SPACE MODULAR SYSTEMS

Overview

Currently US space systems are not operationally responsive to the warfighter nor cost effective to the nation. US space systems are custom-assembled on the launch pad where they sit, sometimes for months, waiting for launch day. John T. Correll, Editor in Chief, *Air Force Magazine*, points out in his article, “Fogbound in Space”, that only four percent of space shots launch on time.[1] This will not meet the future warfighting commander in chiefs' (CINC) needs. Today's large payloads drive the heavy lift requirements. Those heavy lift requirements are both costly and require long lead times. Reducing the typical payload weight is key towards reducing the need for heavy lift and increasing the operational response times for the combatant CINCs.

This paper advocates the use of small, lightweight modular satellites placed into orbit by light lift, then mated to a permanent support infrastructure in orbit--called the motherboard. One motherboard can be placed into orbit using one heavy lift mission. The motherboard will provide all support services currently aboard every independent satellite, such as power, communications, and fuel. With this capability resident on the motherboard, satellites will no longer need heavy, expensive support, or redundant systems. Modules can perform all the functions carried out by today's independent, expensive satellites. As a result, mission capabilities will increase, while lift response times shorten and operating costs decrease. The SPACECAST team believes the modular concept is the best, most logical, and efficient solution to provide for the increasing needs of the CINC. Consequently, there are several key aspects of the modular concept important to understand:

- The military has pointed out a critical need for space systems to be operationally responsive to the warfighter. This means cutting the delay time between mission approval and actual launch. Today's time frame is unacceptable.

- By breaking the paradigm of large, independent, heavy, and expensive satellites, the US can fully support its military and civilian needs from space more efficiently by taking advantage of the economies of scale offered by standard interfaces coupled with the motherboard.

- Thinking, attitude and imagination are key to changing the paradigm. Just as global power does not require concentration of all aerospace assets on one base, a space system's function need not be provided by enclosing all its capabilities within one skin.

- This concept proposes a modular approach and common satellite interface system to support payloads, thereby requiring smaller and less complex lift.

- The motherboard will be capable of supplying its own energy means and transferring additional energy to packages when needed.

- Given the four organic capabilities of energy, fuel, communications, and self-defense, the motherboard can fully support and defend a myriad of modules and missions sent to it.

- A goal of the modular satellite is to be able to plug-in any type of module into any standard port on any motherboard. This concept can best be exemplified by the way nearly any electrical appliance is able to plug into any standard 110v wall outlet and receive the power it needs to operate.

- Modules will have the ability to:
  -- operate while docked to the motherboard,
  -- operate independently from the motherboard for weeks at a time, and
  -- operate independently by mating with a services support pack provided by the motherboard.

- The ultimate goal of the modular approach is to have distributed systems that are electronically, not physically, connected and cross-linked.

This concept is evolutionary, not revolutionary. It demands a change in philosophy as to how we deploy and support space assets as opposed to a mere change in technology. The modular satellite proposal will employ small modules--each having unique capabilities (such as communications, imagery, energy transfer, etc.) able to support our combat forces. The intent initially is to position a motherboard in orbit that will provide all necessary support functions to the modules (such as power, communications, housekeeping, etc.) through a standard interface system. The modules will contain only equipment necessary for their specific mission (communications, navigation, imagery, weapons, etc.). The motherboard frame will be assembled in space, using a common configuration designed to accommodate multiple support functions. This will allow for maximum flexibility in designing different configurations of modules.

The concept of the motherboard represents a new means to operate in space. During times of crises, the National Command Authority (NCA) and the combatant CINCs will have the flexibility and short-to-immediate response capabilities to crises, which are currently unavailable. To implement the modular satellite concept, there will have to be a change in the way we think of satellites and the exploitation of space. Speed and cost must be the drivers. The best systems do not have to be the most expensive ones. The modular concept allows us to place in space only what is needed to accomplish the specific mission, yet build them to design standards for interface with the motherboard. Modular satellites will provide a building block approach to the most complex of systems. A shift in thinking of space exploitation as an expensive adventure of enormous cost, in terms of time and money, is essential. As the Secretary of the Air Force, Sheila E. Widnall, said, "Customers can't afford every launch to be a unique engineering event. What they do want are dependability, availability on demand, and high reliability at a competitive price."[2] Once this culture shift occurs, the modular satellite concept will become the attractive choice for future satellite operations.

The Capability and Its Relevance

The military has pointed out a critical need for space systems to be operationally responsive to the warfighter. This means cutting the delay time between mission approval and actual launch. Today's time frame is unacceptable (table 1).

Launch Vehicle	***Time to Launch***
Pegasus	***2 days***
Taurus	***5 days***
Delta 7925	***23 days***
Atlas II	***55 days***
Titan IV	***100 days***
Shuttle	***150 days***

Table 1. Launch Delays[3]

Heavy Lift Requirements

Motherboards will be positioned in the common user orbits (i.e., low earth orbit [LEO]--100-500 nm, medium earth orbit [MEO]--11,500 nm, and geosynchronous earth orbits [GEO]--22,500 nm) to maximize operational responsiveness and flexibility (figure 1). Each motherboard structure can be placed in orbit with current heavy lift systems such as the Space Shuttle or Titan IV. Further advances in modular technologies may eliminate the need for heavy lift to place motherboards in orbit.

