HIVE: A Space Architecture Concept

Allison B. Taylor (Systems Engineering Division), allison.b.taylor@aero.org
Henry Helvajian (Physical Sciences Laboratories), henry.helvajian@aero.org
The Aerospace Corporation
El Segundo, CA

Abstract

The increasing number of spacefaring nations and agendas, miniaturization of subsystems, and trend toward integrated systems are no doubt influencing the evolution of space systems. The diversification of space architectures has surged at an unprecedented rate in recent history with initial deployments of planned mega-constellations. This paper explores HIVE - a reconfigurable small satellite system primed to revolutionize the concept of modular space systems and future space architectures.

Based on a mass producible functioning unit consisting of nested rings, HIVE is a comprehensive satellite design harnessing advancement in robotics, software and machine learning, precision scale manufacturing, and novel materials with multifunctional properties. HIVE is addressing solutions for detailed design of interconnected hardware, engineering analysis for multi-payload applications, and policy to accomplish modularized, in-space deployment and reconfiguration.

The HIVE unit design lends itself to the “infinite possibilities” of space mission architectures and presents a revolutionary way to design, integrate, and operate missions from space. This paper provides and overview of the HIVE concept development and provides examples of applications for HIVE to showcase the range of possible systems and architectural advantages; such as space domain awareness, large service structure, and planetary surface infrastructure. Finally, we will discuss technology transfer and possible pathways to making a resilient, adaptable, and continually upgradable space infrastructure a reality.

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Introduction

Over the past 3 years, The Aerospace Corporation has sponsored an engineering study to explore the types of spacecraft that could be developed, if presented with a "clean sheet" and if noted technology advances could be applied. Project HIVE explores a space architecture that comprises an assembly of mass-producible satellite units. Each unit has self-functioning capability but also the capability to connect/disconnect with adjacent units. The ensemble with its numerous sensors is designed to work as a whole and has transformable functionality which is solely dictated by the surrounding environment [1]. Imagine a robot as an assembly of near equivalent mass producible modular units with the capability to disassemble and reassemble to maximize functional efficiency. In the case of HIVE, the reconfiguration is done solely by the concerted action of multiple reaction wheels without the need for free-flying maneuvers. Reconfigurable or polymorphic robots open wide the capabilities for future space systems development but become a necessity for cogent exploration of the many planetary bodies within our solar system. For example, upon physical contact with any planetary body, the risk for mission failure increases with the lack of detailed knowledge of the local terrain and/or "weather". Consequently, only an adaptable or a reconfigurable system, can mitigate some of this risk.

HIVE Unit Design Motivation

The initial HIVE concept was based on the CubeSat form factor which served as the fundamental functioning unit. Designs that connected CubeSats were addressed coupled with the fundamental HIVE requirement that power, data and in the future, fuel be transferable among the connected assembly. Engineering difficulties arose which limited the usefulness of the CubeSat as a building block model [2]. For example, 1) Even with full body mounted solar arrays, there is not sufficient power generated within a CubeSat unit for the non-propulsive reconfiguration maneuvers which is one hallmark of HIVE, 2) thermal transfer between units was also a problem. Thermal modeling showed that multiply connected CubeSat units, even to form a 2D construct (e.g. 3x3 connected array) produced "hot spots". Finally, 3) the prismatic form factor of the CubeSat limited the assembly of curvilinear space constructs (e.g. an antenna dish). The CubeSat form factor was tossed in favor of a structure that resembles a set of nested hoops in which the hoops serve as the "railroad" track to the 1U CubeSat "tram" modules.

