Space Science and Technology Partnership Forum: In-Space Assembly Data Collection and Analysis

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The Space Science and Technology Partnership Forum was established in 2015 to identify synergistic efforts and technologies across the government. In-Space Assembly (iSA) is the focus of the topic area that NASA is currently coordinating with other government agencies. This paper focuses on the data collection process, the data analysis of that information, and preliminary insights gleaned from the data. The goal of the analysis is to understand the linkages within the collected data, identifying synergies and gaps, and provide visualization of the current state of iSA needs and capability development across the government. Capability roadmaps, Venn diagrams, bubble charts, and scorecards (an overview of each individual iSA capability) are used to visualize the results of this analysis, which reveals areas of possible inter-agency collaboration, investment gaps in capabilities relative to the need, and capabilities that warrant engagement across multiple agencies to eliminate potential inefficiencies.

I. Introduction

The Space Science and Technology (S&T) Partnership Forum was established in 2015 with participation from the United States Air Force (USAF), the National Air and Space Administration (NASA), and the National Reconnaissance Office (NRO). Seeking to leverage synergies and influence agency portfolios with a focus on key pervasive and game-changing technologies, the S&T Partnership Forum successfully identified and prioritized several

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collaborative topics areas with high potential for future cross-agency work. One of the thirteen collaborative topic areas identified was In-Space Assembly (iSA).

Under the leadership of NASA and the direction of NASA's Office of the Chief Technologist, a team was assembled to focus on the topic area of iSA. An overview of the S&T iSA facilitation and analysis team's efforts to establish a value proposition, develop a strategic framework, and assess of capability needs leveraging data collected from the S&T Partnership Forum and other government stakeholders, inclusive of the affiliate partners is detailed in *Williams et al. (2018).* [1]

This paper describes the iSA data collection and analysis process that the NASA-led facilitation and analysis team implemented. Data were collected from the S&T Partnership Forum and other government stakeholders on the iSA capabilities, or the lower level functions that combine to perform tasks to assemble a system. The origin of the iSA capabilities is discussed in *Williams et al. (2018).* [1] Data were also collected on operational missions, which are the future missions where iSA capabilities are applied, such as a large aperture telescope or artificial gravity habitat. Technology demonstration missions, or flight missions where iSA capabilities are demonstrated, as well as technology development activities, or ground activities performed to advance a given capability or sets of capabilities, were also included in the collected data set.

The data analysis performed by the facilitation and analysis team consists of a mapping between the various types of data – capabilities, operational concepts, technology demonstration missions, and technology demonstration activities – with the intention to identify connections between activities, missions, and needs. Relational database-style tables, capability roadmaps, and data visualization techniques were leveraged to capture the many-to-many relationships between the data types and to visualize the intersection of activities. Examples of the resulting capability roadmaps and visualizations containing notional data are presented in this paper. Finally, this paper contains some initial insights gleaned from the data analysis process. A more detailed analysis of joint-demonstration concepts, including a quantification of the joint priorities of the participating agencies' needs and an assessment of the readiness of existing or expected in-space venues to support demonstrations, is presented in *Hamill et al. (2018)*. [2]

II. S&T Partnership Analysis Overview

An overview of the data collection and analysis framework is depicted in Figure 1, which shows the connections among the data, analysis results, and decision support.

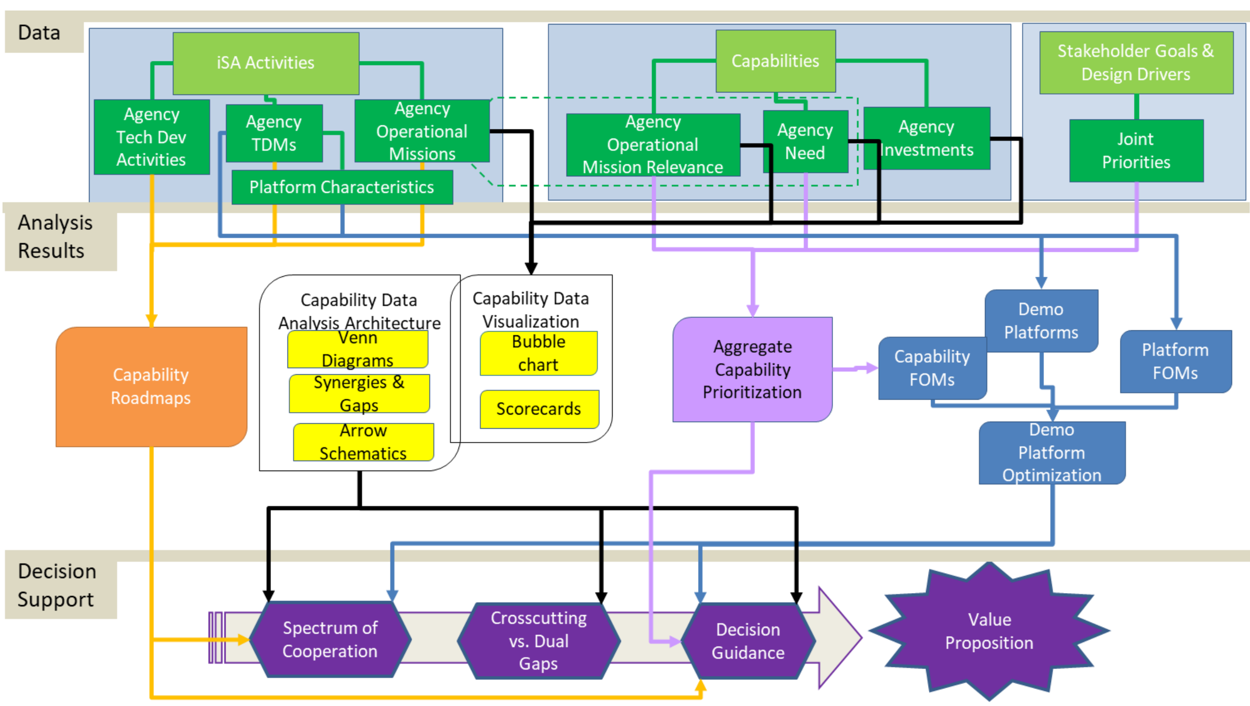

Figure 1: Flow diagram for analyses performed in support of the in-space assembly S&T Partnership.