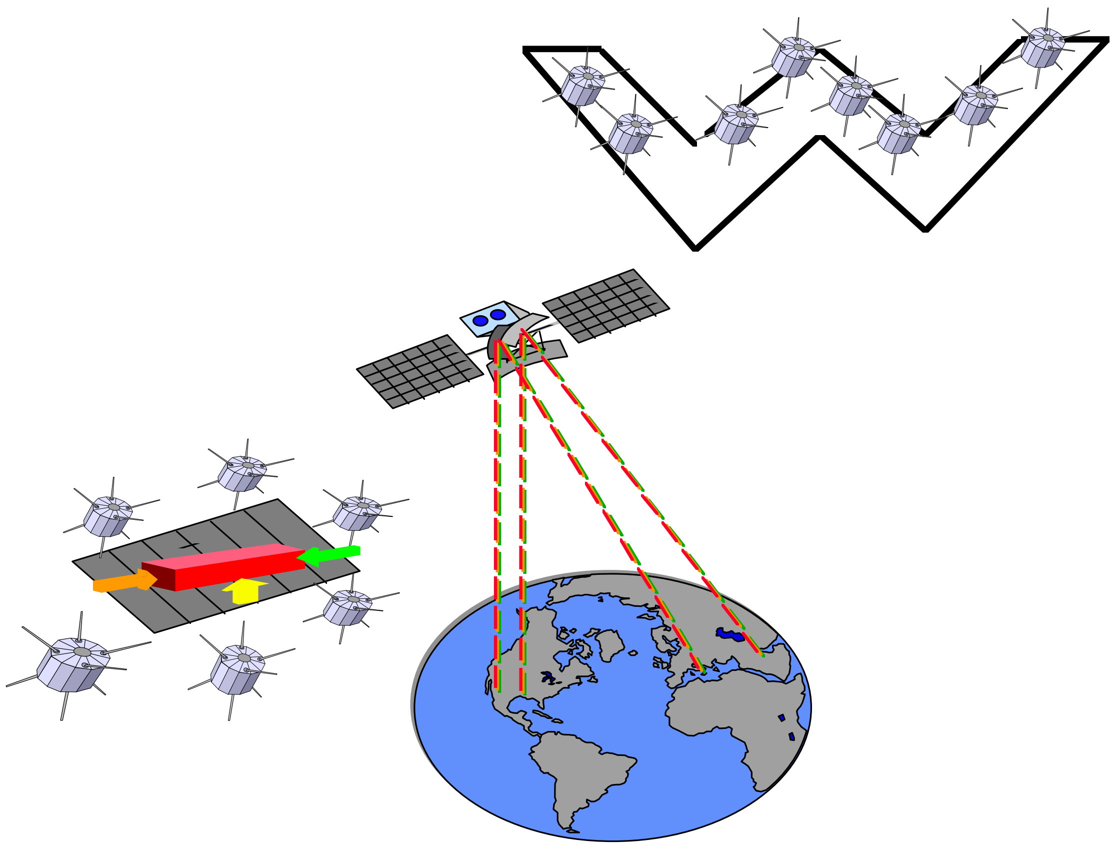

Figure 1. Motherboard Orbits

The Space Shuttle can lift 55,100 pounds (65,000 pounds in 1999 with use of new boosters) to a standard 110 nm LEO. The Shuttle's payload bay is approximately 60 feet long, 22 feet wide, and 13 feet deep. The motherboard will be designed to collapse and fit into the Space Shuttle and will require a single launch to place the entire structure into LEO. On the other hand, the Titan IV, the newest and largest unmanned US space booster, can be used to lift the motherboard beyond LEO. The Titan IV can carry payloads equal in size and weight of the Shuttle. Depending upon the design of the motherboard, the Titan IV nose payload faring could be modified and the use of current options in nose fairings could be applied.[4] As the modular technology advances in the future some of the smaller launch systems could be used for modular lift.

Light Lift Requirements

By employing the modular satellite concept, lift platforms can be reduced in size, weight, and bulk. Flexibility and responsiveness will be the resulting hallmark. Moreover, if packaged properly, multiple modules can be launched on a single booster. To reduce cost and lead time for development of new lift programs, some current systems and ideas can be used. Some may require modifications and enhancements, but the idea of using light lift boosters makes fiscal sense with today's limited budgets. Just as important are the time savings obtained by not reinventing the wheel by developing new expendable boosters.

Pegasus is a three-stage, solid-propellant, all-composite-winged rocket. It provides a cost-effective, reliable, and flexible way of placing small payloads into sub-orbital and orbital trajectories. Because of the launch parameters and location, this system has fewer down range safety considerations than conventional US systems. It can be launched over the ocean. Many factors add to the performance of the Pegasus. First, the potential and kinetic energy are contributed by the carrier aircraft (NB-52/L-1011). The second factor is the reduced drag to lower air density at higher altitudes where Pegasus is launched. Third, are the higher nozzle expansion ratios at higher altitude for improved propulsion efficiency along with the reduced gravity losses due to the unique flat trajectory and wing-generated lift.[5]

