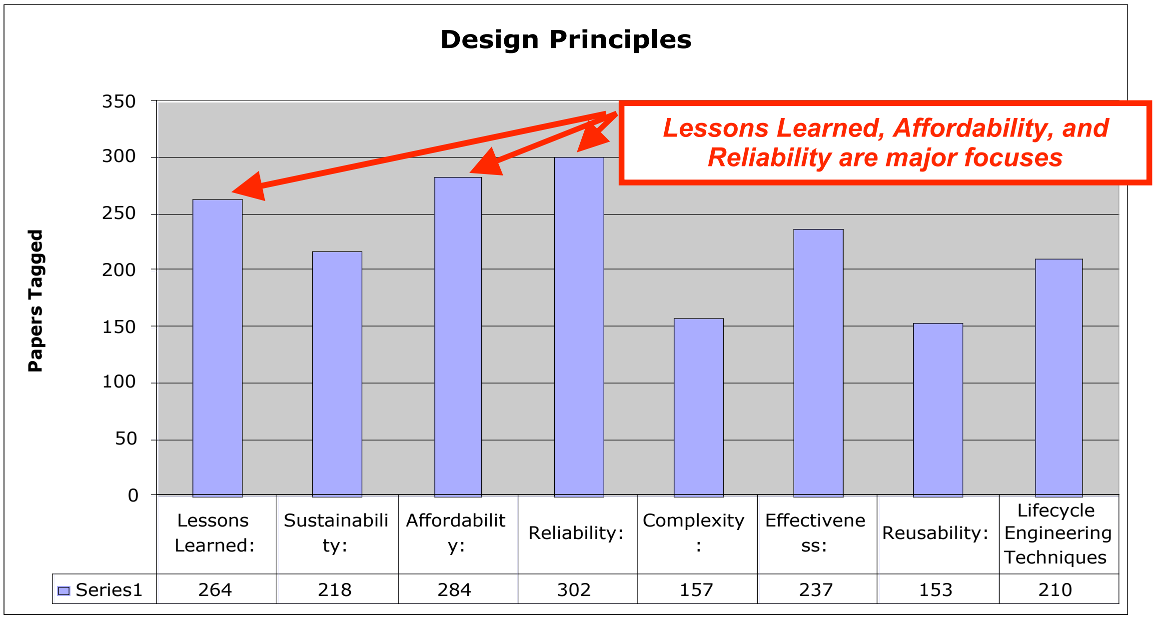
Dear RFI Respondent A. Scott Howe,

Ten weeks ago, you contributed to a crucial first step in NASA's implementation of the Nation's new Vision for Space Exploration. In a broadly-focused Request for Information, the Office of Exploration Systems sought white papers analyzing key technical and programmatic issues relevant to the execution of a sustained campaign of human and robotic exploration of the solar system.

The complement of 998 responses that we received have not only affirmed a high level of external interest in the Vision, but have stimulated and refined our formulation of requirements, technology portfolios, and acquisition strategies. Responses came to us from a diverse array of government research centers, private companies, university research laboratories, student organizations, non-traditional sources ranging from architects to computer game developers, and at least two Nobel Prize winners.

Upon our receipt of the responses, we commenced an evaluation process that judged submissions on their demonstrated effectiveness, innovation, and potential to improve performance in cost, schedule, or risk. In this process, our evaluators also tagged submissions for relevance to multiple RFI focus areas, Work Breakdown Structure (WBS) elements, and technology types. In combination with keyword searches, these evaluation metrics and metadata now support our utilization of RFI contributions for purposes of formulating requirements and program plans.

Generally, we were impressed by the high number of quality submissions provided in the "Program Management" RFI Focus Area, where responses focused on Requirements Formulation, System-of-Systems Development Strategies, and Modeling & Simulation. We noted that a high number of submissions emphasized the importance of lessons-learned, affordability, and reliability in the "Design Principles" Focus Area. Among "Cross-Cutting Design Drivers," respondents cited commonality, autonomy, and mission operations as critical elements of optimal exploration architecture. (See following charts.)


