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Enabling Hybrid Architectures and Mesh Network Topologies to Support the Global Multi-Domain Community

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ABSTRACT

The turn of the new decade also represents the dawn of a new shift in domain operations. Concepts such as "Space Dial Tone," reliable global access to internet, on-demand Earth observation, and remote sensing, while still not fully realized, are no longer purely imaginative. These concepts are in high demand and are coupled with the goals of Global Multi-Domain Operations (MDO). Small satellites (smallsats) have emerged as functionally reliable platforms, driving the development of next-generation satellite constellations. To achieve the potential of tomorrow's technology, these constellations must embrace space mission architectures based on interoperable, open-system constructs such as hybrid architectures and mesh network topologies.

This paper presents the full timeline for realization of multi-node, disparate (sovereign, coalition, commercial, etc.) multi-domain (Space, Air, Maritime, Land, and Cyber) systems to support future space mission architectures. It identifies and discusses the underlying technologies needed to bring new "system-of-systems" concepts to operational capability. Technologies to be discussed include: message-agnostic physical/protocol "Bridges"; Machine-to-Machine (M2M) data sharing enabled through Electronic Data Sheet (EDS) standards; and, new concepts related to Artificial Intelligence (AI) enabled human decision making. Tying these technologies together effectively will positively impact the smallsat market and fundamentally change mission architectures in the near future.

SECTION 1: INTRODUCTION

Historically, the "Global Multi-Domain Community" has had a functional, but segregated existence. Each functional domain (Space, Air, Land, Maritime, Cyber) has been relatively isolated from the other domains, with limited success in integrated operations. Technology development and advancement, while truly ground breaking in many cases, have typically been focused within their own, isolated domain.

More recent technology developments have progressed and begun to demonstrate the advantages in integrating technologies and information/sensing modalities across domains.

However, the integration of these cross-domain technologies have been done via brute force. Cross-domain integration and compatibility within the domains has been done in "one-off" specialized or technology specific cases.

Today, the global community is more and more demonstrating a need for instantaneous access to data, actionable intelligence, and a desire to interconnect platforms without complications. The emerging global demands have two major anchors:

- Higher levels of quality data (better data products)
- Reduced data transport latency (access to data in real time)

The COVID-19 pandemic this year has further underscored this need. The global shutdown and stay-at-home orders have wreaked havoc on the economy, and the aerospace industry has not been immune. A perfect example is the 2020 AIAA/USU Conference on Small Satellites, normally held in-person in Logan, UT, will be, for the first time in its 34 years, hosted virtually. This year, the global small satellite industry will rely on data access and sharing platforms in order to adapt to the current conditions and continue the progress and exchange of ideas which are important for the future of the industry. The SmallSat Conference will demonstrate the adjustments much of the world is making to cope with unforeseen events, and will be a stepping stone to the possibilities of fully, integrated multi-domain technologies required for a "new normal."

Not ironically, small satellites have and will continue to play a major role in the future of a Global Multi-

Domain Community. To achieve the two main anchor demands, increased data product quality and reduced data latency, the smallsat industry is developing the first generations of hybrid architectures and mesh network topologies. These architectures, built upon the core competencies of smallsats, are the necessary operational approach to achieve the demands for a Global Multi-Domain Community.

The intent of this paper is to take an in-depth, comprehensive look at the role smallsats will play in these hybrid architectures and mesh network topologies. The paper will first look at the history of smallsats and reflect on the technology progressions that have promoted smallsats to their current utilization today, map the capabilities of small satellites and the enabling technologies that will continue the technology roadmaps, and discuss the innovative impact that the future endgame technology will have on us as a global community.

SECTION 2: A HISTORY OF SMALLSATS

When analyzing how smallsats will be used to construct the first generation of hybrid architectures, it is useful to remind ourselves of the history of smallsats and how they arrived at their current state.

Over sixty years ago, the launch of the first artificial satellite marked the beginning of the Space Age. During these early days, spacecraft design was constrained by both launch vehicle payload mass and on-board computer processing performance ceilings. The limitations of launch vehicle throw-weight during the 1950's and 1960's made smallsats the original satellite class, while low computing power limited their utilization to technology development and experimentation.[1]

It wasn't until the 1970's and 1980's emergence of the personal computer revolution that increased processing capabilities were introduced in spacecraft bus and mission designs. The advanced functional and performance capabilities enabled by the related innovations allowed more capable spacecraft to be built. Though access to space remained expensive due to limited launch opportunities, satellites were finally considered high performance, operational satellites. The primary method of ensuring these enhanced capabilities were realized included ensuring a long mission life, which required a high degree of reliability. Increased reliability was achieved through over-design, redundancy, and extensive test programs, resulting in larger and more expensive satellites. These Capital Assets (large, expensive, rigorously designed, highly reliable satellites with long lifespans) emerged as the dominating design for operational missions.

The "faster, better, cheaper" attitude toward satellite development was adopted by the space industry in the 1990's, heavily favoring smallsats. While many smallsat developers loudly claimed smallsats could do everything Capital Assets could do, these statements were unsupported. In reality, it was difficult for satellites to possess all three of these qualities since faster and better satellites were expensive, but cheap and quickly-made satellites were not as reliable as Capital Assets. Most smallsat development at the time resulted in overly expensive, scientifically insignificant missions that did not achieve the success of Capital Assets. For smaller satellites to imitate the performance and functionality of their larger counterparts, they needed better navigation technologies and enhanced systems on board for multi-vehicle configurations. These technologies were only just beginning to develop and were difficult to integrate with the smaller satellites. Though there was great hope for smallsats to overcome Capital Assets in popularity, government bureaucracy and industry rigidity stifled the market for many more years.

It wasn't until 1999, when Stanford University and Cal Poly San Luis Obispo defined the original cubesat standards, that the first "Smallsat Revolution" began. As cubesats grew in popularity, government and commercial parties experienced increased, cost-effective access space due to their compact design and reliability. The rise of cubesats encouraged satellite designers to innovate, making new technologies more efficient and smaller to operate within the constraints of cubesat standards.

The introduction of cubesats widely standardized the smallsat industry, making it easier to grow, innovate, and develop new technologies. Around the same time, standards known as Modular Open Systems Architecture (MOSA) were developed to ensure interoperability between software and physical interfaces for greater efficiency. Since the early 2000's, MOSA has been progressing and nurturing the trend toward constellations and operational systems. The fundamental importance of MOSA technologies on the road to a Global Multi-Domain Community will be discussed in depth further in this paper.

In 2002, shortly after initial standards development began, the development and release of the EELV Secondary Payload Adapter (ESPA) marked a major advancement in smallsat utilization. The ESPA ring enabled a number of smallsats and cubesats to launch on rideshare opportunities with the Capital Assets as secondary payloads. With launch and access to space now at a fraction of the previous cost, smallsats were once again considered as an operational solution in space rather than purely for Research and Development (R&D). The combination of ESPA capabilities with standards development signaled the beginning of the migration from large Capital Assets to smallsats.