Orbex is compatible with Pegasus payloads. It can carry 425 lbs to 400 nm polar orbit and 885 lbs to 200 nm equatorial orbit. Orbex has vertical payload integration and horizontal vehicle assembly. It employs a dual purpose launcher and transporter combination allowing for check out of the vehicle in the horizontal position and launch in the vertical position. The launcher, designed and built for the Scout Program, has a rotatable base permitting control of azimuth to 140 degrees and an elevating pitch control to the 90 degree vertical position.[6]

The Multi-Service Launch System (MSLS), derived from the now retired Minuteman II ICBM, provides the capability to place up to 1300 pound payloads into orbits to 400 nm. By using standard aircraft flight control systems, a modular approach to vehicle design, horizontal processing, and a PC-based launch control system, MSLS provides a rapid launch capability at low cost. A similar derivative of the Peacekeeper could place several thousand pounds into LEO and a 500 pound satellite into a MEO.[7]

There are other potential options for launching modular systems such as the TAV concept, covered in the lift portion of this study and the single stage to orbit (SSTO/Delta Clipper), or two-stage to orbit (TSTO) lift systems. Also, heavy systems like Titan IV often possess contain unused space within the fairing, offering modular payloads free or extremely cheap lift.

To place modules in orbit, light lift vehicles like Pegasus, Taurus, Minuteman or Orbex could be used. Their payloads of 400 to 1000 pounds will require the packages to be designed to this requirement. With the modular concept, different modules on the motherboard could function as a distributed system and provide the same service that much larger, heavier satellites do today. By using light lift vehicles for the modules, launch points will not be limited to one or two locations. The Pegasus concept of lift is a good example. Small (600 pound) payloads are launched on a Pegasus booster from a B-52 to save 35,000 to 40,000 feet of altitude travel and gravity pull. The modules launched on these boosters can still be sophisticated in design, yet require far less organic or permanent internal support systems since the motherboard will provide these services throughout most of the system's lifespan. Launch concepts advocated in the Air Force Institute of Technology-led SPACECAST Unconventional Lift Study, have very near-term potential or are on the visible horizon and will benefit this concept's needs.

Design Options For the Motherboard

Various possible designs exist for a motherboard (figure 2). Each offers flexibility and survivability, crucial to the satellite's mission. One configuration could have the motherboard at the center, shaped as a flat plane with the modules arrayed around the edges (the top portion of figure 2). This design allows a large number of modules to be connected to a single motherboard. It provides greatest capacity per board. A second configuration could have the motherboard consist of several long rods connected at their ends similar to joints in human limbs (the bottom portion of figure 2). The modules would be connected at docking ports that are arranged along the limbs. The docking ports would rotate along the limbs' axis to minimize the chance of obstruction or interference between modules. This configuration gives the satellite a "Tinker Toy"™ appearance while providing a more survivable design than the first configuration. If the satellite is hit by an object, only the portion directly damaged would be affected. Another advantage of these two configurations is the capability of transferring modules between motherboards for added survivability and operational flexibility. Without the modular satellite capability, the cost of placing many large, complex satellites in orbit would be overwhelming. Other variations are limited only by one's imagination. Further advances in technology may result in the ultimate goal: a wireless structure without physical connections, similar to the current cellular phone system, but still able to provide support for various modules. The first step, the unfreezing event, is to begin envisioning how large capabilities can be provided by small, interactive parts.

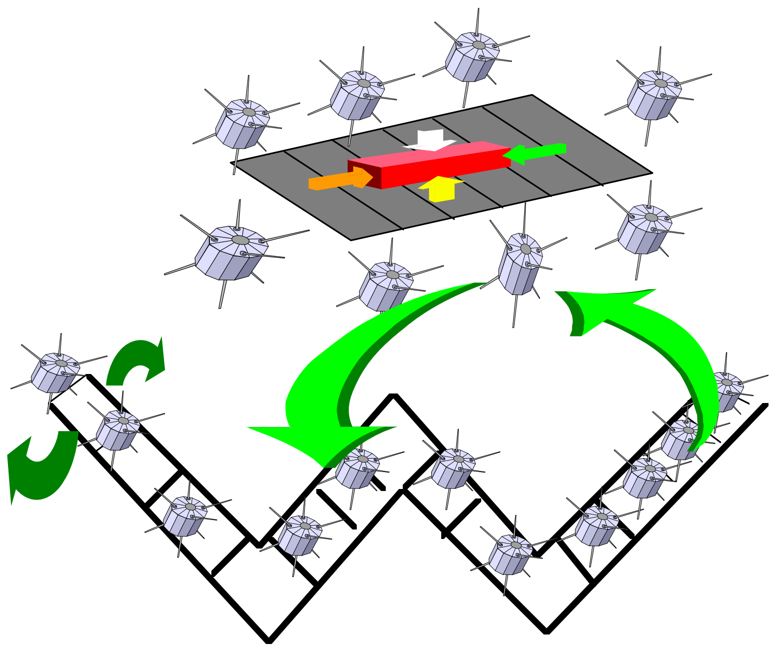

Figure 2. Two Examples of Motherboard Configurations

Future Satellite Interface Standards

Standardized, modular, miniaturized components and virtual reality technologies are providing significant improvements. The flexibility of being able to travel with, and use, electronic equipment worldwide adhering to a common set of standards is coming of age. Logically, similar approaches will be taken for space assets. Standardization will provide the economies of scale necessary for more successful commercial space endeavors. The parallel can be made to the computer industry and the RS-232 interface cable. Modularity will allow the trend in product specialization to further enhance commercial enterprise. The parallel, again made to the computer industry, is the motherboard approach accommodating a variety of chips, allowing you to upgrade to newer chips as they become available. Miniaturization, whether in space or on earth, translates to mobility, flexibility, and the sheer power to do more with less. Commercial space systems using the standardized, modular design concepts can also take advantage of the support capabilities of the modular system.

