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Breaking the Monolith: How Modular Architectural Thinking Can Save the UK Space Industry

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ABSTRACT

In the recent decade, Cloud computing infrastructure has gained sufficient power and cost-reduction to completely dominate online applications. Companies are now realising that moving from an on-premises single-block (monolith) application to remote managed micro-services (individual, asynchronous functions that can be scaled easily to demand) can reduce cost by orders of magnitude and importantly enhance redundancy, security and risk contingency.

The Space Industry, including that in the UK, generally takes the Monolithic approach to missions, either due to legacy or due to lack of belief or success in scalable, flexible architectures. This is even with the use of scalable lean development processes. These can have some success but it does not mitigate the reality that the risk of failure for any mission when reaching Launch and Early Operations Phase (LEOP) is around 1 in 10. This has dire consequences if your mission is built around a single spacecraft launch, itself a product of monolithic thinking.

Recent developments by companies such as Space X and Blue Origin are now forcing such a change of thinking. In some cases a byproduct of the successes of Space X are that established technologies are having their core business models seemingly made redundant.

To try and address how to change the thinking, this paper gives three examples of space technologies that have an alternative modular approach to fuel growth yet appear fixed to monolithic thinking.

Following on from this, a scalable, self-assembly satellite stack network is proposed as an example of how the UK Space Industry could build a more robust and contingent space infrastructure and at the same time, benefit from a fragmentation and enrichment of the industry. Space debris considerations are also considered and discussed.

INTRODUCTION

The purpose of this paper is to argue that with the current state of the space industry, adopting a modular mission architecture as opposed to a monolithic approach will be preferable and sustainable. This is primarily due to the recent observation that modular approaches are now progressing faster than monolithic missions, an example of which will be presented in this paper. It is therefore contingent on organisations and companies to consider reducing the exposure of monolithic design thinking in a mission, or series of missions. This may mean a radical redefinition of goals into multiple objectives rather than pushing for a single objective.

Monoliths and Modules

The concept of a “monolith”, or a single functional entity to achieve whatever tasks it is designed for, is best encapsulated in software, where its counterpart is the “modular” architecture. To briefly summarise the difference [1]:

- A monolith is an application whose architecture contains a series of dependent functions all contained within the bounds of the application or sub-system of that application.
- A modular application is designed such that the application has some baseline functionality that can be added to and scaled with ease. Functions can interact with other processes more easily