Common standards of the early 2000's were iterated, improved, and further pushed the innovative limits of smallsats by the turn of the decade. It is observed from Figure 1 the number of large, Capital Assets launched into space has held relatively steady in numbers. By 2012, both government and commercial sectors began a significant increase in smallsat launches. Between 2012-2019, more than 1,700 smallsats have launched, representing an 11-fold increase in proportion of upmass sent to space.[2] Most of this increase can be observed more recently, in the years 2017-2019 (Figure 1). This most recent trend in smallsat launches suggests a second wave of the "Smallsat Revolution" is upon us. Though, this second "Smallsat Revolution" has a much different focus than the one experienced in the early 2000's.

Smallsats in the first revolution were heavily R&D focused (Depicted in Figure 2 as Technology Development). Even during the early 2010's, R&D smallsats represented more than 50% of all smallsat utilization. The R&D distribution began to pay dividends by the middle of the decade. Remote sensing payload technology is one example of technologies becoming both more capable and encompassing a smaller form factor to enable smallsat hosting. Technologies like Synthetic Aperture Radar (SAR) and Hyperspectral Imagers are great examples of technologies emerging from the R&D phase of smallsats, and are now commonly hosted on smallsat and cubesat platforms.

The need for high quality data, at a cheaper overall cost has always been a desire for the Global Multi-Domain Community. Now that the means to achieve the data were possible, the aerospace industry responded. Large constellations of smallsats for earth observation began to emerge. By the middle of the decade in 2014, the share of R&D focused smallsats dropped to between 28%-43%, with Remote Sensing smallsats overtaking the lion's share of smallsat utilization, reaching up to 66% in 2017. This new distribution was largely driven by successful remote sensing commercial constellations, such as BlackSky and Planet. During the previous decade, Planet owned and operated 55% of the remote sensing smallsats launched. The successful operations, at an affordable price point, of these remote sensing constellations represent one piece of the puzzle for Global Multi-Domain Community: quality of data.

A second, important piece of the puzzle, is access to the data. Just as important as the quality of the data, is the time in which the data is received. In many scenarios, old data is not at all useful, regardless of the quality or accuracy. Thus, the need for better space-based

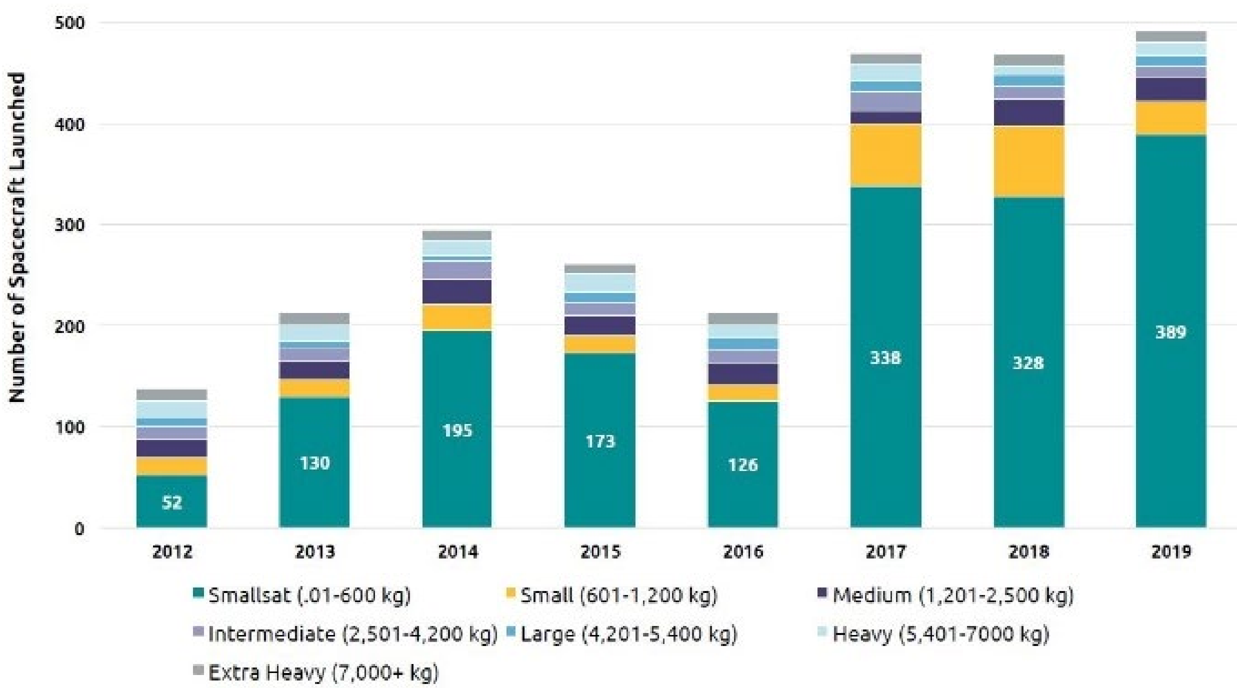

Figure 1. The Big Picture of Smallsats: Smallsats in Context[2]

communication architectures emerged. Again looking at Figure 2, evidence of this is apparent. Between 2017-2019, Remote Sensing smallsats dropped from 66% to 26%, while communication smallsats exploded from <2% to 38%. Again, the commercial industry saw the need and began to respond, with SpaceX alone owning nearly 50% of communication smallsats in that time period.

The growth in smallsat utilization by the global industry has translated into large economic gains for the satellite industry as a whole. In 2018, the Global Space Economy was estimated at $360 billion representing a 3% growth from the previous year. The largest sector gain in the global space economy was realized by the launch industry. Commercially-procured launches made up 81% of the launches in 2018, with 37% coming from the United States alone.[3] This further confirms the impact (relatively) inexpensive access to space has had on smallsat utilization. The second largest gain was seen in the satellite manufacturing sector, to the tune of a 26% increase. This result is also expected based on the number of constellations of smallsats recently deployed. These economic metrics are a direct correlation with the trends of the industry for increased smallsat utilization.

Over the last decade, smallsats emerged as the driving platform for the global space industry. As the new decade begins, more structured, coordinated architectures consisting of hundreds of smallsats hope to drive the next decade of innovation.

SECTION 3: CURRENT ENVIRONMENT

The economic boom in the satellite industry has also ushered in a new era of space development, commonly referred to as New Space. The term "New Space" is meant to juxtapose how the global space industry approaches space development with that of the traditional methods, and combined cutting-edge technologies and practices for lean, reliable space missions. Satellite Industry Associations President, Tom Stroup, said "much of the excitement surrounding the 'new space age' is centered on recent innovations and growth seen in the commercial satellite industry."[3] The recent trends in small satellites, especially the new constellations, is driven by New Space members of the community.

Each year, a publication of the Top 1,000 companies embracing New Space approaches is released by NewSpace People (NSP).[4] The most recent report offers a unique insight into the global commercial makeup of the New Space market (Figure 3). The results of the NSP survey are consistent with the smallsat trends discussed herein, with "Bus and Payload" providers representing almost a third of the distribution. This segment promises to remain strong throughout the next few years as large constellations will maintain that demand.