A. Data

Two interagency technical interchange meetings with the S&T Partners and several follow-on exchanges were held to obtain data for the analyses, including details about proposed operational missions with related capability needs, ongoing technology development activities, planned technology demonstration missions, and capability investments. As shown by the organization (in light green boxes) at the top of Figure 1, the data can be grouped into three broad categories: in-space assembly activities, in-space assembly capabilities, and the S&T Partnership stakeholder goals and iSA design drivers. For the category of in-space assembly activities, input data received from the S&T Partnership agencies for iSA activities fell into one of the following three categories:

- Operational Mission: a current or future mission where the iSA capabilities are applied to perform a mission (e.g. large telescope, artificial gravity habitat).
- Technology Demonstration Mission (TDM): flight mission where iSA capabilities are demonstrated (e.g. Restore-L). For the TDMs, data were also obtained on technical attributes of each TDM or demonstration platform, and those attributes, such as its planned capabilities and limitations, were incorporated as input for the analysis described in *Hamill et al.* (2018). [2]
- Technology Development Activity: ground-based activity performed to advance a given capability or set of capabilities (e.g. specific technologies like manipulators/robotics, algorithms for autonomous operations).

The second broad category of the data used in the analyses was the iSA capability need. To provide a common framework for analysis and activities across the different agencies, the team developed and refined a comprehensive list of the technical functional capabilities that would be needed by the variety of in-space assembly applications. These capability needs were sorted into fourteen functional categories. The capability categories and individual capability needs are enumerated in *Williams et al. (2018)*. [1] For the list of over 40 individual capability needs, two qualitative attributes were assigned for each agency relating a given capability need to the agency's operational missions: agency operational mission relevance and agency need. These attributes are described in later sections of this paper. Each agency also assigned a third qualitative attribute for agency investments in each capability need, and later sections of this paper describe this assignment and its incorporation into the analysis in further detail.

In addition to the iSA capabilities, the third overall data category of stakeholder goals and Tier 1 design drivers was defined during the first Technical Interchange Meeting (TIM) with the agency partners. The stakeholder goals communicate long-term performance targets for the S&T Partnership Forum stakeholders. A design driver is a particular property or application of a concept that serves as the rationale for the concept's design to achieve its objective. At the TIM, five were designated Tier 1 design drivers, represented as the highest rated demonstration objectives. *Williams et al. (2018)* [1] lists and describes the four stakeholder goals and five Tier 1 design drivers. At a second TIM, each of the capability needs was assessed collectively by the participants on the degree to which it supported each of the five stakeholders and the four Tier 1 design drivers using an ordinal scale. Those assessments were a subset of the third data category and designated as joint priorities, as shown in Figure 1, and served as inputs for the aggregate capability prioritization analysis in *Hamill et al. (2018)*. [2]

B. Analysis Results

The collected data were used to feed multiple analyses depicted in the middle of Figure 1. The results of the multiple analyses are grouped into the four areas of capability roadmaps, capability data analysis architecture & visualization, aggregate capability prioritization, and demonstration platform assessment and optimization, which are shown in Figure 1 as the orange, yellow, purple, and blue boxes, respectively. Similarly, Figure 1 shows the linkages between data input and analysis results as color-coded lines, and those linkages are also summarized in Table 1.

Table 1: iSA Data Inputs for Analysis Results

		Data						
		iSA Activities			Capabilities			Stakeholder Goals & Design Drivers
		Agency Technology Development Activity	Agency TDM	Agency Operational Mission	Agency Operational Mission Relevance	Agency Need	Agency Investments	Joint Priorities
Analysis Results	Capability Roadmaps	●	●	●				
	Capability Data Analysis Architecture & Visualization			●	●	●	●	
	Aggregate Capability Prioritization *Hamill et al. (2018)*				●	●		●
	Demo Platform Assessment & Optimization *Hamill et al. (2018)*		●					●

This paper focuses on the data within the relational database-style tables, capability roadmaps, applied data analysis architecture, and data visualization techniques, represented as the orange and yellow boxes in Figure 1, that were leveraged to capture the many-to-many relationships between the data types and to visualize the intersection of activities. The goals of these analyses were to: (1) show the current landscape of in-space assembly across the government partners via the specific technology development activities and TDMs planned across those agencies and (2) understand the current state of play for iSA within the government and find capability synergies and gaps across the partnership agencies. To that end, the analysis team investigated several approaches for sorting, grouping, and visualizing the analysis results from the multiple agency partners.

Hamill et al. (2018) [2] has a detailed discussion of the results of the aggregate capability prioritization and platform assessment and optimization analyses that were conducted to investigate the potential applicability of planned technology demonstration mission systems to perform additional near-term iSA capability demonstrations, with a focus on high priority capabilities. The aggregate capability prioritization and demonstration platform assessment and optimization activities (purple and blue boxes and lines in Figure 1) relied on data from the initial data set, and the prioritization results also fed directly into the platform assessments.