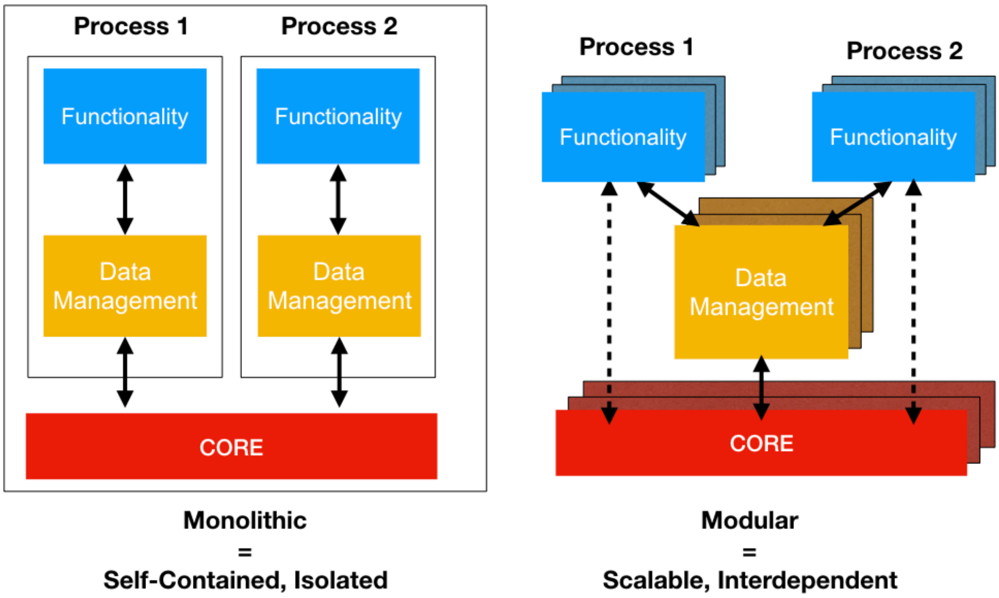

Figure 1 - Monolithic software versus Modular software

These differences are presented schematically in Figure 1. The monolithic architecture is sometimes referenced as the "smokestack" model [1] where there is little interaction or use of processing capability with other processes or other applications on the system. Some element of the architecture must be scaled beforehand to deal with the worst-case load and is typically fixed in size. A modular software architecture can achieve much of the same functionality but has the ability to deal with key loading scenarios as they arise. Functions can be scaled to deal with load. For example, if Process 1 has to handle intense computational load it can be scaled along with the data management. Importantly *the modular architecture can be adapted easily with feedback without compromising the system integrity*.

There is therefore a caveat to modular approaches: in order to optimise them it is often necessary to scale and adapt the underlying infrastructure. A modular architecture is thus a more abstract concept than a monolithic one and may not require full planning from the outset. Development can be incremental.

In recent years with the rise of Cloud computing services from companies such as MicroSoft and Amazon, significant benefits have been realised with a modular approach [2]. These are:

- A reduction in infrastructure cost for the same computational load
- The ability to maintain operation even with failover events i.e. built in redundancy
- A reduction in cost for the same application development and for use in production.

The move to Cloud-based modular applications has been so strong in recent years that the large majority of applications that people use today and are projected to use into the early 2020s will be modular [3].

Monolithic and Modular Processes

Monolithic thinking has been codified into certain types of developmental approaches One of the more well-known models is the "Vee" (or 'V') model that was originally developed by NASA [4]. In this process the development, qualification and delivery form a "V" where levels of the V are linked depending on the detail of each level (Figure 2). The process takes a customer specification and decomposes it into parts that are associated with desired functionality. Each step decomposes the concepts further until the smallest unit is reached. This is the lowest level functionality that is tested first with the level above tested next. The process repeats until the overall system concept is tested.

The V-model process does not tend to develop the low level elements before an understanding of the higher level concepts is made. This does not prevent informal development of elements of the system though and this is often encouraged for the purposes of risk mitigation.

However because the official process progresses through "gates" (the boxes in Figure 2) where the next stage is only released if the authority deems it is time to do so, actual measurable work is delayed. Levels are tested one by one and often this leads to not testing the complete concept as quickly as possible and continuously. It is heavily dependent on the initial planning and understanding which will then dictate the next stages. It is impossible to know this without direct feedback from the customer of the actual system to be delivered.

The process does not prioritise functionalities and requirements so that it is not immediately obvious that the V can be looped to "mop up" holes in specification coverage. Hence very often the progress only moves along stage by stage, a linear "monolithic" process.

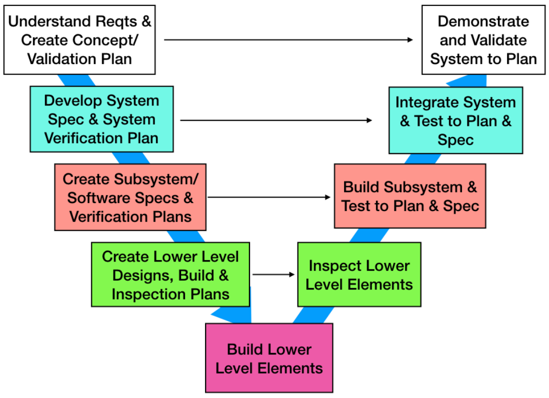

Figure 2 - The "Vee"-model (V-model)

In contrast, a popular modular approach is the Minimum Viable Product (MVP) coined by Frank Robinson of SyncDev [5] and often promoted by entrepreneurs such as Eric Reis, who is famous for his concept of lean development [6]. The MVP represents an application that fulfils the basic project requirements, relying on user feedback to drive the next stage.