Today, there are well over 2,000 satellites operating in

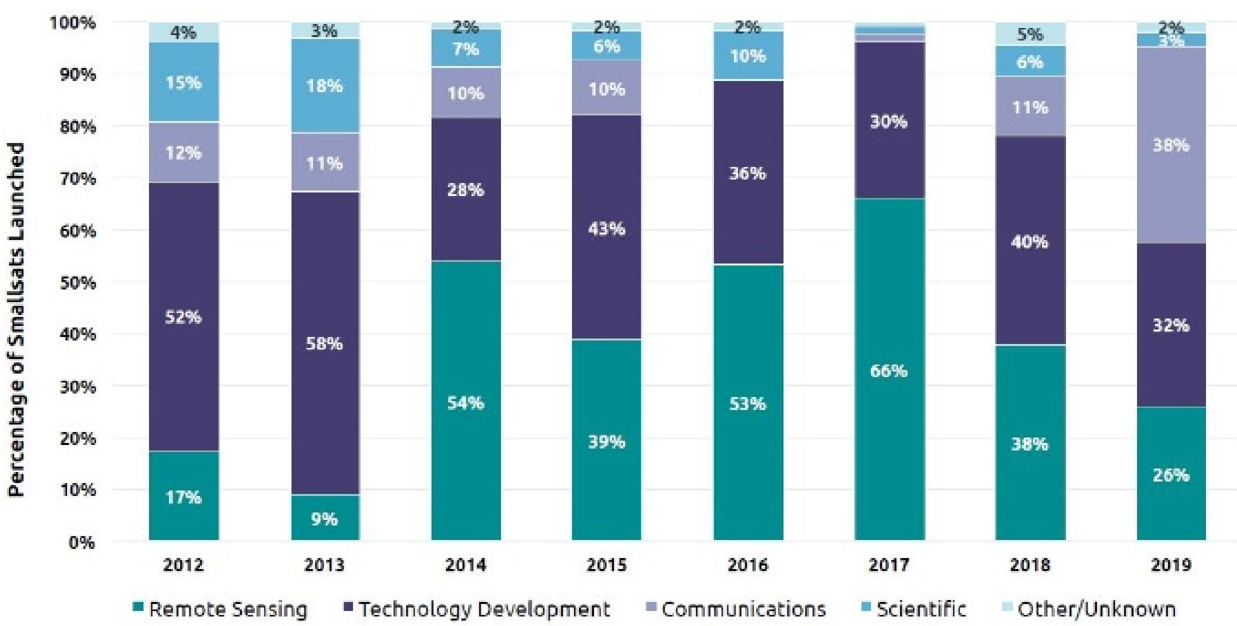

Figure 2. Share of Smallsats by Use (2012-2019)[2]

space. Again, as evidence of the current pandemic and its impact on global data sharing, that number is only expected to continue into this new decade. As the demand for better quality data in a shortened delivery timeline has grown, the smallsat industry has organically responded appropriately. According to Bryce Space and Technology's Smallsats by the Numbers Report, "smallsat telecommunications operators have said they plan to launch tens of thousands of smallsats. Initial deployment of these large constellations will dominate smallsat activity in the next few years."[2]

This is true for data collection constellations as well. SAR technologies are particularly important to the data quality aspect of Global Multi-Domain Community since it has the ability to image Earth both at night and during the day. SAR technology has traditionally been relatively expensive, and only maintained and operated by a few governments. The technology advancements enabled by the R&D utilization in the second smallsat revolution have now made SAR constellations possible at a fraction of the original cost. From Seraphim Capital, "this means that, for the first time, large constellations of SAR satellites capable of revisiting areas of interest every few hours will now become a commercial reality. Such a paradigm shift is expected to unlock a wide array of new SAR-enabled uses cases both for governments and corporations. The prize for whoever delivers on this potential could be huge. There are currently just a handful of start-ups vying to dominate the emerging smallsat SAR market such as Iceye, Capella Space, Synspective and Umbra Lab. Each of these companies have different technical approaches, different imaging capabilities and a focus on different market segments. 2020 will show which of these contrasting approaches holds the most merit and hence which company is primed to become category leader."[5]

Constellations like SAR and Telecommunications, among the many other planned architectures, will provide a new data collect infrastructure within the Space domain. To take the next steps towards hybrid architectures and mesh networks in the next few years, the aerospace community will need to begin the integration of the space infrastructure, agnostic to owner and operator. This success will serve as the first generation of hybrid architectures and mesh networks, paving the path toward the Global Multi-Domain Community.

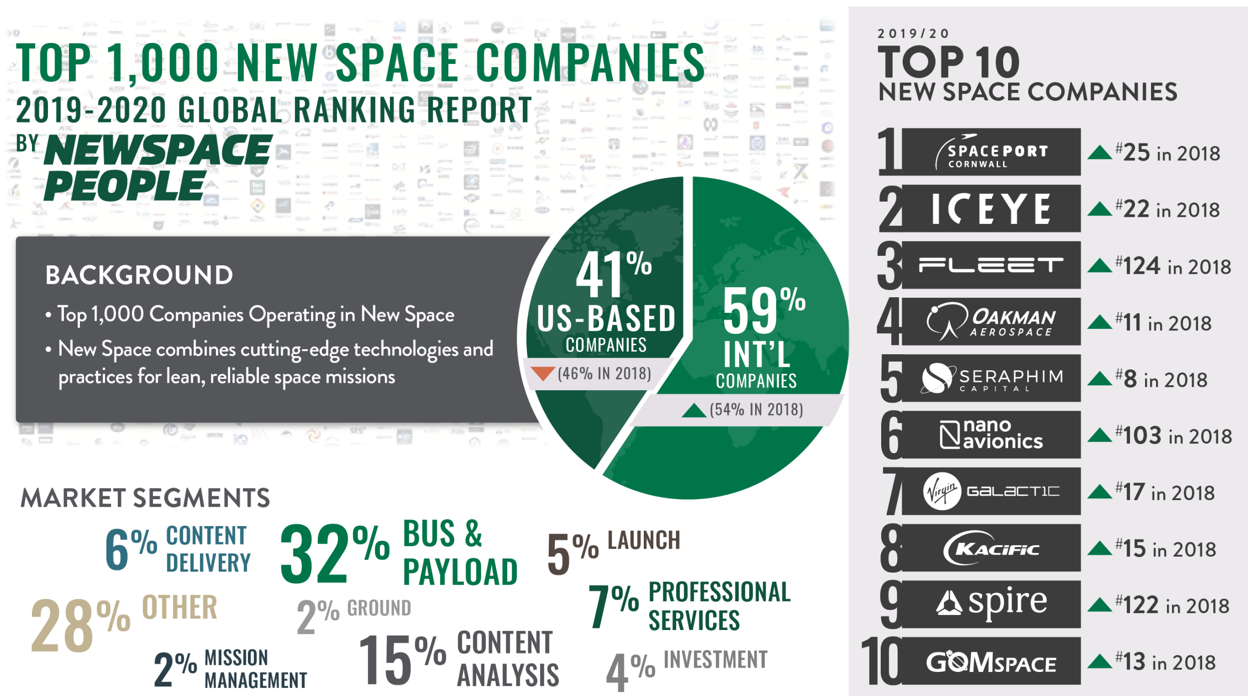

Figure 3. Top 1,000 New Space Companies 2019-2020 NSP Global Ranking Report[4]