C. Decision Support

Finally, Figure 1 also presents how the multiple analyses provided by the analysis team feed into the decision support for the S&T Partnership Forum. Results of the analyses will be used to help shape recommendations to the S&T Partnership on options for executing joint demonstrations and maximizing opportunities for collaboration to more effectively advance iSA and deliver the value to the Partnership agencies discussed in *Williams et al. (2018)*. [1]

III. Data Collection and Storage

The data to accomplish the analysis objectives for this paper were collected from and/or validated by S&T partnership representatives with specific knowledge of each of their agency's mission needs, program plans, and technology investments. As described above and shown in Table 1, two major sets of data were collected for this analysis: information to identify and characterize the various iSA activities within the agencies and information to enumerate and assess the relevance and investments of the various technical functional capabilities that are needed to support in-space assembly. Information from the Stakeholder Goals & Design Drivers (third data category in Table 1) guided the aggregate capability prioritization and demonstration platform optimization analyses in *Hamill et al*. (2018). [2]

Within meetings, discussions, and focused interviews, each of the participating organizations identified planned operational missions relating to in-space assembly. Combined, Air Force, Defense Advanced Research Projects Agency (DARPA), and NASA identified a set of thirteen operational missions within this area. Each organization first compared their operational missions against the list of capability needs and then identified: (1) the degree to which the capability needs were relevant to the operational missions and (2) qualitatively whether the organization is investing in technologies to develop the capability.

For the relevance to operational mission and organizations, each organization rated all the capabilities against each operational mission as one of the following:

- <u>Enabling</u>: the particular capability is required for the particular mission;
- <u>Supporting</u>: the particular capability is not required for the particular mission but would improve its performance, cost, or other important consideration; or
- <u>Not applicable</u> (N/A): the particular capability is not relevant to the particular mission.

Similarly, each organization also assigned a qualitative rating for its current level of investment in each capability as one of the following: Significant, Some, or None.

Once data are elicited from partners it requires storage in a manner that supports future analysis. The goal of the analysis is to understand the linkages within the collected data, identify synergies and gaps, and provide visualization of the current state of iSA needs and capability development across the government. Therefore, a relational database is used as the storage schema as it supports the use of modern data analysis techniques including sorting, grouping, and pivoting. This schema, implemented in *Microsoft Excel* and the *pandas* package in *Python*, also supports the types of mappings (many-to-many, many-to-one, etc.) that appear in the collected data. The following discusses how data are stored and how relationships are captured.

The collected data are stored in two types of tables: data storage tables and mapping tables. The data storage tables contain aspects of iSA data elicited from partners as shown in Figure 2. Each of the categories of data collected from the partners has its own table with relevant information and data source tracking where appropriate.

Figure 2: Data Storage Tables

The relationships between these elements are captured in mapping tables. The mapping tables are comprised of elements from two data storage tables and capture the relationships between them. The aspect of the relationship of interest varies with the pair of data elements selected. For example, the Capabilities-Concepts mapping table documents the level of dependency of each concept on each of the capabilities (“Enabling,” “Supporting,” or “N/A”) while the Partners-Capabilities table documents the qualitative relative investment that each partner is currently expending to develop each capability (“Significant,” “Some,” or “None”). These two particular tables are also used to generate the bubble charts and scorecards discussed in following sections.

Figure 3 displays these mapping relationships graphically. Each of the arrows is labeled to clarify the relationship between the two data table elements. For example, the Concepts-Capabilities mapping table stores the strength of the dependency each concept has on each capability.

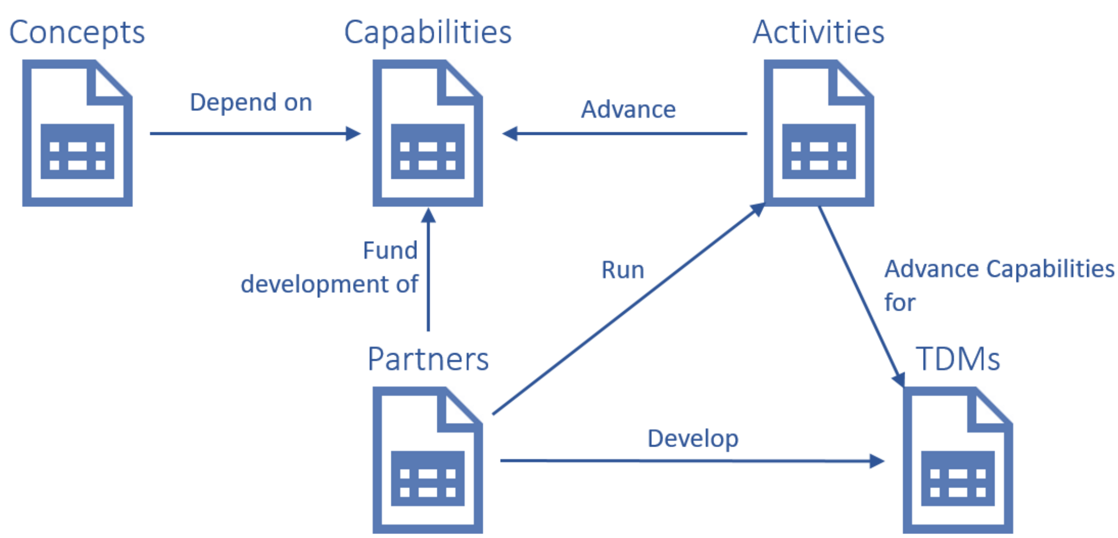

Figure 3: Data Mapping Tables

These relational mappings are useful for analysis because they provide the links between disparate aspects of iSA. The user can start at any point in a data storage table and discover the types and strengths of relationships with other data tables. A partner interested in developing a particular operational mission can see which capabilities that concept is dependent on, which other agencies are investing in those capabilities, and which upcoming technology demonstration missions could be supported to speed the development of needed capabilities. The capability roadmaps, bubble charts, and scorecards discussed in the following sections all rely on these data products to generate their visualizations.