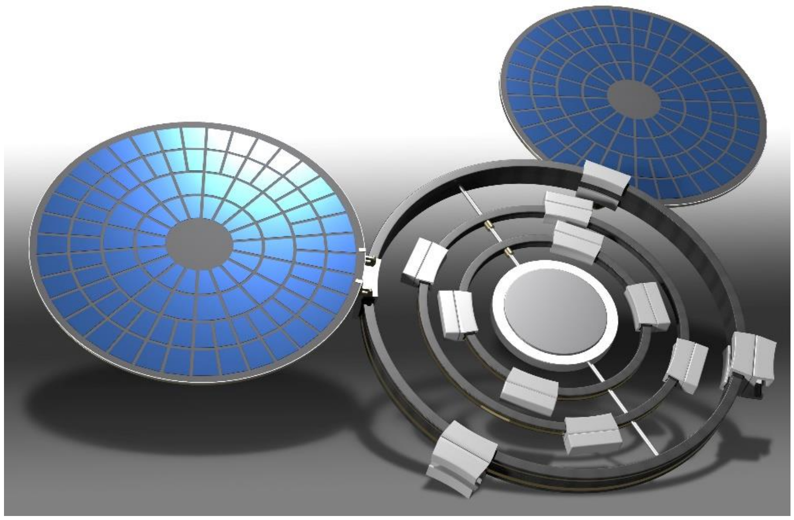

Figure 1: CAD drawing of a HIVE unit that is mass producible. The structure is shown in the un-stowed configuration.

HIVE 2.0 Unit Design

Figure 1 shows a CAD drawing of a solitary HIVE unit while Figure 2 shows three connected units. The trams are the modules mounted on the hoops. The inner hoops rotate about the center of axis offering a 360-degree space situational awareness if one of the 1 or ½ U CubeSat trams supports a camera/telescope. The outer hoop also has multiple trams, two are used to grasp solar panels (i.e. the mickey mouse ears) and two others grasp other HIVE units. The grasping mechanism is prehensile. It serves as a "single point" connection which transfers power and data but can also bend out-of-plane. This enables the solar panels to be stowed flat during launch. Multiple HIVE units can be stacked in a launch faring with adjacent units connected. Once in orbit, the stacked system deploys and extends. The outer hoop diameter can be large (~ 4m to fill a faring, Falcon-9) or much smaller (e.g. ~50 cm). The center flat section, called the "nucleus", holds the unit's functional systems (e.g. flight and Comm hardware, batteries, reaction wheels etc.). The HIVE concept places the payloads and key subsystems (e.g. star tracker) onto mobile trams that can move along the hoops. Power is drawn from the hoop "track". Thermal modeling, 3D dynamics simulations, and other analysis show that this open structure design mitigates the problematic issues that limited the CubeSat form as a HIVE unit. Dynamic analysis shows that space constructs 100's meters in length can be assembled in space. Moreover, configuration changes in the construct topology are possible by the concerted action of multiple small reaction wheels which enable the formation of not only 2D shaped structures but curvilinear (e.g. 10 m dia. antenna dish) and full 3D "caged" structures. Data, power are shared among the units. Trams carrying propulsion hardware draw fuel from within one of the hoops. Finally, HIVE uses a distributed control algorithm [3] that communicates on a modified mobile ad hoc network (MANET).

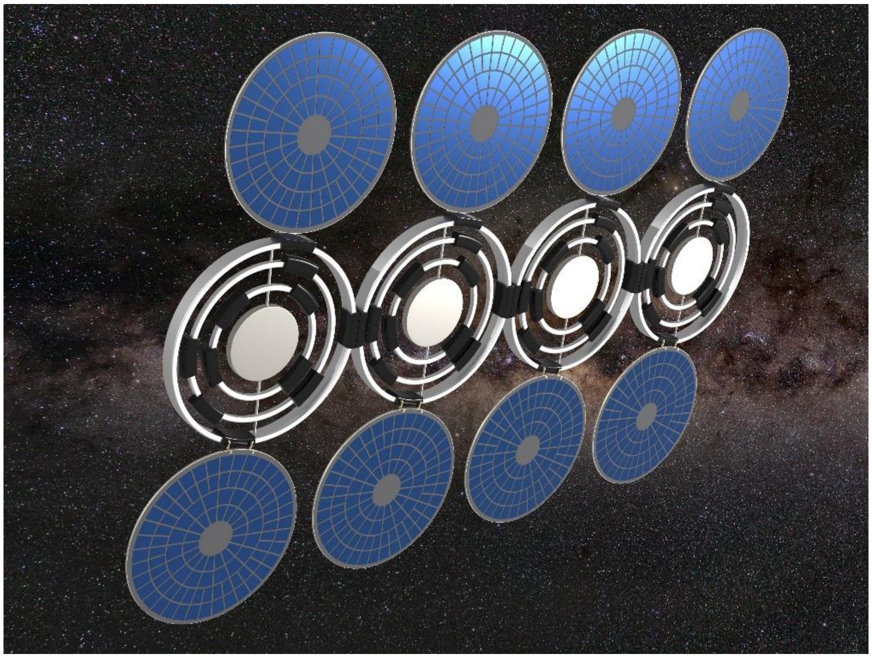

Figure 2: A CAD drawing of 4 interconnected HIVE units during a space mission. The trams are shown in black. The inner hoops are shown in the planar configuration but can rotate about a center of axis to allow the payloads (on the trams) to have out-of-plane visibility.