SECTION 4: FUTURE OF SMALLSATS, EMERGING CAPABILITIES AND CONCEPTS

It can be predicted that the future of the smallsat industry will represent a truly revolutionary shift. Far from the initial government-driven development of space-based capabilities, large constellations of operational smallsats are envisioned to provide the world with instant access to data and satellite services. The idea of ubiquitous global connectivity supported solely by space-based infrastructure is commonly referred to as Space Dial Tone. The resulting increased reliance on data provided by these constellations will further cement the world's dependence on Space. Now, the technology advancements in the Space domain are driving a shift to new dependencies with new capabilities.

This highly connected future will be the result of innovations and technological advancements sustained by MOSA and interoperability. Large smallsat constellations, or mega constellations, imagined to support future capabilities will be reliant on further efforts to enable interoperability. In order for the vast amount of captured information, from many disparate operators, to be realized into actionable insights, data transport standardization must ensure interoperability between smallsat constellations and across differing data transport paths.

As satellite data is accessed by more and more users in an increasingly connected future, data harmonization will be fundamental to ensuring the quality of insights derived from large volumes of data. Successful harmonization will lead to the eventual commoditization of space data, allowing even more users to leverage big data for higher quality, actionable insights. In the near future, data captured by smallsats "will not be owned, but rather shared"[6] in order to generate valuable insights for future decision-making.

A future of harmonized, commoditized space data also means information acquired by smallsats will be more readily available to, and shared between, different domains. The transition from data owned to data offered by both government and privately owned smallsat constellations will lead to a paradigm shift in which accessible information will enable faster innovation.

Enabled by innovative on-board processing advancements, smallsats will be able to more effectively process the vast amounts of captured payload data and deliver better data products. Effective integration of Artificial Intelligence (AI) with space data is key to realizing value within vast datasets collected. Furthermore, combining AI with cutting-edge Machine Learning (ML) capabilities will facilitate the advancement of on-orbit data processing, increasing the efficiency of smallsat constellations.

Megaconstellations of the future will enable rapid ML development purely due to the vast amounts of data provided by the satellites. According to Dan Nevius of Analytical Space, "as computational power on [space-based] platforms increase you have the ability to do edge computing. There are applications where that makes a lot of sense, especially ones that have well defined analysis and are not too computationally expensive. However, there's also huge value in trying to get down as much data as possible, because you can use it as training data to develop new machine learning algorithms. The more training data you have, the more applications you can then start to model."[6] The effective utilization of AI/ML within smallsat constellation data analyses enables predictive, machine-led decision making with fewer humans in the loop. This capacity for fast, data-driven decision making will be a game-changing capability for armed forces, commercial, and academic entities alike.

Though many aspects of the future of smallsat utilization will be commercially applicable, government development of space-based architectures will continue to pave the way for the advancement of smallsat capabilities. In the next ten years, space will be required to accelerate quickly as an operational domain for armed forces. The most apparent evidence of this is the stand-up of the U.S. Space Force. The growing capabilities of space architectures to provide actionable intelligence to government forces means those assets may become a point of contention between allied countries. The inevitable focus on national space systems will result in opportunities for allied countries to share space assets and collaborate for national security purposes.

Future reliance on space-based data for rapid decision making will fundamentally change the world. Smallsat development toward this future is dependent on the successful development of hybrid architectures and mesh networks for interoperability. During this pivotal time in the smallsat industry, solving future technical challenges promises to reap exciting rewards for all.

SECTION 5: CURRENT CHALLENGES IN SMALLSAT UTILIZATION

The advancements in technology discussed above have made the production and launch of large quantities of smallsats a reality. Smallsats will be the key space-based platform for enabling space hybrid architectures and the Global Multi-Domain Community. However, there are still some hurdles in the utilization and operations of the large smallsat constellations for hybrid architectures. For example:

Satellite Design and Development

One such hurdle is the production of satellites at an efficient rate. Spacecraft design traditionally carries too high of cost and schedule burdens to meet the demands of the next generation constellations. A smallsat lifecycle typically revolves around a two-year development cycle. Vertical integration is an approach used by the large prime contractors and heavily VC funded companies with some success. However, to engage the entire New Space community, novel, innovative, and disruptive techniques must be developed to enable efficient horizontal smallsat design and development solutions.

Lack of Commonly Accepted Standards

While the evolution of MOSA has certainly helped to propel the smallsat utilization and spawn the New Space age, the widespread adoption and implementation of MOSA has been slow. There are a few reasons for this. First, some "open" standards developed by large prime contractors are often not open at all, but rather closed to their own internal use. Interfacing with these standards is generally difficult or restricted due to intellectual property concerns. This leads to a number of "open" standards being developed in parallel and without collaboration. With many standards available, it becomes difficult for a single, truly open standard to emerge as the internationally adopted standard. Globally, it can be observed the lack of MOSA implementation is mostly due to the inability for a common, open standard to emerge as the dominating standard in the industry.

Stovepiped Space Architectures

As a result of non-availability of commonly accepted standards, most space system designers and developers revert back to "stovepiped" space architectures. This is not done with any malice of intent, but rather as a necessity to implement designs that can either meet the mission technical requirements, meet the revenue generation requirements, or meet the programmatic schedule requirements. It should be noted that some internal stovepiping is inevitable and occasionally should be encouraged. For example, if a particular mission/payload sensor requires high data-rate, multi-channel communications interfaces for functional/performance objectives, then it should not be forced into a sub-optimal open-standard interface. However, once the data is captured (via some Instrument Electronics Box [IEB]), it should be available via common publish/subscribe (pub/sub) services to the rest of the architecture.

Most "Integration" done via Ground Activities

Two factors drive today's integration activities being executed predominately via ground infrastructure: 1) The cost/capacity of on-board vs. off-board data processing resources; And, 2) The rigid structure of current space systems architectures that do not allow for easily updating communications paths and algorithms within the space segment. The first driver is being addressed through higher and higher performance general purpose and special purpose processing frameworks. The second factor is being addressed through multi-path communications and proliferated on-orbit and ground entry point (GEP) communication nodes. These "service" providers in turn require users to conform to physical and protocol standards to complete the architecture. The authors believe that over time more and more integration and product generation will be moved on-board and/or within the space segment in order to minimize latency and mission critical information/content delivery for decision-making and revenue generation activities.

Today's New Space companies are at the forefront of game changing technologies, and are helping to expand the limiting boundaries prohibiting the full realization of hybrid architectures and mesh network topologies.

