High Leverage Technologies for In-Space Assembly of Complex Structures

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In-space assembly (ISA), the ability to build structures in space, has the potential to enable or support a wide range of advanced mission capabilities. Many different individual assembly technologies would be needed in different combinations to serve many mission concepts. The many-to-many relationship between mission needs and technologies makes it difficult to determine exactly which specific technologies should receive priority for development and demonstration. Furthermore, because enabling technologies are still immature, no realistic, near-term design reference mission has been described that would form the basis for flowing down requirements for such development and demonstration. This broad applicability without a single, well-articulated mission makes it difficult to advance the technology all the way to flight readiness. This paper reports on a study that prioritized individual technologies across a broad field of possible missions to determine priority for future technology investment.

Nomenclature

COTS	=	Commerical, off-the-shelf
ISA	=	In Space Assembly
ISS	=	International Space Station
QFD	=	Quality Function Deployment
TRL	=	Technology Readiness Level

I. Introduction

The International Space Station (ISS) demonstrated that assembling structures in space can vastly expand the capabilities of space systems when compared with the single-launch paradigm used in the Apollo program. ISS's approach to in-space assembly involved docking or berthing complex, pre-integrated modules together at standard, nodal interfaces, supplemented by hands-on astronaut labor performing intra- and extra-vehicular activity and directly operating robotic arms.

Next-generation in-space assembly could more closely resemble construction, bringing together simpler, more primitive elements to form contiguous structures that are too large to be launched as single modules packaged into launch shrouds. Structues would be assembled primarily with robots being operated from Earth. Technology for this advanced, in-space assembly (ISA) of large, structural modules has been built upon earlier development work and flight experiments going back to the 1980s[1].

Too often, a new aerospace technology falls into the notorious mid-Technology Readiness Level (TRL) "valley of death" between the time it demonstrates its feasibility and when it has validated its flight readiness by performance in a relevant environment as part of an integrated system. The modest levels of technology-push funding that got it to the functional breadboard stage cannot support the more expensive, extensive testing needed to cross that gap. If the technology can prove its advantages for a high-interest mission, then more generous mission

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funds with well-defined system and environmental requirements can pull it across the valley of death. However, broadly applicable technologies like those needed to enable the next generation of in-space assembled space systems have a difficult time attracting this kind of mission-pull funding.

The technology base for in-space assembly involves dozens of component technologies at various levels of technology readiness. Many future systems, especially future large space telescopes that are still conceptual, will require this technology to enable the next leaps in mission performance, and many others NASA missions could greatly benefit from it. Yet for all its potential, no single mission can justify the investment needed to pull the required technologies across the mid-TRL gap for the benefit of all.

Organizations that have a mandate to advance these generically-useful technologies, like NASA's Space Technology Mission Directorate, seek to know which technology investments are likely to have the highest leverage in supporting future mission capabilities. To answer this question, technology managers at NASA Langley Research Center conducted a study to sort the full set of in-space assembly technologies against the widest spectrum of NASA missions in order to inform investment priorities.

II. Methodology

The methodology selected for this study was the Quality Function Deployment (QFD)[2]. QFD is a standard industrial methodology credited with being key to the quality improvements in the Japanese auto industry in the 1980s. The portion of the QFD method used in this study compares the value of multiple approaches to achieving multiple objectives with consideration for when those approaches are conflicting, synergistic, or non-interacting. Both the approaches and the objectives can themselves be weighted by intrinsic factors, and the weights propagated into the overall assessment.

In the QFD parlance, the desired objectives are called the "WHATs". The approaches to achieving those objectives are called the "HOWs". The center of the QFD analysis is a matrix that deploys the WHATs, listed along the vertical axis, against the HOWs, listed along the horizontal. The compatibility of the various HOWs are assessed in a triangular half-matrix above the list. The relevance of each WHAT and HOW is noted in the body of the matrix. The resultant figure has a characteristic house-like shape and is called "the House of Quality" (Figure 1). This study did not consider the compatibility of the various HOWs in the "roof" of the House of Quality.