The modular satellite concept relies heavily on several core ideas essential to understanding its feasibility as a future method of using satellites in space. Among these core ideas are the need to develop and adhere to standardizing packing dimensions, docking, electrical, data, and matter transfer (such as fuel). Consequently, we must take the initiative to implement a set of technologically superior standards to lead the way.

A goal of the modular satellite is to be able to plug-in any type of module into any standard port on any motherboard. This will allow for easy replacement and configuration of modules on any motherboard giving multiple combinations for all satellites. Also, it will greatly simplify repairs, testing, or troubleshooting at any of the docking ports. System problems can be observed and repairs accomplished via a remote telepresence from ground-based space operations centers using remote robotic systems in orbit. Software standards will also have to be designed. This demands evolutionary improvements in space similar to the process evolving with central processing units (CPU) in the personal computer industry (e.g., 286, 386, 486, Pentium, and whatever will follow Pentium).

Satellites not meeting the interface standard can still have their utility extended by designing coupling devices enabling those satellites to dock with a motherboard.

Currently, several efforts are underway to develop small, light satellites in a modular fashion.

Motherboard Organic Capabilities

Each motherboard is designed to operate independently and offer support services for a number of modules. As a minimum, each motherboard must include organic energy, fuel, communications, and defensive capabilities necessary for its own operation and for the modules on board. An energy source is essential for all satellites. The motherboard will be capable of supplying its own energy means and transferring additional energy and fuel to modules when needed. Energy production on the motherboards can include solar, nuclear, thermal, anti-matter, inertial, electric batteries, or any future power source that can be packaged and attached to a standard interface. Fuel to maneuver the motherboard to varying orbital positions will also be required, if maneuvering is desirable.

Refueling individual modules will be one of the primary missions for the motherboard. Bulk fuel may be flown to the motherboard occasionally to replenish fuel supplies. Ideas for fuel storage vary widely to include hydrazine storage tanks, high-density solid fuel packs, and nuclear fuel rods for possible future nuclear engines. Since fuel accounts for much of the weight of a satellite, independent storage tanks could be lifted in bulk to the motherboard. Modules could be launched, nearly empty of fuel, and refuel at the motherboard once in space.

Communicating between the motherboard and ground, air, and space stations, as well as between motherboards and modules, will also be vital for the operation of this concept. Moreover, the motherboard will have the organic capability to facilitate a JTIDS-type (Joint Tactical Information Distribution System) information network for the CINC and the warfighter on the battlefield via its own CPU and communications net (figure 3). Finally, a self-defense capability must be organic to the motherboard.

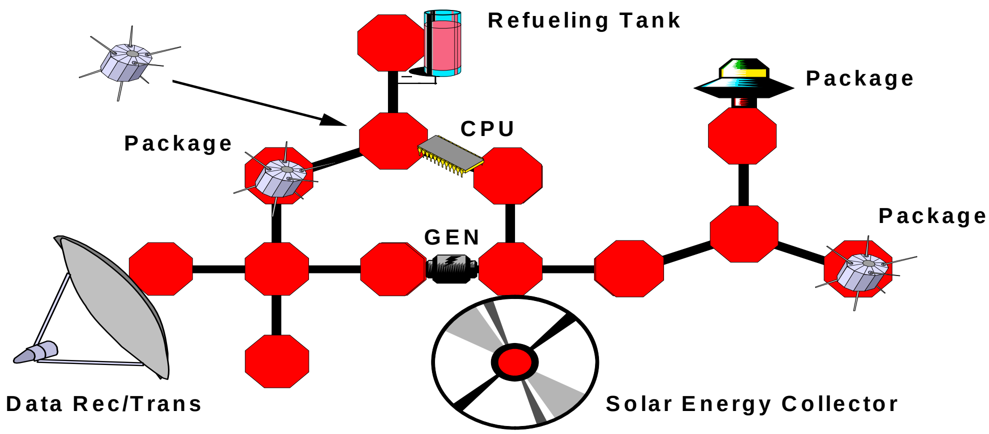

Figure 3. Typical Motherboard Support Capabilities

Although the modules can separate and disperse from the motherboard when threatened, further self-defensive attributes should be incorporated within the motherboard. Stealth technology for the modules and the motherboard would enhance their ability to perform their respective missions almost unseen by adversaries. Anti-satellite weapons will further strengthen its defensive posture. The motherboard can fully support and defend a myriad of modules and missions sent to it.