SECTION 6: TECHNOLOGY ENABLERS

Significant effort and progress are being made to overcome the hurdles listed above. The resulting technologies being developed will be key enablers for hybrid architectures and mesh network topologies. The authors of this paper have identified a number of relevant enabling technologies, and divided them into the following three main focus areas:

1) Communications Enablers
2) Network/Messaging Enablers
3) Satellite development Enablers

6.1 COMMUNICATIONS ENABLERS

It is incumbent upon the space community to develop true space hybrid architectures and mesh networks in order to achieve Global Multi-Domain Operations (MDO). The data communications structure for these hybrid architectures and mesh networks are critical technologies that are still being developed. The following enabling technologies each focus on supporting the communications requirements for hybrid architectures and mesh networks.

Electronic Data Sheet (EDS) Standardization for Machine to Machine Data Sharing

A key tenant of true hybrid architectures, and especially mesh networks, is interoperability between systems. Successful hybrid architectures and mesh networks, by definition, must be agnostic to which sub-architectures are able to rapidly integrate and share a pre-defined data set. This is not to suggest that all hybrid architectures and mesh networks must integrate with any desiring sub-architecture. Rather, the architecture interfaces must be designed and implemented in such a way that the given hybrid architecture could integrate with a previously unknown/undefined architecture assuming the proper security permissions and trust factors are satisfied.

Standardized Electronic Data Sheets (EDS) will serve as the foundational backbone for interoperability. Today organizations such as the International Standards Organization (ISO) and the Consultative Committee for Space Data Systems (CCSDS) are working diligently to baseline EDS standards globally. In April 2019, CCSDS released the XML Specification for Electronic Data Sheets "Blue Book". Hybrid architectures and mesh networks will require reliable, consistent, and standardized EDS to enable the machine to machine data sharing. This automated, machine-based data sharing is the construct to support the rapid integration of sub-architectures into a mesh network and overall space hybrid architecture. For the vision of space hybrid architectures, interoperability and rapid integration of large space architectures to include multi-national government, academic, and industry participants will rely on common EDS standards.

Digital Twin for Fault Management

A relatively new concept being developed for space systems architectures is the idea of on-board and off-board "Digital Twins." A Digital Twin is an "an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc."[7] Specifically in this context, Digital Twins can be used to identify anomalous conditions that are either natural or man-made. In addition, Digital Twins can be utilized to predict future modes and state transitions of the physical entity and provide fault management and vehicle safety system inputs for decision making and fault recovery.

Dynamic Relative Telemetry Calculators

In order to support multi-vehicle, multi-cluster communications in future hybrid architectures, communications/network connectivity topologies require near-instantaneous temporal and spatial information. To this end, concepts like N-N matrices have been developed to bookkeep and disseminate these data sets to the architecture. Oakman Aerospace, Inc. (OAI) has developed the Dynamic Relative Telemetry Calculator (DRTC) for this purpose (Figure 4).

Hybrid architectures will utilize the DRTC information provided through electronic Interface Control Documentation (eICDs) coupled with communication/network constraints (i.e., RF Doppler cut-off frequency, etc.) in order to establish and maintain meshed-network connectivity.

6.2 NETWORK AND MESSAGING ENABLERS

Modular Open Systems Architecture (MOSA)

In engineering design, MOSA is considered a design approach for highly complex systems. The MOSA approach has been successfully implemented in a number of other industries, including automobiles, mobile phones/app marketplaces, operating systems such as Linux, computer interfaces such as USB, and others. Seeing the benefits other industries have achieved with MOSA implementation, the U.S. Department of Defense (DoD) unofficially adopted the approach over the last two decades. Recently, congressional legislation has mandated the adoption of MOSA across a variety of programs. According to the Defense Standardization Program (DSP) Journal, "the Office of the Secretary of Defense (OSD) has concluded that continued implementation and further development of MOSA-enabling standards is needed to ensure rapid sharing of information across domains with quick and affordable updates or improvements to hardware and software components." The DoD implemented MOSA in order to achieve five main goals: 1) enhance competition, 2) facilitate technology refresh, 3) incorporate innovation, 4) enable cost savings, and 5) improve interoperability.[8]

Message Agnostic Physical/Protocol "Bridges"

Without the emergence of a common open standard, future hybrid architectures and mesh networks must be able to adapt, integrate, and message between systems operating on multiple, disparate messaging systems. These architectures will utilize message agnostic physical/protocol applications to integrate disparate messaging systems into a common architecture. These

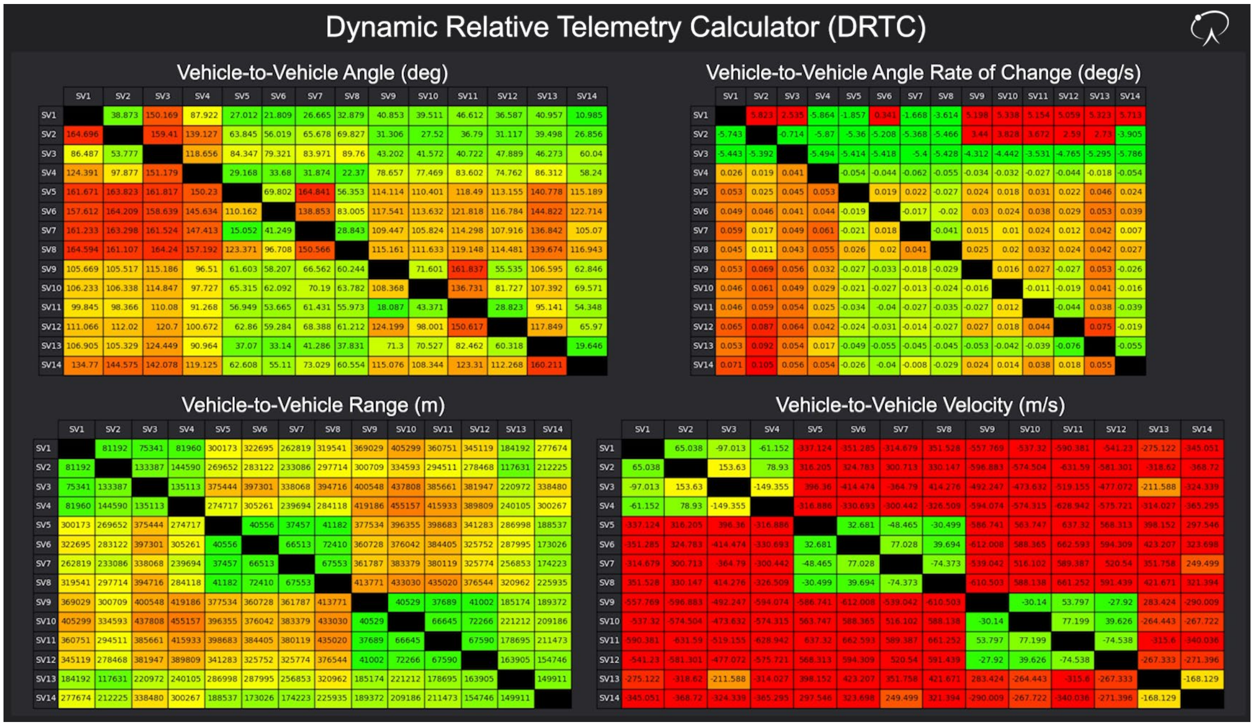

Figure 4. Dynamic Relative Telemetry Calculator (DRTC)

physical/protocol layers, or "Bridges," are a configurable abstraction layer that allow for efficient integration of subsystems, systems, and/or entire segments with little to no impact on the rest of the architecture. Applying this concept to complex systems will make the overall architecture both hardware and software agnostic. Architectures embracing MOSA standards combined with these message agnostic physical/protocol "Bridges" will help to evolve the early hybrid architectures being developed today into a more fully realized architectural framework, specializing in the integration of multiple systems into a common environment for overarching mission analysis. This is a critical functionality for the next generation of hybrid architectures and mesh network topologies.