IV. Capability Roadmap

Visualizing the current landscape of iSA across the government uses a roadmap that incorporates all of the data provided by the partners, including the technology development activities, planned TDMs, and capabilities/operational missions that those activities support. The capability roadmap visualizations use the *bokeh* data visualization package in *Python* to extract data from the relational database and create the capability roadmap visualization.

An example layout of the capability roadmap with notional data is presented in Figure 4. This visualization can be sorted and changed to visualize different slices through the data. A common use case is to present all of the technology development activities, TDMs, and potential operational mission needs for each capability area. Other groupings can be achieved when it is desired (e.g. sort by partner). The Preliminary Design Review (PDR), launch, and operational dates for each TDM and the technology development activities are presented chronologically on the capability roadmap. In production, the capability roadmaps contain hover text that includes, for each TDM or technology development activity, more information such as a description or an indication of which partner is funding the activity/mission. TDMs and activities are color coded to the partner that is running it, and the operational missions that the given capability area supports or enables are included.

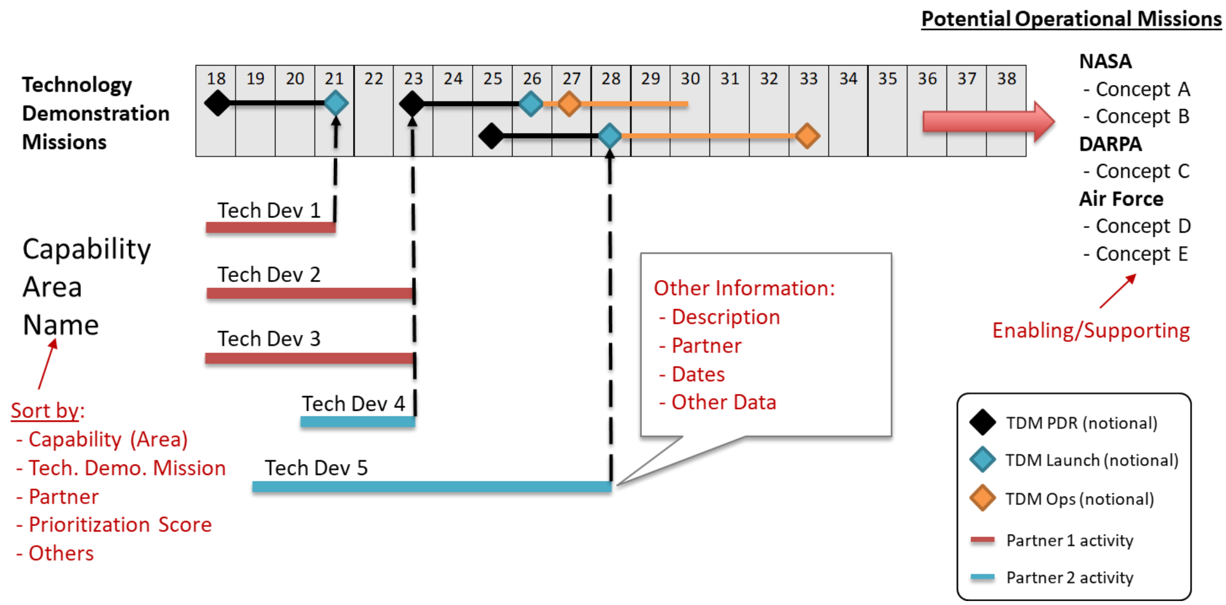

Figure 4: Example Capability Roadmap with Notional Data

This type of visualization can lead to pointed questions, such as:

- "Are these technology development activities sufficient to develop the given capabilities needed for the future operational missions?"
- "Can two agencies collaborate on their respective technology development activities to provide more value to the government?"

Answering the first question would indicate if the current and planned technology development activities are sufficient to achieve the needed iSA capabilities, or if government and industry should pursue additional technology development activities. Answering the second question ensures that government resources are being spent efficiently to achieve the goal of using iSA in operational missions.

V. Data Analysis

One of the primary objectives of the data analysis was to determine the synergies and gaps in activities across the government. The important data to determine synergies and gaps are the operational mission needs (Capabilities-Concepts mapping) and agency funding for each capability (Capabilities-Partner mapping). This information has been represented in a bubble chart to show, across all of the capabilities, where there are potential synergies and gaps. The partners can then explore more information using Venn diagrams and scorecards to present the lower-level data.

A. Displaying Aggregate Data in Bubble Charts

From the operational mission need and agency funding data, bubble charts were produced to reveal relationships between agency need and investment. First, the commonality of relevance of each capability need to the three partners was categorized into four groups:

- Crosscutting: all three of the partners identified the capability need as either enabling or supporting one of its operational missions;
- Bilateral: two of the three partners identified the capability need as either enabling or supporting one of its operational missions;
- Unilateral: only one partner identified the capability need as either enabling or supporting to one of its operational missions; and
- No Need: none of the partners identified the capability need as either enabling or supporting one of its operational missions, i.e., all of the partners identified the capability need as not applicable to their operational missions.