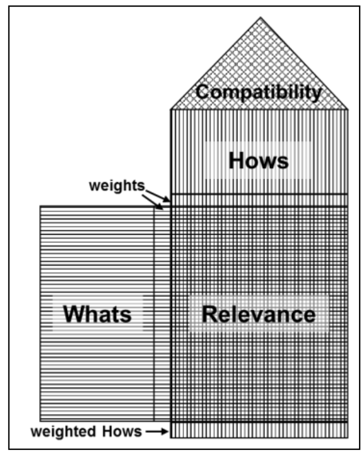

Figure 1: QFD "House of Quality"

The quantitative score for comparing approaches (HOWs) is generated arithmetically by the following generic procedure, which was implemented in this study in an Excel spreadsheet:

1. A weight reflecting the value of an intrinsic quality is assigned to each WHAT and each HOW as appropriate. If multiple intrinsic factors are considered appropriate, they are combined multiplicatively into a single score.
2. An assessment of the relevance of each WHAT to each HOW is made and quantified.
3. The score for each WHAT-HOW pair is the WHAT's weight times its quantified relevance to the particular HOW. This is registered in the matrix in the WHAT's row of the HOW's column.
4. The score for each HOW is the sum of all the WHAT-HOW scores in the HOW's column multiplied by the HOW's weight.

Optimally, the intrinsic weighting factors are based on some market or engineering parameter that is inherently quantified, but the methodology allows the possibility of qualitative assessments that are quantified to allow arithmetic manipulation. That was done in this study and will be described in detail below. The scoring selected for this study was small integer values in the range of 0 or 1 to 4 or 5.

One power of the QFD methodology comes from its ability to handle a sequence of assessments. Once the approaches (HOWs) have been enumerated and quantified, they can become the objectives (WHATs) in a subsequent assessment, with the score from one iteration becoming the intrinsic weighting of the next iteration (Figure 2).

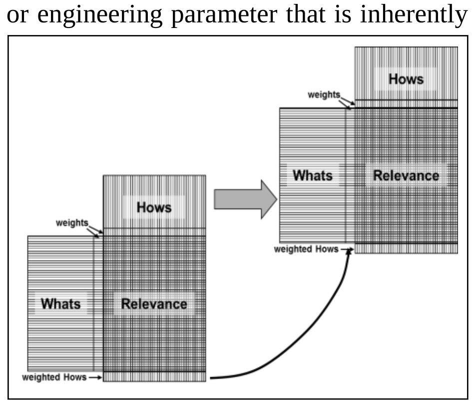

Figure 2: Iterating on the House of Quality

With multiple iterations, the multiplicative nature of the scoring causes some very large numbers. These are not in themselves particularly informative, but they create a helpful dispersion of the results. The multiplication also helps to thin out the space for consideration: any WHAT or HOW that receives a zero intrinsic weight is inherently eliminated from further consideration.

III. The Assessment

The present study used two iterations on the House of Quality, as illustrated in *Figure 3*. In the first iteration, the team surveyed NASA missions that could benefit from in-space assembly, compiled a list of the capabilities needed for ISA, and assessed the relevance of each capability to each mission. In the second iteration, we then compiled a list of the specific technologies that could provide the various capabilities and assessed the relevance of each technology to each capability. Relevance was assessed as either "enabling", "supporting", or irrelevant (unscored). Definitions and scoring of these assessments are shown in Table 1. The result quantified the relevance of each ISA technology to all the idenitified missions.

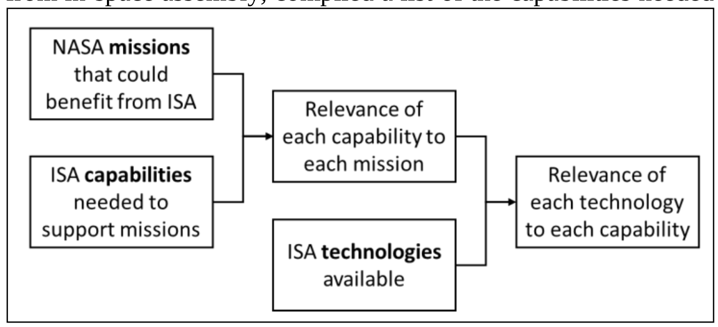

Figure 3: Assessment of relevance of ISA technologies to NASA missions.