6.3 SATELLITE DEVELOPMENT ENABLERS

Rapid Satellite Development

The large constellations that will provide the infrastructure for hybrid architectures and mesh networks will require a high volume of satellite production. Many of the current smallsat constellations, as discussed in earlier sections, achieved this volume output at a cost effective price point through vertical integration. This approach is not conducive for many of the innovation drivers of the New Space age due to its homogenous nature and high upfront costs.[9] Additionally, vertical integration limits the upgrade capabilities for satellites while they are on the production line. For example, if a new, upgraded technology is desired on a vertically integrated spacecraft bus, the new technology must either completely adhere to the bus's internal messaging protocols (which are typically closed in vertical integration), or require a spacecraft bus redesign to accommodate.

MOSA, message agnostic physical/protocol "Bridges" and other enabling technologies, as discussed in the communications and network/messaging enabler sections, can also be leveraged to allow more efficient and shorter timelines for satellite development. These constructs allow the design and development of horizontally integrated satellites. Horizontally integrated satellites refer to those spacecraft which use subsystems and components from many various vendors within the supply chain. The interoperability constructs also ensure that disparate, commercial off the shelf (COTS) components can not only communicate within an integrated system, but easily and quickly be interchanged with a similar component.

The interchanging of components in horizontal integration provides some major advantages for large constellations and hybrid architectures. First, a spacecraft does not need to undergo an elaborate and time consuming redesign. A baselined spacecraft configuration can easily accommodate an alternative hardware/software solution while on the assembly line. This is referred to as continuous spacecraft upgrades, as opposed to traditional "block" builds. Spacecraft manufacturers for constellations can now ensure their spacecraft are kept on schedule (by replacing a behind lead time component with an alternative), within budget (by replacing an expensive component with an adequate, less expensive component), and achieve optimal performance (by replacing a component with new technology). Large constellations, especially those with projected numbers in the hundreds or thousands, will need to replace on-orbit assets at a regular interval. The horizontal integration strategy, supported by the enabling technologies, will allow future hybrid architectures and mesh networks to stay effective and operational through the next decades.

Machine Learning (ML) / Artificial Intelligence (AI)

One of the most fascinating, and difficult, enabling technologies being developed is Machine Learning and Artificial Intelligence (ML/AI). These technologies, once fully realized, will represent the new operating procedure for hybrid architectures. ML/AI promise to serve many roles within constellations and hybrid architectures, including constellation management, mission and battle management command and control, and fault detection/management systems.

Over the last decade, neural networks and heterogeneous computing clusters have been made possible by significant advances in on-board technology. Most notably, advances in on-board resources required to conduct the powerful computational analysis have been realized through state-of-the-art Graphics Processor Units (GPUs). As such, ML/AI engineers have begun to develop their frameworks to integrate GPUs when developing training networks. These advancements in compute power, which can now be hosted on platforms fitting on a smallsat, have opened the possibilities for not only large constellations to operate autonomously, but for multiple constellations to interact and coordinate for common missions as defined by end-users. This capability will drive hybrid architectures to prove to be a successful endeavor, and lies at the heart of a Global Multi-Domain Community.

Integrated Design Environment (IDE)

It should be noted, much of the global small satellite industry consists of small, commercial businesses seeking to change the industry's landscape. Small businesses are often more agile and take greater risks, leading to innovations and game changing technologies. Inherently, however, small businesses (and their innovative potential) are limited by financial and human resources. In the spirit of hybrid architectures and the "collaborative" ideals they are based on, integrated design environments will be necessary for international small businesses to access complementing technologies. Globally distributed IDEs can foster greater diversity in engineering technologies and leverage a wider range of varying resources. IDEs expand the technical potential for international partnerships. Hybrid architectures and mesh networks stand to gain significantly when a wider range of small commercial partners are able to interact, design, and iterate within a common, distributed engineering environment.

Once again, MOSA and "Bridge" application technologies discussed above can be leveraged to support IDEs. MOSA-based IDEs will be flexible, extensible, and agnostic to specific space vehicle electrical interfaces, software/firmware modules, and hardware/subsystem components. The message agnostic "Bridge" applications enable the integration of disparate components and messaging systems into the common architecture of the IDE. The IDE nodes can utilize any messaging layer (SSM, AMQ, ROS, etc.) which is important in the scaling and integration of additional development nodes worldwide. Through this MOSA approach, the established IDE is a distributed testbed specializing in the integration of disparate architectures into a common testbed for overarching mission analysis.

IDEs allow development in the following areas:

- *Software-Based Modeling and Simulation:* Faster than real-time modeling and simulation, requirements development and definition, detailed trades and analyses/analysis of alternatives (AoA), CONOPS evaluation and verification.

- *Hardware Integration and Testing:* Rapid hardware integration with minimal engineering. Hardware-in-the-loop testing and verification against the defined Design Reference Missions substantially reduces mission risk and increases mission assurance.

- *Multi-node Analyses:* Virtual machines can be configured to conduct test and analysis for multi-node systems. Virtual machines within the IDE network can be easily configured to create as many nodes within a given scenario. This includes both homogenous and heterogeneous architectures.

IDEs will support hybrid architectures and mesh networks by enabling small, New Space companies to collaborate and innovate on a global scale in a cost effective and time reduced manner. More seamless collaboration will spawn innovative technologies which are sure to be integrated within the Global Multi-Domain Community.

SECTION 7: EARLY ADOPTERS OF HYBRID ARCHITECTURES AND MESH NETWORKS

As has been the pattern in space technology development, government and military are usually the early adopters for large, game-changing concepts. In the United States, a number of groups within the DoD are actively partnering with other defense groups as well as commercial partners to develop and demonstrate hybrid architectures and mesh network topologies.

BlackJack/PitBoss – DARPA

One of the first adopters for hybrid architectures within the U.S. DoD has been the Defense Advanced Research Projects Agency (DARPA) under the BlackJack and PitBoss programs. The overarching goal is to develop and validate critical elements of global high-speed autonomous networks in Low Earth Orbit (LEO).