Similarly, the commonality of the level of investments in each capability by the three partners was categorized into four groups:

- Common Investments Among Agencies: all three of the partners identified as investing in the development of the capability need;
- Dual Agency Investment: two of the three partners identified as investing in the development of the capability need;
- Single Agency Investment: only one partner identified as investing in the development of the capability need; and
- No Investment: none of the partners identified as investing in the development of the capability need.

A Venn diagram, such as the one in Figure 5, is a useful tool to understand these commonalities. Assuming that the Venn diagram has been created based on the needs of the agencies, the red circle represents the set of all capabilities enabling or supporting Agency 1's operational missions. Crosscutting capabilities would belong in section G of the Venn diagram, as they are enabling or supporting to all agencies. Sections D, E, and F of the diagram would contain the capabilities of Bilateral Need, and the Unilateral Need capabilities would fall into section A, B, or C of the Venn diagram.

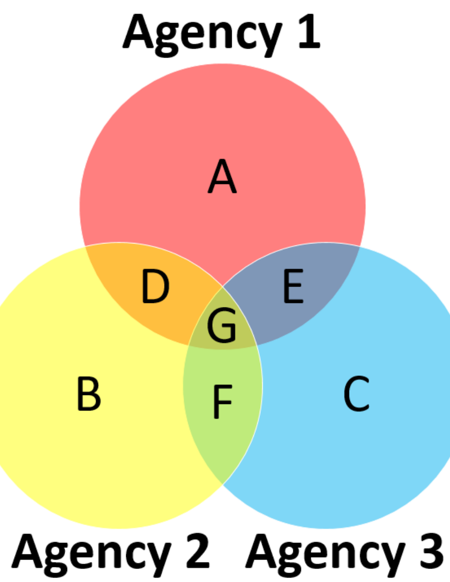

Figure 5: Venn Diagram for Need or Investment across the Partners

The same Venn diagram can also be used to explain the investment level commonalities. Now assume that Figure 5 diagrams agency investments, where the red circle represents the set of capabilities in which Agency 1 has a medium or high investment. Under this new assumption, capabilities invested in by all three agencies would belong in section G of the Venn diagram and would be labeled Common Investments Among Agencies. Sections D, E, and F would be comprised of capabilities of the Dual Agency Investment group. Single Agency Investment capabilities would be located in section A, B, or C of the Venn diagram.

The sections of the Venn diagram correspond to portions of the bubble chart, as shown by the labels next to the axes in Figure 6. The bubble chart plots agency need along the y-axis against agency investment along the x-axis. The values on the y-axis of the bubble chart have three letters, each signifying the agency need of one partner. Agency need is defined as the highest level of need across all operational missions for a given agency. For example, if Agency 1 identified four operational missions and listed a capability as enabling to two missions and supporting of the remaining two missions, then Agency 1's agency need value for that capability would be enabling ("E"), as it is the highest level of need. If Agency 2's agency need for the same capability was supporting ("S"), and Agency 3 determined that the capability was not applicable to any of their operational missions ("N"), that capability's y-value would be "ESN." The letters are not ordered by agency name on the bubble chart; an ordered "SEN" and "ESN" would both be plotted as "ESN." Likewise, the values on the x-axis are also three letters, though each letter stands for one agency's level of investment in a capability. A value of "HMN," for example, indicates that one agency has a high investment in the capability (corresponding to "Significant," as labeled previously), another has a medium investment (corresponding to "Some," as labeled previously), and the third has no investment.