Assessment	Definition	Score
Enabling	This WHAT cannot be achieved without this HOW.	2
Supporting	This WHAT can be achieved without this HOW, but it is easier to achieve the WHAT with the HOW.	1

Table 1: Relevance definitions and scoring.

A. Mission - Capability Needs Assessment

Before the missions were enumerated, the team identified two independent, intrinsic weighting criteria:

- Realism / Probability. Certain future missions seem more likely to be eventually fielded based on their importance to NASA, their costs, and their technical feasibility. A Realism / Probability criteria was defined and scores established per Table 2. Missions considered highly unlikely were not included in the assessment. No definitions were articulated for these ratings since there are no objective, quantified probabilities available.[5]
- Mission Timing. The timing of the future mission was also considered important. Missions that were expected to freeze their design concept in the nearer term were considered less likely to take advantage of the technologies, since the technologies are unlikely to be available when needed, but they were considered to have some mission-pull benefits nonetheless. Missions that were unlikely to be fielded before some indefinite future were also considered less intrinsically important for guiding investment decisions, independent of their ultimate probability of being fielded. Thus there is a "sweet spot" in the mid- to long-term that is most likely to drive technology investment priority. Table 3 describes the criteria and scoring. All assessments are relative to the study timeframe, mid 2015.

Mission Systems Realism / Probability	
high	5
medium-high	4
medium	3
medium-low	2
low	1

Table 2: Scoring mission realism / probability

Assessment	Definition	Score
ASAP	mission selection has already occurred OR system concept development is in progress OR mission decision is imminent	2
near term	1 to 5 years in the future	3
mid term	5 to 15 years in the future	4
far term	more than 15 years in the future	3
indefinite future	timeframe is hard to pin down, but it's decades in the future	1

Table 3: Mission System Timing

[5] In the absence of an objective, quantified metric, subjective assessments were made and the quantization needed for arithmetic manipulation was applied *afterwards*.

The mission list and understanding of the needs of the mission systems was based on discussions with subject matter experts; the details are described in the literature[3]. The missions and their scoring are listed in *Table 4*.

Mission Systems	Realism / Probability	Timing	Combined weighting
Exploration Augmentation Module	high	mid term	20
High-definition visible space telescope	low	indefinite future	1
Planet finder occulter	medium	mid term	12
Artificial gravity habitation system	medium	far term	9
In situ resource utilization station (surface)	high	far term	15
Solar electric propulsion	high	near term	15
Sun shade	medium-high	mid term	16
Space dock	medium	far term	9
Repurposed solar array at Mars	medium	mid term	12
Commercial space station	medium-high	near term	12
Long focal length x-ray telescope	medium	far term	9
Far IR observatory	medium	indefinite future	3
Life-finder	medium	far term	9

Table 4: Mission drivers and scoring of their intrinsic importance for technology investments

Against the Mission WHATs are deployed the Capability Need HOWs. A “capability need” is understood as some function that is foreseen as relevant to in-space assembly without consideration for exactly how that function is provided. For example, primary structural members can be secured together by either mechanical connection or welding, so “joining” in some form is captured as a needed capability.

Two intrinsic criteria were identified for these capabilities. They were explicitly assessed for their use in space, including remote operation.

- Technical maturity. Because this assessment seeks to guide NASA investment priorities, capabilities that are already mature were rated lower than capabilities that had achieved an intermediate of maturity. Similarly, capabilities that have not established their feasibility are also rated lower. The criteria and their scoring are provided in Table 5.

Assessment	Definition	Score
conceptual	Approaches to providing this capability are still conceptual.	0
experimental	This capability appears feasible, but applicability questions remain.	3
prototyped	This capability has been demonstrated in a prototype system.	4
demonstrated	This capability has been demonstrated by realistic hardware in a realistic scenario.	1
operational	This capability is already operational.	0

Table 5: Maturity considerations for capability needs

- Availablity without new investment by NASA. Capabilities that are already in development for commercial or Air Force use, for example, are rated lower than capabilities that are more dependent on the type of NASA development activity this study seeks to prioritize. The criteria and their scoring are provided in Table 6.