The BlackJack program is focused on the spacecraft buses and payloads. The approach is to identify a handful of spacecraft bus manufacturers and multiple payload developers. The spacecraft buses are intended to be designed to be agnostic to payload and orbit, as much as possible. So far, DARPA has selected Airbus, Blue Canyon Technologies, and Telesat as the bus providers. The final selection of buses is expected to happen in 2020.

The payloads are to be designed with size, weight, and power as the anchor design constraints. A further required design feature is the ability to mass produce these payloads. In order to achieve the endgame goals of Multi-Domain Operations, BlackJack's approach is to saturate LEO with an abundance of sensors. DARPA is considering a number of payloads developed by commercial entities such as Collins Aerospace, Raytheon, Northrop Grumman, SA Photonics, and L3 Harris.

The PitBoss program will serve as the autonomy driver for the BlackJack program. SEAKR was chosen as the PitBoss lead performer and is focusing their efforts on AI/ML assisted autonomy algorithms to conduct the BlackJack Constellation.

If successful, these two programs will demonstrate a much needed capability, providing the DoD with "highly connected, resilient, and persistent overhead coverage."[10] However, this architecture is not a true hybrid architecture. The BlackJack/PitBoss architecture is still closed to itself, with only the selected contractors integrated into the fold. Long term, especially when seeking to achieve Global Multi-Domain Operations, true hybrid architecture capabilities must be embraced. True hybrid architectures mean rapidly, almost instantaneously, integration of a new space architecture to achieve a needed objective at a reduced timeline. This will rely on the enabling technologies discussed, especially the interoperability and mesh network constructs enabled by MOSA.

Casino – Space and Missile Systems Center

The USAF Space and Missile Systems Center (SMC) is providing funding to the BlackJack and PitBoss programs through a partnership with DARPA. Col. Dennis Bythewood, Program Executive Officer for Space Development at SMC, has stated "SMC is planning a transition of the [BlackJack] architecture to a program called CASINO [Commercially Augmented Space Inter Networked Operations]."[11] CASINO will expand the efforts of the DARPA BlackJack program and will seek to add space-based resilience to the DoD persistent-ISR capabilities. CASINO will leverage government, commercial, and foreign allied constellations to achieve this, taking a significant step towards truly integrated hybrid architectures.

Space Development Agency

Similarly, the Space Development Agency is also planning to transition the DARPA BlackJack concepts into their own hybrid architecture implementation in support of the National Defense Strategy (NDS). This strategy is intended to integrate future space capabilities in order to provide the DoD resilient sensing and data transportation using a proliferated LEO architecture. SDA has defined their hybrid architecture into seven (7) layers: 1) Data Transport Layer, 2) Battle Management Layer, 3) Tracking Layer, 4) Custody Layer, 5) Navigation Layer, 6) Deterrence Layer, and 7) Support Layer.

SDA has already solicited commercial proposals addressing the Data Transport Layer. Arguably, the Data Transport Layer may be the most important concept in order to realize hybrid architecture success. SDA has adopted a spiraled approach to the Data Layer establishment, with the Spiral 1 demonstrations expected by 2022.

AFRL MSMU and Joint Exercises

During 2018, the AFRL Small Satellite Portfolio (SSP) office coordinated a set of exercises (Microsatellite Military Utility, MSMU) in parallel, leveraging assets from the Space domain. Participants in the MSMU exercises included ~220 operational satellites operated by both international coalition forces (U.S., Norway, Canada) and commercial constellations (Planet, BlackSky). It also included a number of analytical and ground support tools owned and operated, in coordination, by multiple nations and commercial providers. These exercises were used to define key performance parameters, critical operational decision points, and identify capability gaps within the current state of the space hybrid architecture. The questions answered in the initial study research and development are:

1. What data (telemetry, memory items, performance characteristics) is key for feeding into a representative test environment to enable deep learning neural network for automated state-machine and response matrix generation?
2. What data (telemetry, memory items, performance characteristics) is key for feeding into a machine learning recommender system to determine the best course of action for mediating the rules based decision process?

RIMPAC 2018 MSMU set the baseline and identified a number of opportunities and needs for developing the Space Hybrid Architecture Approach.

SECTION 8: HYBRID ARCHITECTURES AND MESH NETWORK TOPOLOGIES

The early adopter programs discussed in Section 7 seek to demonstrate proof of concept and (relatively) low-complexity hybrid architectures in space. If successful, those programs will answer some questions surrounding the technical feasibility, but more importantly, will generate new questions regarding the potential applications of Space Hybrid Architectures.

The newest, and smallest, U.S. Military branch, Space Force, will rely significantly on the wide array of advanced technologies available by leveraging military with commercial assets in Space Hybrid Architectures. Col. Eric Felt, head of the Air Force Research Laboratory's Space Vehicles Directorate, stated, "there are many commercial capabilities that can be used to meet military needs …for space systems one way to do that is with a hybrid architecture." This ability will make the Space Force the "most high tech of all of the services."[12]

Once Space Hybrid Architectures are operational, mesh networks will enable end-users to fully access, receive, and utilize data products from any trusted source, despite the originating owner/operator. Mesh networking is the design architecture concept of joining a node (satellite, in this case), with as many reachable nodes in the system as possible. Without Space Hybrid Architectures, satellites are limited to other nodes within their own constellation. With Space Hybrid Architectures, the number of accessible satellite nodes available for a given satellite is orders of magnitude larger. Mesh networking applied to Space Hybrid Architectures will exponentially increase the access to quality data products and drastically reduce the data transfer latency to an end user. End users, in this case, are not only U.S. military war fighters, but global commercial end users as well.

SECTION 9: MULTI-DOMAIN OPERATIONS (MDO) CONCEPTS AND POSSIBILITIES

Hybrid architectures and mesh networks of smallsats, enabled by emerging and developing communications, message/networking, and satellite development technologies, will be the backbone for future, Global Multi-Domain Operations. Multi-Domain Operations are sure to change the way the world works. This is true for both military operations and the general world population.

In the U.S. military, Multi-Domain Operations are considered to become the newest warfare strategy. Some may even argue the U.S. military has been operating in multi-domains for some time, via Joint Force operations.[13] Joint Force operations are certainly examples of a multi-domain operation, but are not executed today at nearly the optimal operating procedure that future Multi-Domain Operations are imagined. In Joint Force operations today, segments such as control, intelligence, surveillance, and reconnaissance (ISR) battle management command and control (BMC2), and the decision makers sitting at various levels of command authority, are layered, segmented and not fully integrated. An integrated understanding of the battlefield layout across all domains has yet to be realized, and, instead, exists with precision in the localized domains and varying reliability in some cross-domain instances.

The future Multi-Domain Operations, once successfully leveraging space hybrid architectures, mesh network topologies, and ML/AI management (business transactional models), will provide precise situational awareness across all domains. The traditional ways of constructing and navigating a battle plan will be completely evolved into a streamlined, multidimensional, and dynamically reconfigurable architecture, as visualized in Figure 5.