Modular Satellites

The motherboard concept is achievable with current technologies. Space must become cooperational, requiring a change of the way we think of space. Satellite designs must become more standardized. The miniaturization achieved during the Apollo space program is occurring exponentially across the spectrum of space and electronics research and development. The focus must include the manufacture of relatively small modules capable of interfacing physically and non-physically with space infrastructures and other modules. The modules must be designed to take advantage of low-cost lift options (Pegasus, Orbex, Black Horse) and to maximize flexibility in launch operations (responsiveness). The modules must also realize a high cost-to-benefit ratio. This effort requires adaptation of standard power interfaces[8] and the use of soft docking and computer vision-based guidance and control techniques.[9] Current research for the Space

Station Freedom is addressing miniaturization and other material problems. Solutions will most likely see the same technology spin-offs as previous space programs. Advances in the development of lightweight materials[10] and the resulting miniaturization of major components will prove ideal for applications where weight and volume are essential. Finally, modular fuel and propulsion packs will increase module manipulation.

The modules will be small packages designed for a specific function or mission and mated to the motherboard with a standard interface connection. Standard interfaces will provide the maximum flexibility for module docking to each motherboard. Any module will be able to dock at any position on any motherboard in orbit, provided it can mate up with the standard interface (figure 4).

With the aid of the small lift vehicle, missions from Earth can remove, replace, reprogram, repair, modify, or return modules in much the same manner as we replace light bulbs. Modules can rendezvous with a motherboard in LEO. However, due to the limitations of light launch vehicles, modules requiring higher earth orbits may boost to higher altitudes with orbital transfer vehicles (OTVs) or strap on a booster support pack module from the motherboard. The purpose of the OTV is to provide a low thrust propulsion system capable of moving within an orbital band, as well as between orbital bands. The modules can also be fitted with small dedicated systems (such as power, propulsion, or communications) allowing them to operate independently of the motherboard for short periods of time, such as days or weeks.

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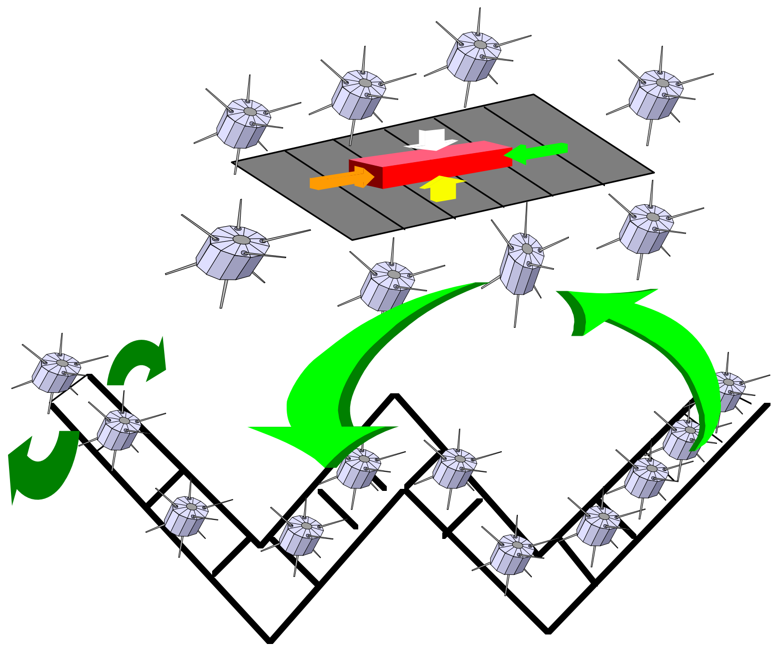

Figure 4. Motherboard Docking

At least three methods for providing operational support to the CINC from the motherboard may be possible. First, modules can separate from the motherboard and enter independent orbits to monitor specific regions (figure 5). Second, modules can be stored on the motherboard. As the CINC's requirements are identified, spare modules on the motherboard can be activated or combined with other modules to provide an enhanced operational capability. For example, modules can combine to increase surveillance capabilities. Additional required modules can be launched on demand with light lift to respond to a particular mission need or threat. Three different types of modular packages give representative examples of applications.

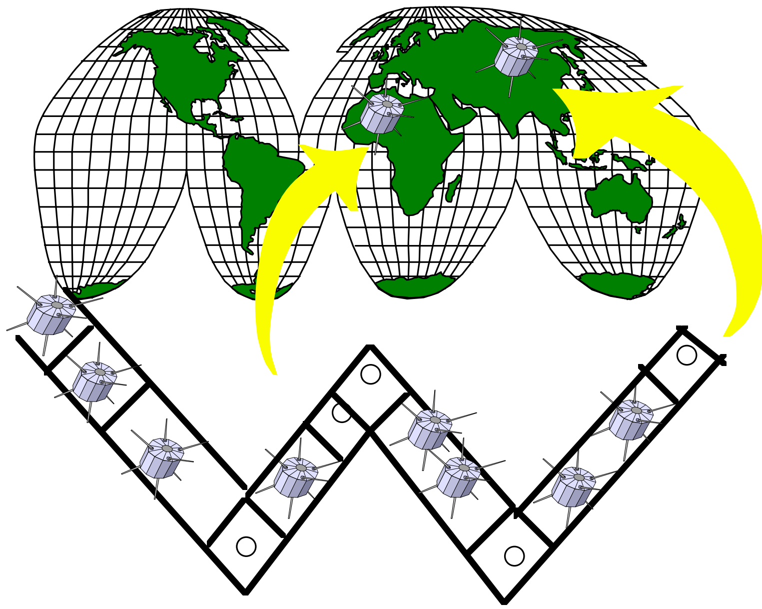

Figure 5. Module Deployment

Emitter Modules

Information is an essential element of the warfighter's ability to win. The need for space-based intelligence coverage is rapidly growing. In this "come as you are" world of globally distributed threats and dangers a global view providing instant coverage of any region is necessary. The CINC's decisions will require the ability to see the area of responsibility (AOR) firsthand. Overhead space assets best provide real-time intelligence information. Fast, accurate intelligence allows the commander to maintain the initiative against the enemy.