Assessment	Definition	Score
not available	Current program baselines do not make this capability available in the future.	4
questionable	Based on current plans and expectations, it's not clear that this capability will be available in the future.	3
limited	This capability should be available in the future, but its abilities may be restricted.	2
assured	The capability will unquestionably be available in the future.	0

Table 6: Capability availability without NASA investment

As before, the list of capabilities was generated by discussions with subject matter experts and the details are not presented here. The capabilities and their scoring are listed in Table 7.

The next step in the methodology outlined in Section II is to assess the relevance of each capability need to each mission using the relevance criteria in Table 1. The format of this paper does not permit display of this assessment.

Its result, the fully weighted and scored capabilities (HOWs) is presented in Table 8. For ease of interpretation, these results have been normalized to percentile and arranged in percentile order from largest to smallest.

Capability	Maturity	Availability	Combined weighting
Soft docking / berthing of modules	operational	assured	0
Deployable subsystems	demonstrated	assured	0
Robotic assembly with joining	experimental	not available	12
Long-reach manipulation	demonstrated	limited	2
Modular design	demonstrated	limited	2
Ability to assemble low mass structures	experimental	not available	12
Ability to assemble high strength structures	experimental	not available	12
Ability to assemble high stiffness structures	experimental	not available	12
Ability to assemble structures with micro-stable joints	experimental	not available	12
Ability to assemble structures with high dimensional stability	prototyped	not available	16
Ability to assemble structures with near isothermal control	prototyped	not available	16
Ability to route power and data across assembled joints	experimental	questionable	9
Surface assembly of structures	conceptual	not available	0
Additive manufacturing / welding	experimental	limited	6
Ability to deploy pressure vessels	prototyped	questionable	12
Membrane deployment	operational	assured	0
Extrusion	conceptual	not available	0

Table 7: Capabilities and scoring for their intrinsic maturity and availability

A few unexpected results emerge from this assessment. In particular, the ability to route power and data around constructed joints is almost as essential as constructing the joints. Technology to date has provided several approaches to mechanical joining but neglected other modes of connectivity. Presumably these could be added with harnesses after the structural assembly, but no technology base has emerged to accomplish this robotically. This seems to be a gap.

The assessment also makes clear that high stiffness is important, but high strength is not particularly important. On reflection, this is understandable because most of a conventional spacecraft's structural strength is need to bear launch loads, which structures assembled in space will not experience. However several important applications, especially in astronomical systems, do require high stability in the structure's geometry.

In-Space Assembly Capability	Percentile
Robotic assembly with joining	100
Ability to route power and data across assembled joints	97
Ability to assemble high stiffness structures	73
Ability to assemble low mass structures	71
Ability to deploy pressure vessels	63
Ability to assemble structures with high dimensional stability	58
Ability to assemble high strength structures	38
Ability to assemble structures with near isothermal control	36
Additive manufacturing / welding	32
Ability to assemble structures with micro-stable joints	25
Modular design	22
Long-reach manipulation	18
Soft docking / berthing of modules	0
Deployable subsystems	0
Surface assembly of structures	0
Membrane deployment	0
Extrusion	0
Robotic assembly with joining	0

Table 8: Relative importance of ISA capabilities needed to support high priority NASA missions

B. Capability Needs – Technology Assessment

The second iteration of the House of Quality converts these previous approaches, the capability need HOWs, into the objective WHATs, and considers the specific technology as the approaches (HOWs) to accomplishing those objectives. The numerical scores from the first iteration are carried forward as the intrinsic weightings of the objectives in this second iteration.

Two intrinsic characteristics of these technologies were considered relevant to this assessment.

- Technology readiness for application in space. Presumably low-TRL technology has yet to demonstrate its feasibility, and high-TRL is more appropriate and available for mission-pull funding. Table 9 shows the scoring for this factor. Although it has a lot in common with the "maturity" assessment against the capability needs, it speaks to the specific technology components of a capability and can be assessed against the more rigorous established criteria for TRL.
- Whether the technology is likely to be commercial-off-the-shelf (COTS), and if so, how much investment would be required to convert it to use in space. Although robotic assembly technology is quite mature for ground operations, for example automobile assembly, these systems generally cannot be used "as is" in space applications. Scoring reflects the assumption that adapting existing COTS technology produces better use of NASA's investment than developing something specific for this purpose. Again there is a "sweet spot" reflecting the idea that if the technology can be adapted directly, it may be higher priority than something that requires dedicated investment. The COTS criteria and their scoring are provided in Table 10.