HIVE Applications

The HIVE concept truly provides "infinite possibilities" for space mission architectures. A HIVE configuration can conduct missions as an interconnected set of units (e.g. multisensory mission spacecraft or a robotic arm with a novel end-effector), as a free-flying formation entity (e.g. sparse aperture), or as a solitary single satellite. [4]. To expand upon these examples and push the bounds of imagination and innovation, we will describe three distinct applications for HIVE.

First, a HIVE configuration to address the mission of Space Domain Awareness (SDA) could take many forms. Multiple payloads, each 1U in size, could be hosted across multiple HIVE units. The configuration could be a large structure, or even an optically connected network of deployed single-payload clusters providing sustained coverage. Lidar sensors could rotate about the HIVE inner hoops providing continuous surveillance of a particular spatial region. HIVE could configure into a large beach ball shape with 360-degree sensor coverage. If the SDA mission detects a target, HIVE could change the pose of the sensors located on the inner hoops on the individual units to provide additional sensor coverage, increasing the amount of information on a target to allow for faster response times in decision making. If for example, the sensors detect an oncoming piece of harmful debris, rather than move the whole HIVE ensemble construct, HIVE has the attribute of performing a dodge maneuver of the particular segment of the construct under attack. There are advantages to a large construct that can change its geometry. 1) it allows the placement of sensors over larger baselines which not only generates stereoscopic vison but also refines the range parameter of the item observed. 2) In deep space missions where radioisotope thermoelectric generators (RTG) must be used to generate power a satellite having a geometry resembling a large diamond shape makes sense. The nuclear power source is placed at the center and the payload sensors placed on the outmost edge of the configuration to limit effects from the nuclear processes undergoing in the RTG.