Emitter modules might include communications, radar, designators, illuminators, navigation, jammers, IFFs, hologram projectors, weather changers, and debris destroyers. Obviously communications modules are necessary as organic parts of the motherboard. However, additional communications packages may be added to the motherboard to enhance its missions or to lease to the civilian sector. Communications modules can range widely from datalink transmitters to television signal transmitters. Individual communications links for the soldier on the ground to the commander in the field will be possible via the motherboard packages. These communications links can vary between mere radio transmissions, teleconferencing, or viewing the battlefield in real-time via a module supported by the motherboard. Radar packages can monitor the entire AOR from the motherboard or an independent orbit and relay information to command and control centers instantly.

A goal to pursue is to have the ability to designate or illuminate specified targets from space for smart munitions' guidance--thereby eliminating the need for separate target designating aircraft in large strike packages. Jammers can cover whole regions of the battle area or specific targets, receiving their tremendous power needs from the motherboard. Friendly troops and equipment carrying miniature IFF transmitter/receivers can be instantly recognized by IFF packages and relayed to the motherboard's JTIDS to help avoid friendly-fire casualties. Moreover, hologram projectors can depict units of US forces in different areas of the battlefield to confuse, misdirect, and demoralize the enemy. Systems designed to generate or control weather patterns can also benefit from the motherboard's support facilities. Modules, designed to destroy or decay the orbits of space debris, could use the motherboard's support features as well.

Receiver Modules

Separate modules on the motherboard can also include receivers such as intelligence, weather, surveillance, and arms control monitoring systems. These systems can be further enhanced in the future to present information in a video-type or holographic format to the warfighter or planner. Receivers will include radio, telephone, television, radar, datalink, telemetry, and holographic transmissions emanating from the AOR.

Weapons Modules

The ability to deliver munitions on target has progressed at an exponential rate. While treaties or agreements may prohibit the basing of any space-to-earth strike weapons, should hostilities commence space provides a superior medium for weapon delivery. Warfighters can greatly benefit from weapon systems based in space to provide precise destruction of targets. The first nation capable of force projection from space will change the entire nature of warfare. Projectiles launched from spaced-based platforms will give the flexibility of total battle space coverage, stealth, and inherent defense. In addition, space-based weapon systems can feasibly locate, assess, and engage targets from a single platform. Weapons modules able to use the motherboard constitute a wide array of ideas and concepts far beyond the scope of this particular section. However, weapons modules can include directed-energy weapons, laser weapons, plasma weapons, kinetic-kill weapons, HARM-type weapons, conventional weapons, and anti-satellite weapons.

Potential Technologies

Virtual Reality

Virtual reality technology needs substantial development before incorporating it into this concept to perform maintenance, refueling, and manufacturing. A near real-time feedback capability from a great distance is required. Research breakthroughs in virtual reality technology require substantial advances before they can be incorporated into this design. In addition, complex operations are required to perform the various housekeeping tasks. A substantial improvement in robotics will also be required to support this concept.

Robotics

Complex manipulations are required to perform the various maintenance tasks. A substantial improvement in robotics, as well as remote command and control ability, will be required. System problems could be observed and repairs accomplished via a remote telepresence from ground-based space operations centers, utilizing remote robotic systems in orbit.

Docking Mechanism and Vibration Control

Efficient docking mechanisms and procedures are necessary. The abstract on advanced docking indicates this technology is very possible.[11] Another major concern for the modular satellite concept is the vibration and transmission disturbances to other operating modules on the motherboard during docking and positioning of neighboring modules. Technology advancements in techniques, materials, and component isolation will be required to reduce these self-induced vibrations. This will undoubtedly drive research to determine which types of modules will be able to work together on the same motherboard. Furthermore, it will lead to configuration management standards for the satellites. Research in soft coupling techniques, laser radar docking, docking mechanics, and sensors will have to be standardized. Further development in manufacturing small tolerance fittings and micro-component machines will be necessary.

Orbital Transfer Vehicle

An OTV capable of moving through space, with less than orbital velocity but sufficient to pull objects from one orbit to another, will be required. This vehicle will not need to have a high thrust, merely a high specific impulse (high efficiency). Since the system will already be in orbit, it can operate autonomously over days or weeks (slow but steady acceleration) in a highly efficient manner.

Beyond the Motherboard

Distributed Systems

A value of the motherboard is that it demands a new way of thinking about space system capabilities. By thinking of “capability” as the aggregated outcome of separate, interactive, contributing components, it is possible to envision new ways of combining the components. The motherboard is the first step. Small, interactive, proliferated systems are the next step.

The motherboard requires small component satellites. This requirement suggests miniaturization, common manufacturing standards, mass production, and a reduced requirement for heavy lift. The ultimate goal is to substitute the physical connectivity of the motherboard with electronic connectivity and cross-linking. Electronic connectivity and cross-linking afford at least three advantages.