TRL for space	Score
<TRL-3	0
TRL-3, -4	2
TRL-5 to -7	4
>TRL-7	1

Table 9: Scoring TRL for space

Assessment	Definition	Score
none	no commercial technology is directly relevant to this ISA technology	1
little	existing commercial technology would require major modifications to be useful	2
some	existing commercial technology would require significant modifications to be useful	3
good	COTS technology would require some minor, low risk modifications	4
direct	COTS technology can be used with little or no modification	3

Table 10: COTS availability of technology

Discussions with subject matter experts generated a brain-storming list fifty-one component technologies. This list was considered unwieldy. It was culled down by subjective considerations of what technologies were likely to be essential, important, nice to have, and optional for first-generation in-space assembly. An additional category called "cool" was added to capture unique technologies that seemed to have some interesting potential. It included things like fully-autonomous robotic assembly and electron-beam welding. Nice-to-have technologies included such things as deployment of hinged and telescoping members and *in situ* measurement of joint stiffness. The optional category included such things as brazing, bolting, and extrusion. An advanced toolset of the indefinite future would likely contain all the technologies, but for this study, only those thirty considered essential, important, and "cool" were carried forward into the analysis. The assessments are shown in Table 11.

ISA technology	TRL	COTS availability	Combined weighting
robotic assembly using supervised autonomy	TRL-5 to -7	good	16
registration and alignment of components	TRL-5 to -7	good	16
open loop metrology	>TRL-7	direct	3
structurally embedded utilities interfaces	TRL-5 to -7	some	12
incorporation of harness-based utilities	TRL-5 to -7	good	16
fluid cooling interfaces	>TRL-7	good	4
joining by snap-together interfaces	TRL-5 to -7	little	8
joining by combination action	TRL-5 to -7	little	8
adhesive joining / release	TRL-3, -4	good	8
vision metrology using fiducial aids	>TRL-7	direct	3
photogrammetry	TRL-5 to -7	direct	12
proof of joint load capability	TRL-5 to -7	good	16
measurement of structural stiffness	TRL-5 to -7	good	16
measurement of geometric precision	TRL-3, -4	good	8
joint nondestructive evaluation	TRL-3, -4	some	6
buildup from complex stock	TRL-5 to -7	good	16
deconstruction / repurposing	TRL-3, -4	little	4
passive thermal contact interfaces	>TRL-7	direct	3
robotic assembly with full autonomy	<TRL-3	little	0
e-beam welding	>TRL-7	some	3
joining by magnetic latching	TRL-3, -4	some	6
active interfaces within joints	>TRL-7	direct	3
buildup from simple stock	TRL-5 to -7	good	16
buildup from deployable units	TRL-3, -4	some	6
free-form fabrication with metals	TRL-5 to -7	some	12
free-form fabrication with composites	TRL-3, -4	some	6
motor-joint arm	>TRL-7	direct	3
tendon-joint arm	TRL-5 to -7	little	8

Table 11: Technologies and their scoring for TRL and COTS availability

As before, the relevance of each technology to each capability need was assessed but is not shown. The final list of technologies, ranked in order and scored by percentile, is presented in Table 12. (Note: the table order preserves rank distinctions that emerge from the raw scores but are lost in the lower precision percentile scores.)

Rank	Technology	Percentile	Rank	Technology	Percentile
1	simple grasp	100	16	joining by magnetic latching	13
2	incorporation of harness-based utilities	64	17	open loop metrology	13
3	registration and alignment of components	58	18	joint nondestructive evaluation	13
4	robotic assembly using supervised autonomy	53	19	photogrammetry	12
5	buildup from complex stock	48	20	dexterous grasp	12
6	structurally embedded utilities interfaces	42	21	motor-joint arm	9
7	proof of joint load capability	36	22	active interfaces within joints	9
8	buildup from simple stock	33	23	e-beam welding	7
9	joining by snap-together interfaces	27	24	free-form fabrication with metals	4
10	joining by combination action	27	25	vision metrology using fiducial aids	3
11	tendon-joint arm	25	26	fluid cooling interfaces	3
12	measurement of structural stiffness	24	27	passive thermal contact interfaces	3
13	measurement of geometric precision	24	28	free-form fabrication with composites	2
14	buildup from deployable units	21	29	deconstruction / repurposing	1
15	adhesive joining / release	16	30	robotic assembly with full autonomy	0