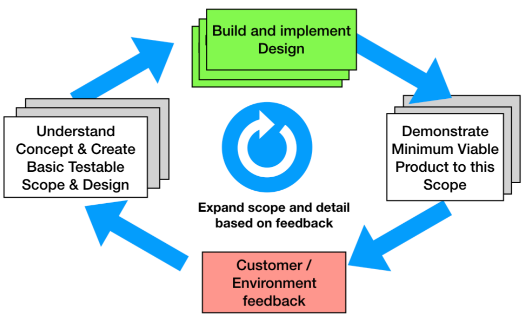

Figure 3 - The MVP (Minimum Viable Product) model

By definition it does not try and fix requirements at the outset but adapts. If it were to follow a V-model, each model would apply only for a short stage of decomposition, development and integration, even just once between product updates. The lean process by its nature only focusses on what provides most value to the customer and hence has a ruthless quality about it. Ideas are continuously tested rather than be driven by assumptions or agreements made in initial scope meetings.

Lower level system functionality may be sparse at an initial stage yet the customer has experience with a product, of which they get updates very often. A version of the final product can be used. For a space mission, this may mean that a basic subsystem is integrated onto a mock-up structure and tested in a vacuum chamber almost immediately. It may even mean parts of the mission infrastructure are launched into space as testbeds for future elements. The key concept of the MVP uses the fact that the "knowledge loop" only closes when there is direct feedback of the product.

Both the V-model and the MVP can use modern development processes such as the Agile Development Process which was defined in a "manifesto" by an international group of engineers in 2001 [7]. Primarily written to address software development it has implications for all types of projects.

A key element in Agile development is that the delivery to the customer happens early and that the scope of the specification grows and adapts to this need. When applied to the V-model, it is often seen as an approach to progress stages of the V so that interim "prototype" or "engineering" models are produced though there are often large time gaps between these. If the MVP model is used updates can happen for hardware in a matter of weeks; and for key software a matter of days.

The Agile development process favours an MVP-style model as both have the customer delivery of some working element as the end goal of a stage, rather than a meeting or a review as often occurs in the V-model. Getting to the goal as quickly as possible to understand feasibility is critical for space missions, primarily due to the main risk factor, that is often overlooked.

The Biggest Risk Factor for All Missions

The risk of a mission not fulfilling Launch and Early Operating Phase (LEOP) is slightly greater than 1 in 10 across all space launches since man started sending objects into orbit [8]. Launch failure is a major contributor to this risk and is lessened as a launcher has more successful launches. However the probability of a expendable launch failure after 10 launches is still of the order of 10%, and only with legacy vehicles does the probability of failure drop to single-digits [9]. The rise of smaller launchers, that are becoming a mission solution in the last few years, skews the probability of failure upwards again.

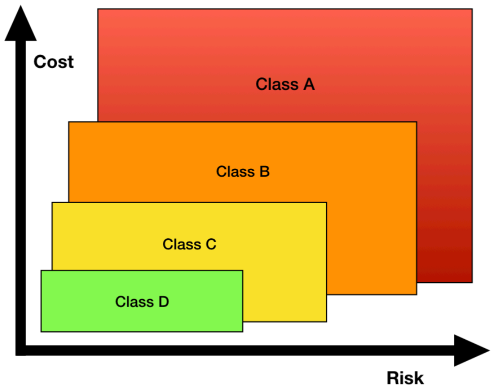

Figure 4 - Schematic of NASA risk classifications and scope of actual risk/cost envelopes

NASA (National Aeronautics and Space Administration) has classified various mission risk scenarios from Class A to D [10,11], often depending on the duration of mission and the parts used. A mission built mostly of Commercial-Off-The-Shelf (COTS) parts carries less development overhead but can also result in a lower-specified or short-duration mission by design. These are Class D missions and can be technology demonstrators. The higher the mission specification the more risky the components and subsystems as these have to be qualified for use. Some may be at a low Technology Readiness Level (TRL) and require years of refining to meet mission specifications. The highest class is Class A and often represents flagship missions such as a flight to another planet. Class A often carry the highest financial loss.

Figure 4 shows a schematic representation of the scope of risk and cost per class. It is worth noting that NASA defines Class A as having the *lowest risk position* due to measures being taken to mitigate risk by design [10], which is the opposite of what Figure 4 depicts. The argument put forth in this paper is that by spending so much time and money designing and trying to reduce risk, the risk actually increases.