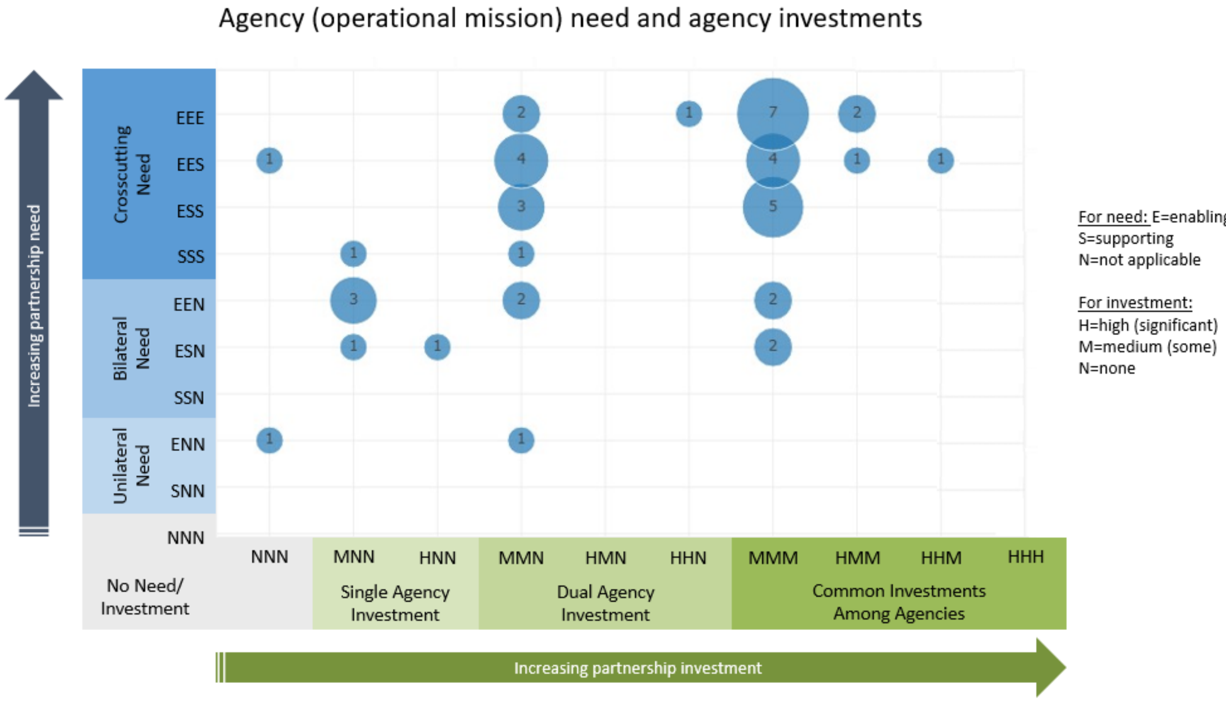

Figure 6: Bubble Chart Representing Need and Investment of iSA Capabilities

Finally, the bubbles were plotted. The size of each bubble increases with the number of capabilities located at the given intersection of the agency need and level of investment. The number of capabilities is also represented as the number in the bubble. For example, three capabilities were marked as "ESS" (a Crosscutting need) on the agency need axis and "MMN" (Dual Agency Investment) on the investment axis.

Next, areas of the bubble chart were categorized into regions of potential collaboration (synergies), gaps, and other groupings for the government development of capabilities. Figure 7 presents one way of defining regions of the bubble chart. The darkest green shaded area in the upper right corner of the chart is the region with the highest potential for collaboration among the partners, as the capabilities represented by the bubbles in this region are of Crosscutting need and Common Investment Among Agencies. The lighter green region highlights the next level of capabilities for partners to collaborate on developing, for at least two agencies have a need for the capabilities and an investment in them. Gaps in development are in the yellow region in the upper left corner. These capabilities have low investment ("Single Agency" or "None") but high need by the partners. The blue region in the lower left corner defines the capabilities that have the lowest need and the lowest investment. The red region in the lower right corner consists of the capabilities with the lowest need and highest investment, which would be areas to investigate for possible inefficiencies in government development of capabilities. It is worth noting that no capabilities in the dataset fall in this red region. Finally, in the purple area between the low need, low investment and possible inefficiencies regions, there is one capability, which could be categorized as redundant if the partners who expressed no need for it have a medium investment in its development; however, if the agency for whom it was an enabling need has an investment in it, it could be considered low need, low investment. The classification of capabilities in this area depends on context, which is depicted in the form of the overlap of the low need, low investment and possible inefficiencies regions.

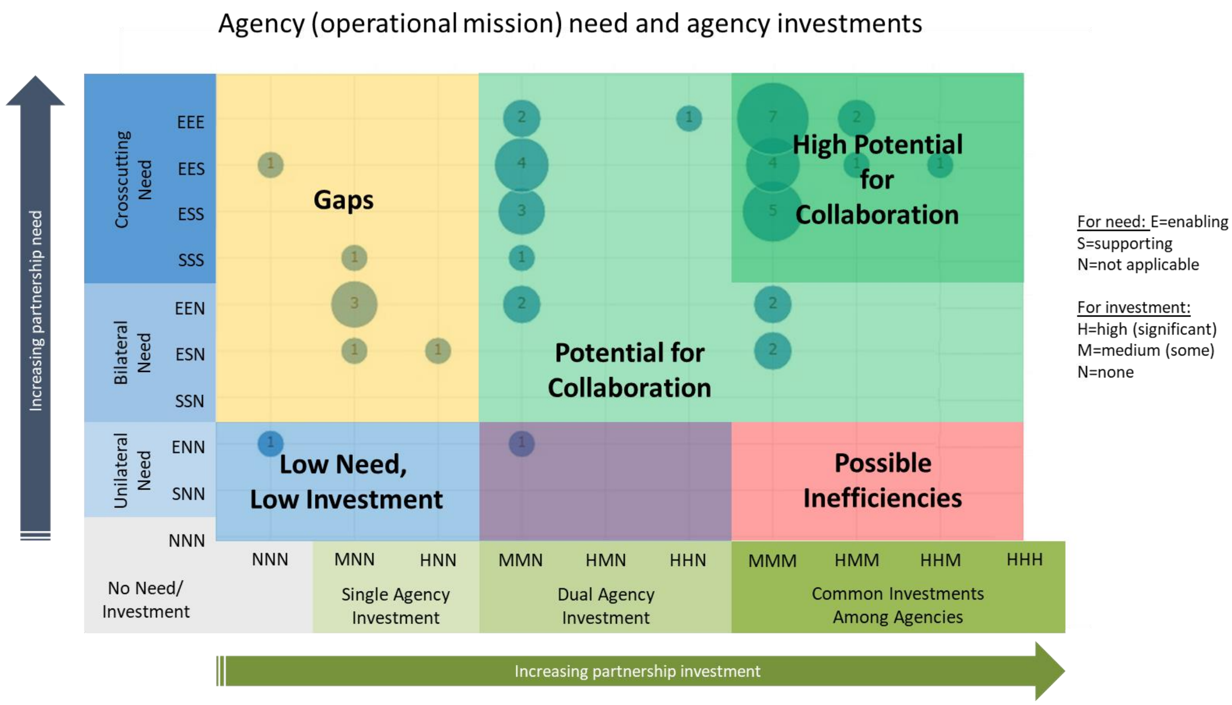

Figure 7: Bubble Chart with Highlighted Regions of Synergies and Gaps

As Figure 7 shows, nearly half of the capabilities lie in the region with high potential for collaboration, and 37 are in the green regions in total. This indicates that the agencies in the partnership can collaborate on and use most of the capabilities for iSA. It's also worth noting that seven capabilities fall in the Gaps region, indicating that certain partners desire a capability for their future operational missions, but are unable to contribute to them at this time.