Table 12: Relative importance of ISA technologies needed to support high priority NASA missions

IV. Discussion

A space-qualified, simple (non-dexterous) grasp (ranked 1) for components emerges from this analysis as the single most high-leverage technology investment by a large margin. It is a ubiquitous, enabling need that is relatively mature and available commercially for easy adaptation to the space environment. In contrast, a dexterous grasp ranked poorly (20), suggesting that there is little need to add that complexity for early applications. Setting the simple grasp technology aside, the top third of the percentile range, that is, technologies scoring between the 64th and 43rd percentile, encompasses a logical set needed to accomplish basic in-space assembly.

The need to incorporate utilities, which emerged as a priority in the first iteration of the House of Quality, is reflected in its priority on this list. Harness-based utilities (2) traded better than structurally embedded utilities (6) because they were assessed as higher TRL and more readily adaptable from COTS sources. This analysis did not include considerations of launch or system mass, which might eventually weigh in favor of embedded utilities, but for a “starter set” of in-space assembly technologies, harness-based utilities seem preferable for their simplicity and adaptability.

Issues of component registration (e.g. jigging) (3) and supervised autonomy (4) are logically next. They are generic technologies that enable almost all activities associated with structural build-up and are in the “sweet spot” for TRL and/or COTS availability. Supervised autonomy[6], which involves humans in the loop remotely but not performing real-time operation, traded better than full autonomy (30) because it is more ready, and because full autonomy is not strictly necessary. Real time remote (ground) operation was not included in the trade space because studies have shown that the communication link delays needed for operation even in low earth orbit can introduce instabilities.

Figure 4: Joining with complex components

Buildup from complex stock (5), where “complex stock” is understood as being made from multiple materials such as a graphite composite shaft attached to metallic ends, as shown in Figure 4, traded better than buildup from simple stock (8) such as tubes or bars that would require joining by an external agent like welding or bolting, and than more complicated mechanical joints (9, 10). Concepts for such complex stock have already been developed and proven in NASA Langley’s lab at the TRL-5 level. Its composite shaft brings stiffness, thermal stability, and low weight, and its metallic ends facilitate joining. Again, this analysis didn’t consider weight or cost. Buildup

[6] Note that EVA astronaut assembly was not included in the trade-space. Although it has been demonstrated in space and may therefore be considered TRL-9, it was ruled out *a priori* as being too costly and dangerous for routine construction.

from simple stock may ultimately prove to be the most cost- and mass-effective, but the advantages of using and joining complex stock seems to be appropriate for this “starter set” of technologies.

Technologies for in-line quality assurance (7, 12, 13, 18), though they received good intrinsic scores (see Table 11), assessed lower primarily because missions that requires the higher precision, strength, and stiffness are longer-term drivers. It was considered that off-line measurements coupled with generous design margins would be adequate for early generation uses.

Technologies for thermal and/or fluid interfaces across joints (26, 27) assessed low because of their technical difficulties and their lack of drivers from near-term missions.

After these preliminary results were generated, several parameters were adjusted to determine the sensitivity of the overall results to the underlying scoring. Although a few items shifted a little, in general, the ranking proved to be robust to these small changes, providing confidence that the details of the assumptions were not critical to the results.

V. Future Investigations

The original intent of the study was to configure a handful of different demonstration experiments and deploy them as the HOWs in a third iteration of the House of Quality against these technologies as WHATs in order to determine an optimal technology demonstration with rigorous traceability all the way back to mission needs. Six different demonstration ideas were generated but events outside the study caused this activity to be terminated before its conclusion. Although there are currently no plans to restart the exercise with a view towards defining such a demonstration, the results could easily be adapted to that need.

It would also be interesting to include the mission needs of other potential users such as the national security space and the commercial communities to test how robust the technology priorities are to the mission set. In particular, the Defense Advanced Research Projects Agency (DARPA) has expressed interest in advancing in-space construction technologies and may be interested in using the QFD tool to investigate which technologies provide high leverage for military needs.

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