If is important to stress that there is *no difference* in LEOP risk between a Class A and Class D mission, even though there can be orders of magnitude difference in mission development cost. In fact, having some contingency can help alleviate this monetary risk, something that NASA is considering [11]. This can either be in the form of monetary reserves or in common development architecture occurring on concurrent missions that can be quickly adapted to help rebuild satellites quickly, as was the case with CryoSat2 [12].

A question is then: if the risk of initial failure is so high and is independent of mission specification, why apply a monolithic approach to mission development and goals? Why go for a single-shot mission to achieve the goal?

One idea is that *if* you can afford to get a higher specification into orbit the returns will be greater. If you can beat the odds of LEOP failure then you will reap the gains. However this can often lead to a sunken cost fallacy situation, where prolonged mission development and over-specification end up with decades-long programs whose technology becomes obsolete before launch; or that a competitor enters the market and makes your mission architecture redundant.

Another idea is that this is a misinterpretation of the risk, in that probabilistic models are used rather than contingency models. This idea is best expressed by Nassem Nicholas Taleb, in his idea of system convexity, where it is better to minimise the cost of failures and fail often with multiple tries [13] rather than use past knowledge, as this often produces false metrics ("Fooled by Randomness"). In a convex approach, losses are contained whereas gains are asymmetric and can be great. For a space mission, using the convex system approach, it is better to build in critical failures of components and spacecraft that do not derail the overall objective rather than "place all the eggs in one basket" and believe that risks are only being minimised by qualification and acceptance testing.

THE MONOLITHIC MISSION

Based on the previous paragraphs, we can define a monolithic mission as one with a single large launch and operation goal in mind. These goals could be:

- Build a satellite to sustain 15 years of operation in Geostationary Orbit
- Travel to another planet using a single spacecraft stack
- Create a scientific instrument to measure a fundamental property of the Universe positioned in an advantageous Lagrangian point

We can then further define it in scope as:

- Uses a V-model for development
- Has stages such as Preliminary Design Review (PDR), Critical Design Review (CDR) and Delivery Review Board (DRB)
- Has a high level of specification per subsystem
- Is single launch based
- Is driven, as a whole or in part, by governmental (i.e. tax payers) money i.e. funding could be long-term and available in an emergency

A reader with experience in any large-scale engineering projects would probably recognise these features, though they are more acute for space missions.

A modular mission can take many forms but in the current environment it would be best described with constellation-type missions such as PlanetLabs Flock [14]:

- Launch tranches of satellites to create an interlinked constellation
- Accept a certain failure rate and loss of satellites

We can then further define it in scope as:

- Uses a lean loop ("Silicon Valley Style")
- Has simple specifications per satellite that may change.
- Has an overall architectural goal that can adapt
- Is careful with cash and has a limit of resources
- Relies on the success of each stage and the feedback to tune the next stage

Not all modular missions will be specified as such, and the example above is meant to drive home the idea that breaking the monolith can only occur if a mission can be re-architected in a way to accept failure and have contingency built in.

EXAMPLES OF MONOLITHIC APPROACHES MEETING MODULAR ALTERNATIVES

The following subsections highlight areas where a monolithic approach is prevalent in the industry, yet there is a modular alternative, which could augment or even replace the monolithic approach.

Ferraris or Trucks

Electric propulsion (also called ion thrusters or ion propulsion) is a plasma-based propulsion technology that allows comparable total impulse to chemical or cold gas thrusters with some advantages. These are: a much smaller fuel tank wet mass and the ability to finely control or manoeuvre a spacecraft over hours and days rather than with bursts of thrust (e.g. bang-bang modes).