First, and indirectly, reduced size and weight allow reduced reliance on heavy lift. Reduced heavy lift requirements allow smaller launch vehicles and more frequent launch.

Small, reusable systems could reduce the cost of lift and lead to space access that is routine.

Second, proliferated and distributed systems allow more resilient networks. If a single node fails, it can more easily be replaced. Proliferated, distributed nodes force an adversary to attack multiple and widely dispersed aim points. If some nodes are lost, brilliant switching schemes could allow other elements of the proliferated system to assume the lost node's function without interruption. The military advantages are obvious.

Third, proliferated and distributed systems can help avoid the technological obsolescence of the on-orbit force structure. As technological breakthroughs occur, and these cannot be foreseen, they can be added to the network without the need to replace the entire network. The same is true for advancements or improvements that cannot be characterized as breakthroughs. A node with the computational capacity of an "886" laptop, for example, can be augmented by a "986" node. The 886 may be technologically obsolete, but it would remain on orbit to augment or serve as a backup for the newer generation node.

Eventually, some satellites may be as small as today's microchip. Unless we have accepted a new way of thinking about systems and space capabilities, our paradigm will reject the opportunities a microchip-sized satellite could provide. Even so, there are some entities that cannot easily be reduced in size, such as human beings (although in the far future genetic engineering may make even this possible for space operations). The motherboard modular idea becomes the foundation for other space applications such as space industrial parks, depots and bases.

Industrial Park

An orbiting, manned platform or Industrial Park, accessible to friendly commercial/civil endeavors will provide the basic infrastructure to support a variety of activities. An operational facility where space is available for customers will encourage space-based manufacturing, innovation, and development. Such an industrial park will perform a wide variety of benefits. The first is a common infrastructure upon which to build. This includes both a physical infrastructure (self-contained pressurized facility, attachment points, gravity for the workers to simplify certain processes), as well as a facility infrastructure (power, communications, docking facilities, and internal transportation) with costs shared by a number of users. The industrial park could take advantage of direct access to solar power, the vacuum of space, and a near zero-G environment to provide some unique manufacturing opportunities. By permanently placing the manufacturing process in orbit, the expense, risk and constraints of lift-off, performing a manufacturing cycle and then de-orbiting will be radically reduced. All that will be transported into space after initial set-up of the manufacturing process would be the raw materials. Only the finished product will be returned to Earth.

Ultimately, the use and exploitation of space will require human occupation. However, it will more likely be the commercial sector, motivated by profits available through space manufacturing and exploitation, that will lead the way. An orbiting industrial park, using the motherboard support concept, will provide the basic infrastructure and real estate necessary for commercial enterprises to risk capital. Rather than forcing a user to invest in high-cost, miniaturized, ruggedized support systems designed to operate in a zero-G environment, this industrial park will enable the entrepreneur to focus on the process without concern for the infrastructure support. The military can, of course, benefit from spin-offs such as space for facilities and storage, manufacturing and assembly near space systems, and real estate from which to conduct space operations.

Manufacturing in Space

Space manufacturing has a number of significant benefits that are impossible or extremely expensive to replicate on Earth. First, in-space production allows access to a zero-G or near zero-G environment. Theoretical predictions of superior quality microchips, high purity pharmaceuticals and super alloys not possible on Earth are some of the benefits of space manufacturing. Second, the pure vacuum of space provides an ultra clean, biologically isolated environment for advanced chemical and biological processes (reactions and separation mechanisms). In addition, space offers direct access to cosmic radiation and solar radiation. Although there is not now a significant demand for manufacturing processes using cosmic radiation, unimpeded access to solar radiation and limitless space for collecting the energy will give an orbiting platform almost limitless energy. Such clean renewable energy will be of great value to energy intensive industries such as aluminum manufacturing, fusion development, and high energy physics research. Commercial spin-offs might include prototyping for film prop makers, architects, urban planners, and surgeons (prosthesis), solid-imaging for chemists, physicists, biologists, police artists, terrestrial topographies, pattern molds for manufacturers, industrial engineers, jewelers, and job shops. Commercial space assets implementing the standardized, modular design concepts can also take advantage of the support operations.

Manufacturing processes require space, facilities, power, process equipment and raw materials. They also require time to set up and optimize, and stabilize. Once established, processes can be operated in a continuous mode, greatly reducing operating costs. In addition, raw materials found in space (iron and nickel from asteroids, the Moon, etc.) can be processed into final product (structural beams, vehicle skin) for in-space application. At a space assembly facility, modular satellites, orbital transfer vehicles and deep space probes can be assembled, tested, repaired, and launched without the shocks and loads associated with current launch environments. Such vehicles will not be limited by the size constraints imposed by launch vehicles.

The machines needed to build the parts in space will vary in size, but may, in some cases be comparable in size to today's large commercial copiers and desktop laser printers. These machines will be part of a manufacturing system combining the applications of CAD (computer-aided design) and CAM (computer-aided manufacture) to fabricate the parts seen on the 3-dimensional CAD screen.[12] Just as word processing text is sent to a printer, by 2020, CAD programs could transmit a 3-D computer image to a fabricator machine where the part is manufactured molecule by molecule from metal, composite, or plastic powder. Similar to an ink jet printer spraying the text or graphic on paper, a fabricator would build a part by spraying droplets of metal powder together to form the part (or some other material). Additional benefits will be discovered once research and development of space processes commence.