Bubble charts are also used to visualize the other analyses completed by the facilitation and analysis team. As an example, Figure 8 displays a bubble chart that incorporates the capability prioritization analysis described in detail in *Hamill et al. (2018)*. [2] The result of this process was a list of the top 20 capabilities based on their support of stakeholder goals and how many operational missions they enable, among other criteria. In Figure 8, bubbles were colored purple if the capabilities that they represent were among the 20 highest priority capability needs. The blue bubbles represent the remaining capability needs. Note that all twenty of the prioritized capabilities lie within the Potential for Collaboration region of the bubble chart, with fourteen actually falling within the High Potential for Collaboration region. These prioritized capabilities will guide how decision makers structure their technology development portfolios, and will help determine activities across the members of the S&T partnership.

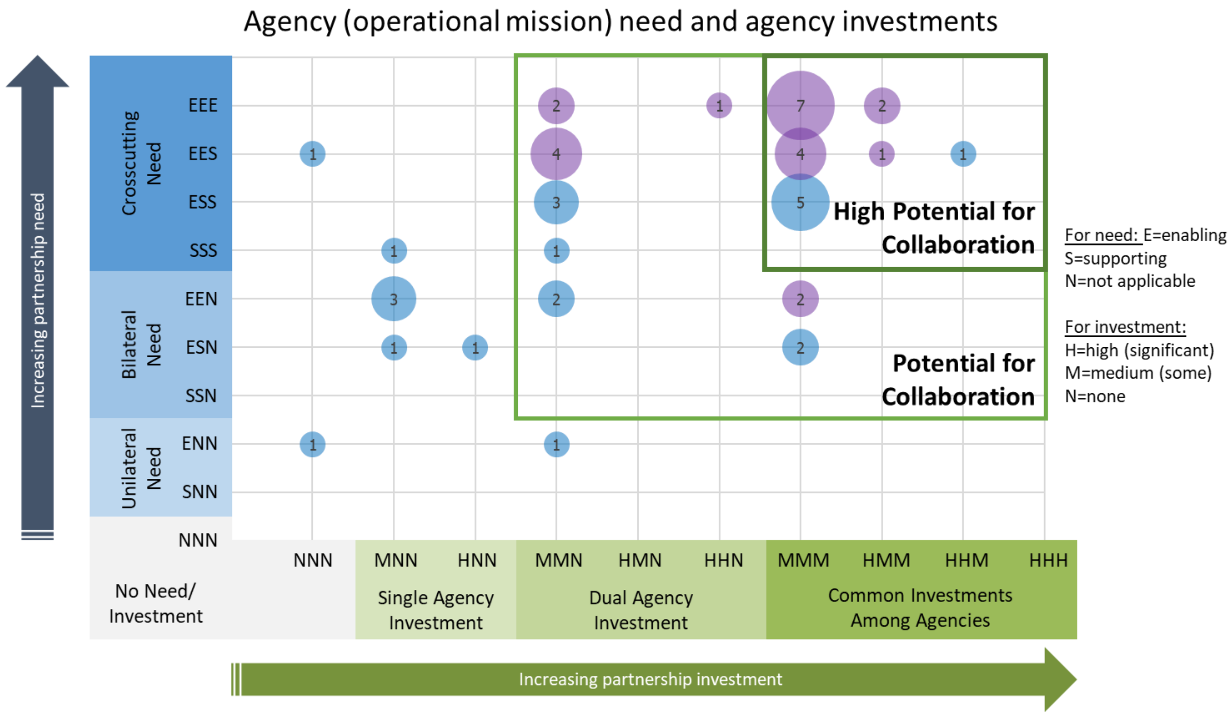

Figure 8: Bubble Chart with Highlighted High-Priority Capabilities (see Hamill et al.) [2]

B. Displaying Individual Capability Data in Scorecards

Bubble charts provide a high-level view of the relationship between the needs and funding levels for capabilities in aggregate. A more detailed view of the capabilities in each classification is provided in a compact but detail-rich abstraction termed a scorecard. Scorecards show detail on what each capability is and what the relationships are between the capability and the partners' needs and funding levels. These scorecards are generated using *Python*, *pandas*, and the *matplotlib* package to allow for automated updates whenever the underlying data are modified.