In today's military, the Domain Space houses each of the domains C4ISR and BMC2 operations. The National Command Authority lives in a centralized realm within the Information and Decision Space, in an attempt to oversee the full battlefield landscape. The advanced data collection and communication technologies within Hybrid Architectures will now seamlessly integrate all nodes within the Domain Space and connect these information networks with the Information and Decision Space. ML/AI business transactional models will minimize human-in-the-loop points (thus mitigating the realized negative effects of system complexity) by autonomously ingesting the Domain Space data, analyzing that data and producing decision operating procedures. The threat level variable will determine the seniority of the human-in-the-loop decision point, and a resulting tactical command will be distributed back to the appropriate warfighter(s) in the domain space. With the emergence of 5G and message/network enablers, this MDO process can be dynamically reconfigurable, allowing for the throttling of data share and distribution based on perceived threats or security concerns. This will completely disengage the static nature of the current chain of command. U.S. Air Force Chief of Staff Gen. David Goldfein has described new MDO processes as human-on-the-loop as opposed to human-in-the-loop.[14] The entire process imagined above is not possible without substantial advances the smallsat community is continuously making in hybrid architectures and mesh network topologies.

While the Space domain is leading the way for future MDO, other domains, represented by branches in the military, are drawing their own lines in the sand for full implementation. The U.S. Army has set their sights on 2028 as their target year for MDO.[14] Similarly, the U.S. Navy and U.S. Marine Corps have also produced operating procedures on interconnecting their various warfighting assets. Though the establishment of the Space Force may falsely suggest a disengagement between Air and Space, those two domains have been successfully integrated for many years. An encouraging step towards successful MDO between the military branch leaders was the communal agreement to adopt MOSA standards and design approaches in January of 2019.

A unique and force-multiplying facet of Space Hybrid Architectures is the integration of foreign and commercial systems into the larger system. Strong advances in cyber security and digital twin fault management systems will now enable military nodes to

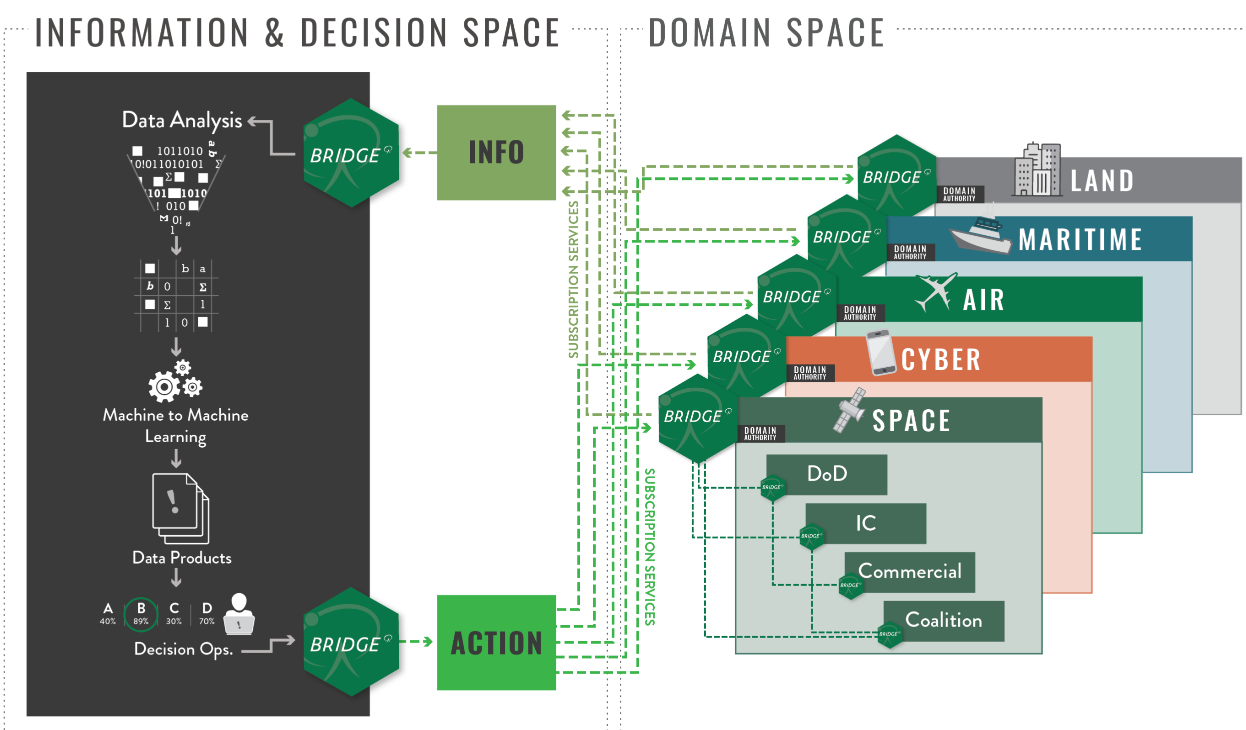

Figure 5. Multi-Domain Operations (MDO) Architecture

quickly and accurately verify/validate the quality of data before feeding the data into a data analysis state machine. Commercial and foreign allied assets are now available data providers to increase the resolution of the multi-domain landscape.

While the focus in the U.S. may be on the military plans to leverage commercial assets through MDO, there exists major, and profitable, opportunities through MDO purely in the non-military (commercial and academia) are seemingly infinite in themselves. MDO will break down global barriers initially held up by distance, logistics, resources, technology, and wealth. The commercial sectors are already working on MDO technologies such as Space Dial Tone and global access to internet (via space Wi-Fi). MDO will spawn new international business adventures, connect university students across the globe, and inject new, innovative ideas into everyday life. The commercial sector will be sure to revolutionize the world we live in today through MDO.

SECTION 10: CONCLUSIONS

The research done and compiled within this paper is intended to describe and annotate the industry-wide roadmap to the next generation of smallsat utilizations: the driving force behind a Global Multi-Domain Community. The history of smallsats, evolving from R&D, high risk and low reliability to a New Space era with operational megaconstellations, in just a matter of three decades, is confirmation that the smallsat boom is here to stay. That being said, it is our responsibility within this New Space era, to answer the call. We must keep pushing game-changing technologies within the communications, network/messaging, and spacecraft development sectors. The industry will need to embrace not a single standard, but the MOSA approach and the message agnostic “Bridges” and EDS’ that tie disparate architectures together. Autonomously managing and assessing the new complex risks and threats these integrated architectures will bring will need to be realized through ML/AI advancements. These same technologies must also support the rapid, reliable, and cost efficient development of smallsats to ensure the health and integrity of the constellations through the timely replacement of the space-based assets. It is paramount that we demonstrate progress and successes in these technologies soon, and to deploy these technologies to support the early adopters dedicated to hybrid architectures. Success for these early adopters is critical in maintaining support and accelerating the timeline.

The next decade and beyond are sure to be dynamic with significant trials, errors, giant leaps forward in technology, stumbles and minor setbacks, and overall life changing innovations. It is exciting and humbling to imagine what a day-in-the-life looks like for the next generation of smallsat engineers. What new, unimaginable technology is possible with a globally integrated space community?

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