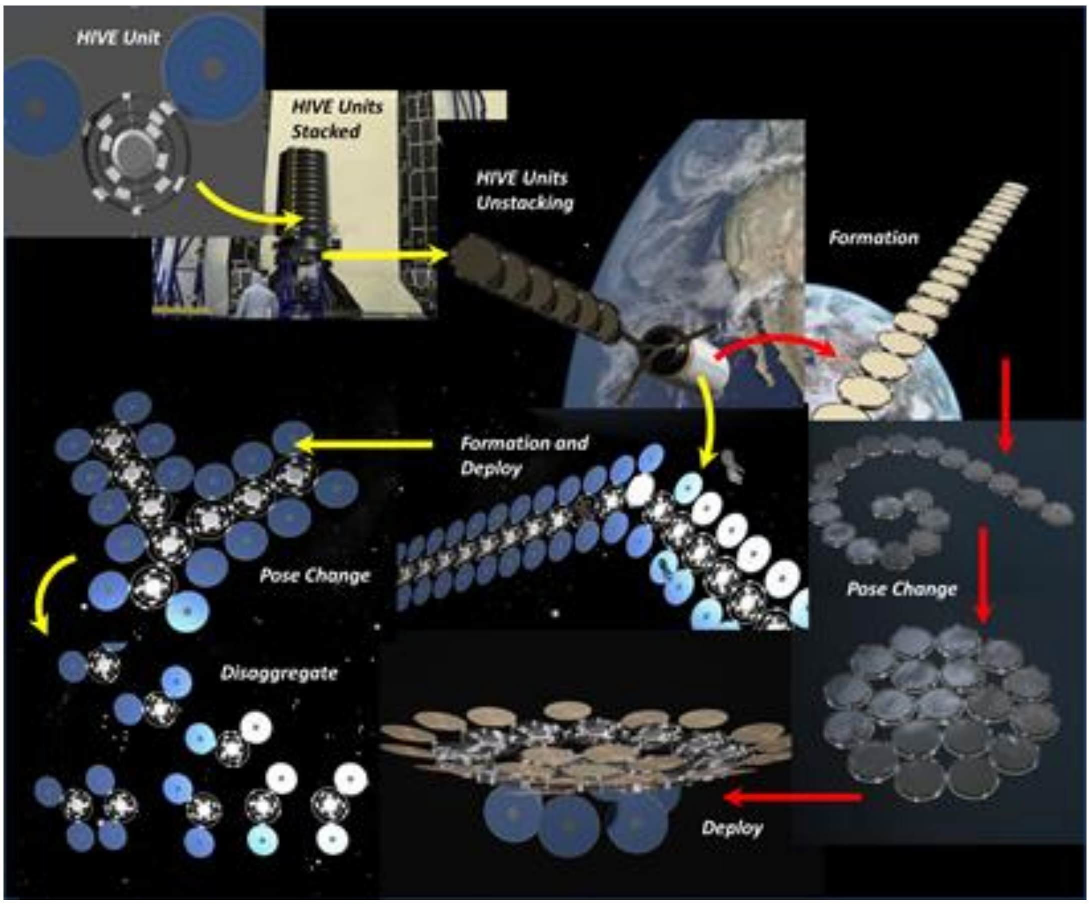

Figure 3: Multiple variations of HIVE configurations

Second, the capability to self-assemble large structures in space enables at least two applications. 1) In many applications (e.g. astronomy) aperture drives the physics. Consequently, the larger the aperture the more light gathering ability. 2) A space argosy, such as a large (1km) HIVE based modular structure that can serve as an on-orbit service depot, where positions on the construct are rented and hosted payloads draw power and perhaps a communication downlink. Given that each HIVE unit can provide a shared 2 kW of power, payload developers could simply provide a xU payload that has a standard interface to a HIVE unit ring. With ample launch opportunities and service "tugs" transferring the payload to the depot with depot-resource owner providing power and downlink COMM. Once a payload has completed its mission, it can be disconnected from

HIVE construct and transferred elsewhere. The location is then freed for another payload. The concept could also instigate prototype space-test developments to increase technology readiness level. The depot could also act as an on-orbit storage location for extra HIVE units, releasing clusters of HIVE units to perform specific missions and perhaps act as a gateway for future servicing or an in-space parts repository. Multiple launches can replenish aging units and provide upgrades. A city of depot towers could be optically linked and if they supported data servers, it would enable the creation of a data cloud in space to host high performance computing. This concept presents a whole new dynamic for providing and operating on orbit services.

Finally, a HIVE-based custom cluster could be transferred in a flatpack configuration and landed on a planetary surface, where it changes its geometry into infrastructure and provides power, communications, and other utilities, as well as acting as base scaffold to house equipment or become a habitat. As a reconfigurable system, HIVE can robotically self-assemble to prepare areas for human operations or additional spaceflight activity. For example, 1) HIVE units could assemble into a communication tower, as a repeater station, to provide connectivity among the different activity sites. 2) HIVE could act as a scaffold and carrying special units which can be filled with regolith material (i.e. enabling In-Situ Resources Utilization (ISRU)) to form a launch pad that can reduce the amount of dust kicked up with surface activity. Or maybe even a vertical barrier that surrounds launch sites to act as a protective barrier. 3) HIVE could even configure into a scaffolding dome shape to house an inflatable system that permits human habitat environments. Figure 4 shows a near-final image from a 3D dynamics simulation that spools up a HIVE linear chain into a dome shaped structure.