Though used on space missions of varying types for at least the last twenty years, interest in having ion thrusters as a core technology has only become significant in the last decade, such that Boeing-Hughes committed to an all-electric satellite series in 2012 and ESA has planned dedicated thruster solutions on NeoSat [15]. More famous achievements in the field are:

- The NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) thrusters on Deep Space 1 [16]
- The Japan Aerospace eXploration Agency (JAXA) μ10 microwave thrusters on HayaBusa (asteroid sample recovery mission) [17]
- T5 Thrusters on GOCE (Gravity field and Ocean circulation Earth Explorer). [18]

In recent years innovative smaller form factor and thrust range devices are being proposed and developed to meet the micro-satellite market [19]. An issue that has occurred with electric propulsion is that due to the typical mission specification e.g. extended station-keeping, devices need to endure longer qualification programs with very high performance goals. Lifetime is a key element, with thruster programs regularly performing some sort of long duration test campaign used to predict End-of-Life conditions (EOL) [20]. Performance requirements and thrust envelopes can be challenging.

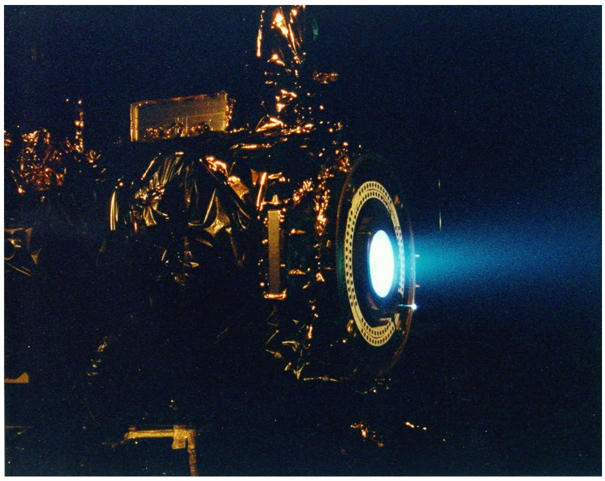

Figure 5 - NASA/JPL NSTAR ion thruster during firing test (Credit NASA/JPL - image PIA04247)

For the GOCE mission, the ion thruster was used to counteract atmospheric drag so that the short-term variation of the geoid along with ocean current circulation could be measured . The geoid is defined as a model of global mean sea level that is used to measure precise surface elevations [21]. These drag effects were compensated for using the ion thruster system which resulted in a challenging performance envelope and a bespoke control algorithm [22].

When preliminary mission results came back, it was found that the actual thrust variation was at the lowest end of the envelope [18]. This was due to the spacecraft experiencing less drag that predicted, resulting in lower thrust levels and less throttling of the thruster. There was more than sufficient lifetime capability of the satellite; so much so that the mission was extended, the altitude lowered and a higher resolution geoid obtained.

Though on paper there are gains made by over-engineering the satellite and the thruster capability, the control could have been simplified and the satellite launched earlier. The mission requirements were driven by a model of the exosphere as opposed to intermediate measurement campaigns to tune the performance requirements. In addition, the satellite was often referred to in press as a "Ferrari' [23] .The T5 thruster would therefore be the Ferrari engine. However a much simpler control algorithm ("Truck engine") may have been adequate if more was known about the satellite environment.

These kind of questions may also encourage the reader to ask why develop complex finely controlled ion thrusters over such a long time anyway? Such devices have their place for deep space missions and long-term station keeping purposes, but perhaps a more redundant approach would suffice? Until recently, monolithic thinking dominated and aimed for the long-duration high-specification goal since there were no situations were a simplified thruster system would be on a comparable satellite.

A significant development in the field that contradicts this idea has been the launch of the first batch of StarLink satellites by Space X [24]. These satellites contained Hall-Effect ion thrusters. In one day the company launched sixty satellites, each with four thrusters onboard. It looks very likely that they have managed to put into operation more ion thrusters than any other company or organisation in as short a timespan. The plan is for one thousand StarLink satellites in orbit at mission completion resulting in a possible four thousand ion thrusters operating. This does not include failures and replacements. SpaceX may have the largest population of ion thrusters in space on completion of the constellation.

A key and relevant part of this development was that the ion thrusters were not the main focus of the mission. They were an essential subsystem but not the means to an end. The mission was not designed as a technology demonstrator. The thrusters were also developed using Kr as the propellant instead of Xe, which reduces fuel cost. There are disadvantages with Kr as lifetime and thruster erosion increases [25].