The exponential integration of CAD and CAM may lead to the real-time computer generated manufacturing of parts in space from raw materials including metal, plastic, fiber, and ceramic powders. Current trends in this new technology are called automated fabrication (AutoFab) and desktop manufacturing. AutoFab is the process of generating three-dimensional solid objects by beaming light on multiple layers of photosensitive plastic polymers.[13] Advances in this technology include computer-numerically-controlled (CNC) milling, micro-machining, CAD/CAM; rapid prototyping, laser sintering, and droplet deposition to streamline manufacturing processes. AutoFab is driving manufacturing towards nanotechnology--where objects are constructed one molecule at a time. The leading experts in AutoFab expect this technology to become mainstream within 20 years. Furthermore, they believe the entire field of man-made and natural materials to be within the domain of additive fabrication, including soft organic tissues and refractory metals.

In short, automated fabrication incorporates the technologies advancing the generation of 3-dimensional solid objects under computer control. The fabrication process takes raw material in some shapeless form, such as blocks, sheets, fibers, powder or a fluid, and turns out solid objects with definite shape. Currently this process operates under three general categories of subtractive, additive, and formative:

- Subtractive--material is removed from a solid block until the desired shape is reached.

- Additive--material is manipulated to build objects one particle or one layer at a time.

- Formative--mechanical force is applied to bend or press a sheet or soft material into a desired shape. Also, the molding of molten or curable liquids into a desired object.

- A hybrid process is also possible by combining two or all three types of these techniques to build an object. Given the potential sources of raw materials in space, additive fabrication offers the best method for use in space. Of the additive processes, droplet disposition presents some intriguing ideas whereby an adhesive liquid is deposited in a controlled pattern to form an object. Ideally, space manufacturing would use the raw materials available in space or recycle space debris.

Space Assembly

In-space manufacturing will augment space assembly. Components or sub-components, both manufactured in space and transported from Earth, will be assembled and checked-out in a space assembly facility. Currently, satellites and other space vehicles are designed and constructed to withstand the rigors and stresses of launch. They include the redundancy and environmental specifications (i.e., class S parts) consistent with the severe environment of a high-G, high-vibration launch. Once the vehicle is deployed, it operates in a near zero-G environment with little, if any, lateral loads or vibration. In-space assembly and check-out will allow a vehicle to be designed and built for its operating environment, reducing cost and complexity. It can be tested in space, with any problems corrected prior to deployment.

Space Depot

A space depot will provide on-orbit repair facilities for transatmospheric vehicles (TAV), OTVs and satellites. Once again, the costs of lift, de-orbiting, and re-deploying a satellite will be eliminated. This depot will also reprocess captured space junk, either repairing and redeploying it, or scrapping and reprocessing, or recycling it as raw material. Implementation of a space depot will provide enormous leverage for the US space capability. An on-orbit depot will provide forward-based logistical support for space vehicles. A facility performing the functions described above can lower the payload weight of space vehicles, extend their operational life, conduct product research, mine space minerals and ore deposits, and improve space asset availability and survivability.

Operating Base

We have long recognized the benefit of deploying to a forward location when engaging in extended operations in a theater of operation. Warfighting capability has historically required the ability to provide a presence in the theater of operations. Such a presence has traditionally focused on the control of bases from which to operate at minimal expenditure of energy. Alexander the Great defeated the Persians by eliminating naval access to their bases (the Mediterranean ports) while arranging for himself prepositioned supplies and safe bases from which to operate. Recent experience with Operations DESERT SHIELD and DESERT STORM showed that power projection still requires a forward operating location relatively near the battlefield.

As space becomes a theater of operation in its own right, rather than a communications and observation high ground, there will be a need for real estate upon which to build a base of operation. Such real estate will require power, structure and facilities to enable forward pre-positioning of hardware, to reduce the time, energy and costs associated with deployment, and simply be near the front.

As an operating base, manned activities of all sorts can take advantage of a 1-G environment for physiological extension, recreation, and reduced lead-time to respond to in-space and on-Earth contingencies. It can also act as a staging and assembly area for preparations for deep space exploration and travel, either manned or unmanned.

Summary

The ability to observe, move, shoot, and communicate remain the fundamental keys to success on the battlefield. However, the expansion of the battle space over which commanders must move and communicate, as well as the speed and accuracy required to select and engage targets, have changed dramatically over the years. A commander's ability to observe, orient, decide, and act upon situations during war fighting is becoming more and more key to defeating one's enemy. Col John Boyd calls this process the OODA-loop.[14] By building a support structure in space, the US can maintain its technological lead over its adversaries and enhance its ability to get inside their OODA-Loop. The modular concept proposed by the SPACECAST team is the best way to provide for the increasing operational needs of the combatant CINCs. Indeed, during DESERT STORM, the satellites diverted from other strategic surveillance missions to positions over the Arabian peninsula consumed enough fuel to shorten their useful life by as much as two years.[15] Unfortunately, the US is currently unable to refuel those satellites in orbit. Adoption of SPACECAST's modular concept will solve this vexing problem.

Notes

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