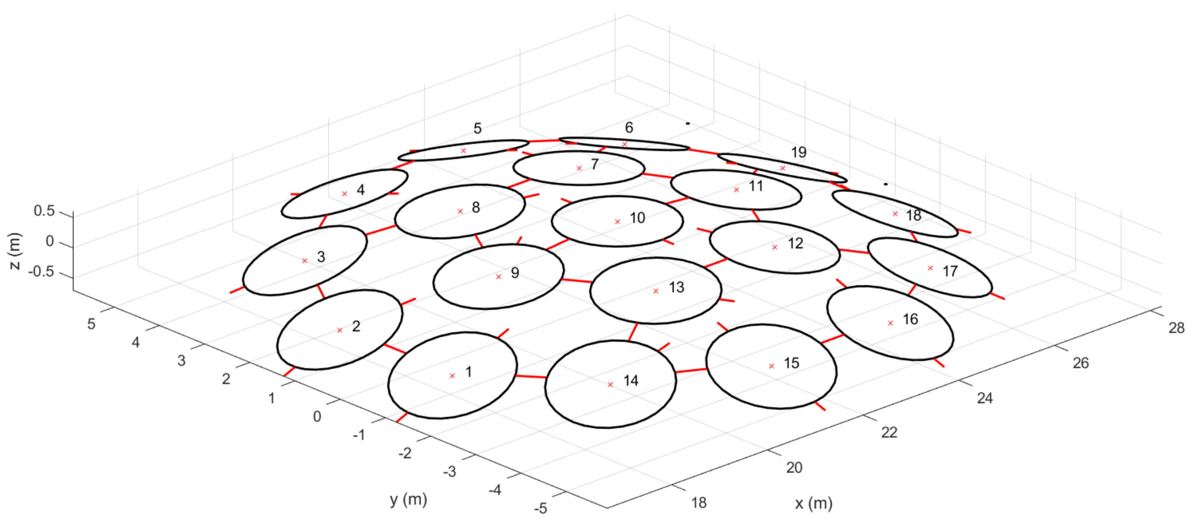

Figure 4: HIVE dome shape to support planetary surface infrastructure.

HIVE Architecture Advantages

Agnostic to specific missions, HIVE can be viewed as a standard mass-producible bus with common interfaces allowing for multiple and interchangeable payloads. At the unit level, the HIVE design directly allows for standard manufacturing and continuous production concepts and allows for a more accessible way to conduct payload and bus assembly, integration, and test. At the system level, HIVE architectures have the added agility to reconfigure interfaces on-orbit using the hoop and tram design, which is unprecedented in the history of satellite design.

Operationally, back up HIVE units can be stored on-orbit and quickly shuffled to replace a damaged unit. New HIVE units can be launched to replenish aging systems or continually upgrade capability at specific orbit locations. Or a HIVE assembly can simply reconfigure for a new mission once the primary mission is completed.

Summary of HIVE architectural advantages for consideration:

- Standard manufacturing and continuous production
- Efficient assembly, integration, and test of payloads and satellite bus
- Flat-pack topology for launch to orbit
- No propellant required for reconfiguration; utilizes reaction wheels and distributed control system design
- Resiliency (replenishment), modularity, continual upgradeability, in-space assembly and reconfigurability
- Data can be shared among units, enabling multli-sensor imaging and fused-data missions
- Telemetry to ground can be per unit for via high-speed downlink
- KW electrical power in each unit, share among units to MW
- Near-limitless arrangements including: Linear, sparse aperture, large structure, disaggregate, formation flying units

Tech Transfer

We are interested in generating interest for HIVE and establishing key partnerships with non-traditional satellite developers, launch vehicle integrators, payload interface developers, and institutes or companies investigating carbon composite additive manufacturing. Those with the ambition to establish space argosies at GEO, establish space cloud web services, generating beamed power from space, are of particular interest. HIVE key elements, e.g. the specific payloads that “ride” on the trams, the trams, the grasper (i.e. connecting scheme) which allows HIVE units to interconnect are still open to further development and IP generation. The one necessary requirement is that the interfaces (e.g. payload to tram, grasper-to-grasper) be open source to allow wide spread use. Ideally, the development and establishment of the HIVE interfaces will mimic, for example, the ubiquitous USB computer connector which has become a worldwide standard [5]. The HIVE concept IP is protected in the U.S. and 6 spacefaring nations, and we suggest one route to demonstrating the first functioning HIVE space system might be accomplished by the establishment of a public-private partnership (P3). The benefit of a P3 would be the contribution and sharing of resources to increase technology readiness levels. Alternatively, a proof of demonstration by a single investor and developer could lead the establishment of a HIVE backbone that can be continually built upon and advertised for realty/power allocations in orbit.

Summary

The current space enterprise is just starting to think beyond stove piped systems to take advantage of commercial services and building capabilities across multiple platforms and is slowly evolving to incorporate protection and resiliency in space systems. The SmallSat-inspired HIVE design evolved into a revolutionary ring & tram system that takes the space industry beyond the current hosted-payload and rideshare SWaP design limits. Applications for a HIVE-based system were described for space domain awareness, large structure aperture or depot, and planetary surface infrastructure. These and other imagined applications cannot be provided with current space acquisition approaches and have a number of shared architectural advantages. We have also provided discussion on key players required to take HIVE technology to the next stage and possible paths for investment and demonstration.

References

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