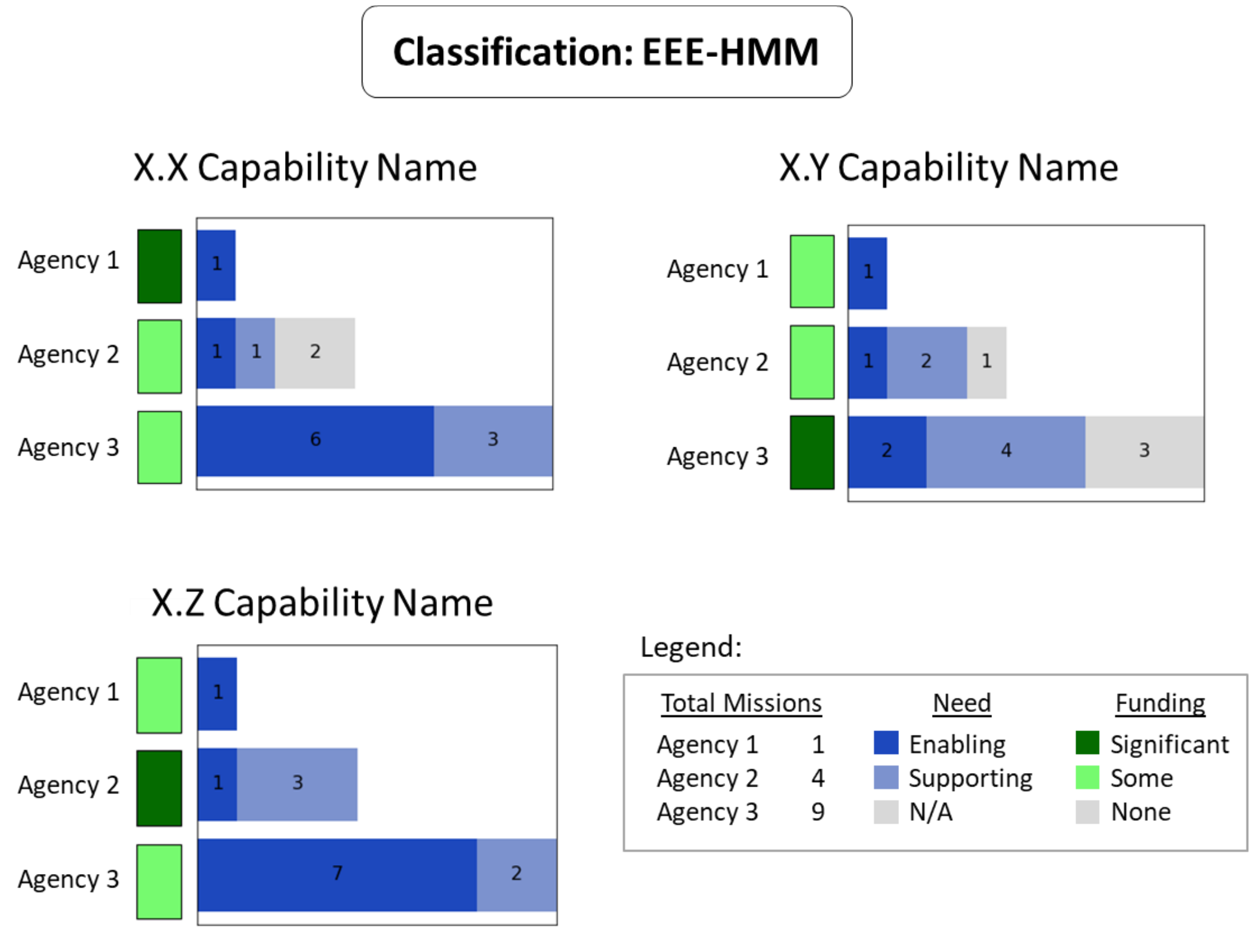

Figure 9: Example Scorecards with Notional Data

Each classification of need and funding level from the bubble chart is comprised of a number of capabilities for which scorecards are generated. Figure 9 shows a notional example of the capabilities comprising the “EEE-HMM” classification (recall that this is the dark green, high potential for collaboration, section). Each scorecard title includes the identification number and name for each capability.

During data collection, each partner highlighted a number of future operational missions and categorized the degree to which those missions are dependent upon each capability. The stacked horizontal bar chart on the scorecards indicates the number of operational missions in each category of need (Enabling, Supporting, and N/A) for each partner (Agency 1, Agency 2, and Agency 3). For example, for Capability X.X in Figure 9, Agency 2 has a total of 4 operational missions. Capability X.X is “Enabling” for 1 of those missions, “Supporting” for 1, and “N/A” for the remaining 2. This visualization allows the user to quickly understand the importance of each capability to each partner.

The level of funding from each partner to develop each capability is shown as well. Funding levels are denoted by the color of the box that appears in between each partner’s name and the associated bar. A gray box indicates no funding, a light green box indicates some funding, and a dark green box indicates significant funding. For example, Capability X.Y in Figure 9 has “Significant” funding from Agency 3 and “Some” funding from the other two agencies.

Scorecards provide an efficient means for conveying the information in the database for each capability. The scorecards allow the user to quickly understand the capability need for each agency compared to their current investments to develop each capability.

VI. Conclusion

In conclusion, this paper presented the data collection, storage, and analysis performed for the Space Science & Technology Partnership Forum's in-space assembly topic area. Data analysis and visualization techniques were used to illustrate the current landscape of in-space assembly across the government and to find synergies and gaps across the various ongoing and planned activities. The data analysis revealed areas of possible interagency collaboration, investment gaps in capabilities relative to the need, and capabilities that warrant engagement across multiple agencies to eliminate potential inefficiencies. These findings will be incorporated into the recommendations to decision makers from the S&T Partnership Forum. The recommendations include investment strategies and areas for cooperation to provide the most value to the partners. The data collection is an iterative process among the interagency partners, so results and findings will morph as agencies continue to advance and tackle new iSA capabilities. This information, while informative within the government, will also be used to engage with Federally Funded Research and Development Centers (FFRDCs) and the commercial sector to determine where those entities can provide value in iSA.

Acknowledgments

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