Design Principles
Lessons Learned, Affordability, and Reliability are major focuses
Papers Tagged
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Lessons Learned:
Sustainability:
Affordability:
Reliability:
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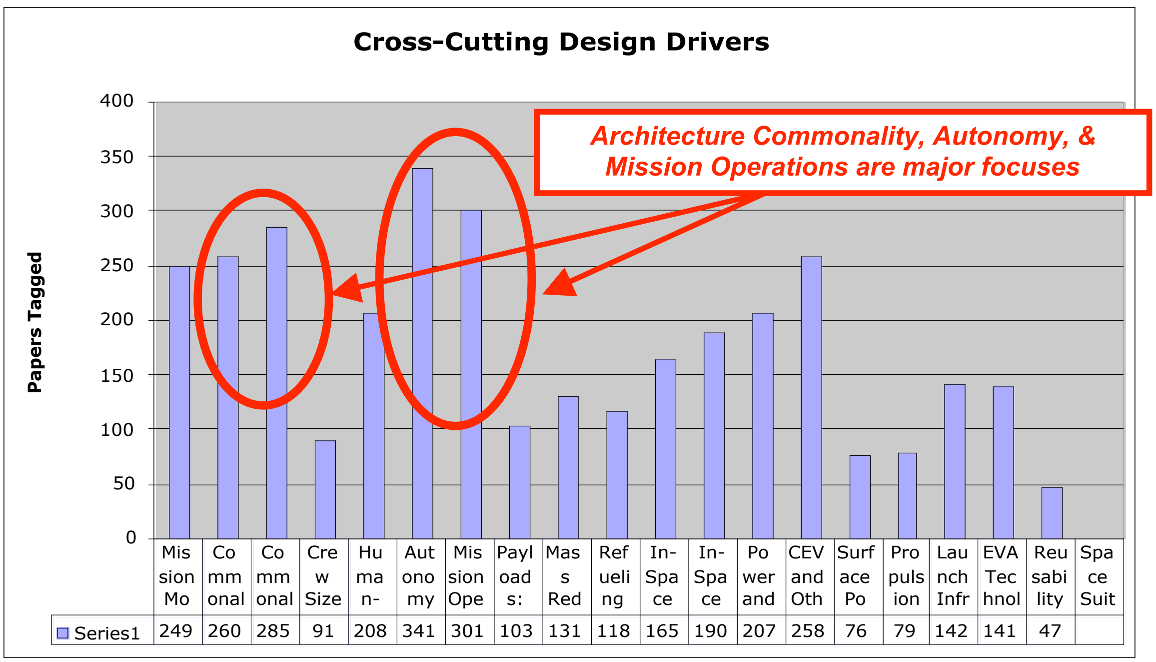
Cross-Cutting Design Drivers
Architecture Commonality, Autonomy, & Mission Operations are major focuses
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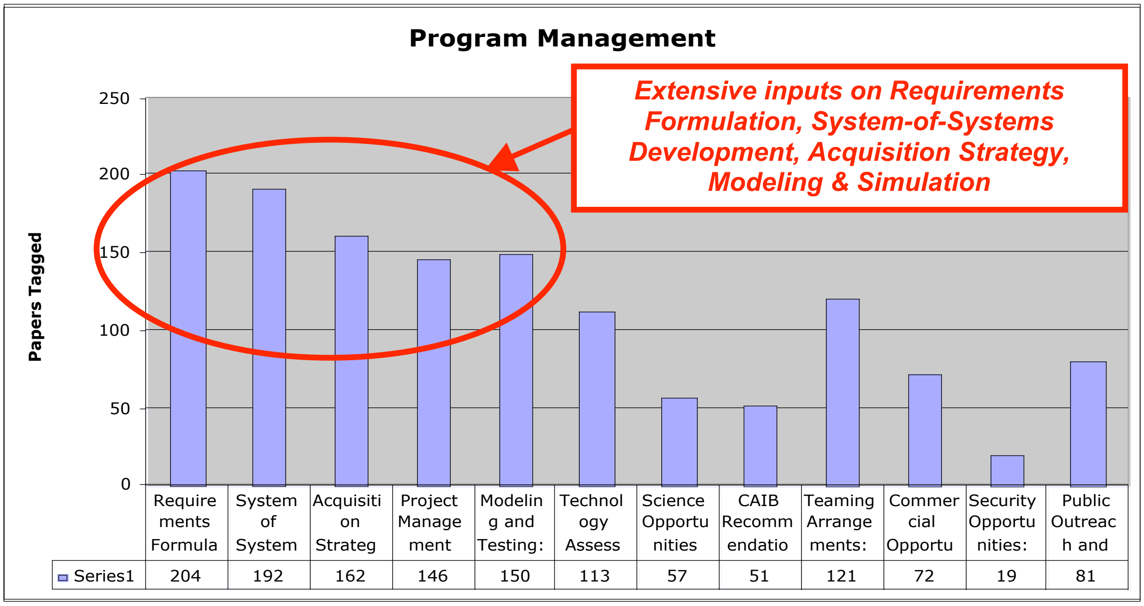

In the evaluation process that concluded in June 2004, your paper, which was submitted in the Crosscutting Design Drivers and Architecture Elements category, received the following scores:

Demonstrated Effectiveness / Technological Maturity: 2
Innovativeness / Variation from Historical Approach: 5
Potential Improvement in Cost, Schedule & Risk: 5

These scores were based on a one- to five-point scoring system, five being the highest possible rank. The scores were compiled based upon comprehensive evaluation guidelines, which can be viewed with other relevant updates on the RFI at the Acquisition Portal of the Exploration Systems website at http://exploration.nasa.gov. While these metrics are a useful piece of metadata that we use in searching our RFI database, they are only one element of the techniques we employ in mining high-value ideas and proposals.

In the coming months, we will be using your RFI response in concert with hundreds of others to inform government analyses and priorities as we bring on an increasingly large population of contractor teams through Broad Agency Announcements and Requests for Proposals. We hope that you will continue to contribute to our nation's implementation of the Vision for Space Exploration by submitting proposals through the mechanisms appropriate to your organization and domain of expertise.

Your input has already served an important role in kick-starting our efforts at NASA, and will continue to be a valuable resource as we proceed. Thank you, and please join us in the years ahead, as we design and build the next generation of systems that will humans and robots on exciting missions to the moon, Mars, and beyond!

Very respectfully,

Craig Steidle
Associate Administrator
Exploration Systems Mission Directorate
NASA Headquarters