However lifetime is not as large a factor due to the design philosophy of StarLink. The mission architecture is such that a compromise on the specification of the technology can be balanced by adaptability and redundancy in how the technology is deployed. This is not available to monolithic-style mission architectures.

The thrusters are also gaining valuable flight heritage and achieving the key TRL 9 level. They can now be considered an option in future mission planning. The question that arises is why would a mission use long-development legacy-type ion thrusters that may not have flown yet, as opposed to flight-demonstrated technology such as the SpaceX devices, that have shorter lifetime?

To the Moon and Mars

For at least the last ten years, NASA has been developing a successor to the Space Shuttle that will enable space exploration into the Solar System, notably, the establishment of a manned presence on the Moon and Mars. To do this a next-generation launcher, the Space Launch System (SLS) is being developed as a critical component to increase the reach of Earth-launched missions [26].

One group that has extensively studied taking a modular approach is Aerojet Rocketdyne. They have assessed different types of architectures for Solar System exploration based on affordability over the last decade, balancing capability updates from NASA with regards to key technologies such as the SLS [27,28]. Their studies stress decoupling infrastructure transfer from human transfer, using common elements of architecture irrespective of destination and mission-type, and adopting a modular approach to the propulsion systems, in this case electric propulsion [29].

One key element in Solar System exploration would be establishing a presence at Earth Moon Lagrange point 2 (EML2), that would be used as a jumping-off point for further missions. A metric used is the idea of moving 20 tons (20t) of infrastructure to this Lagrange point. By incorporating electric propulsion this means that approximately twice the mass could be transferred using a less powerful launcher and electric propulsion "tugs", with the time taken being 1.5 years as opposed to 6 months [28]. However as the establishment of the full infrastructure would take 10 years this is an acceptable compromise.

Further, using electric propulsion means that less launches are needed; or if there is contingency, there are *backups* for each launch. The chemical approach does not provide this type of redundancy.

Developments have occurred such that the impulse gap between the mass the launcher can place in orbit, and the mass that can be moved by in-space propulsion, has lessened considerably over more recent years. The result of this is that very high powered (>50 kW) ion thrusters that have been proposed do not need to be developed and current high power thruster candidates such as the 13 kW Hall Effect thruster [29] can be used.

In addition to Aerojet Rocketdyne, in 2011, researchers at Alta proposed a modular architecture, again using ion thrusters, but also inflatable structures [30]. Current launch capability was considered and they showed that key elements of Solar System exploration programs could be put in place allowing progress in parts rather than wait for one large mission.

Considering that heavy launcher development is progressing, driven to a large extent by SpaceX, the mass per kilogram costs of launch are reducing. Mass margins versus program development costs are becoming a realistic set of metrics such that consideration is being made, for example, to not develop onboard recycling for manned missions and use resupply instead [31]. Why spend more years developing highly-specified spacecraft systems when current capability can allow a large part of that mission infrastructure to be put in space now or in the near future and maintained with new equipment?

In addition, the less highly specified equipment may require redundant units and a slightly higher launch cost, and more time to reach the appropriate destination, but it will be in space rather than in a lab. Launching parts also ensures an opportunity to achieve TRL9. If there is a launch failure the module should have the capability of being rebuilt. If this approach was there from the outset of mission planning would there now be some presence in orbit of or even on the Moon? And would this extend to Mars?

The Multi-Million Dollar Battery

Nuclear power has been used in various ways on satellite missions over the last 50 years, to a large extent consisting of Radioisotope Thermal Generators (RTGs). These have been used on the Apollo, Voyager, Cassini [32] and recent Martian missions [33].

An RTG consists of a metallic-oxide pellet where an anion is a radioactive isotope, such as plutonium (Pu) or Americium (Am). The pellet is wrapped in a series of protective layers and surrounded by a thermocouple assembly [32]. The basic concept is that electricity is generated using the thermal gradient between the pellet core and its surroundings. The typical power density metric is W/kg, with values ranging from fewer than a Watt to approximately 5 W/kg (for Pu-based devices) at beginning of life for different designs and materials This is the total power divided by the total system mass. For Cassini, a 55.9 kg device produced 300 W of power [34]

Since the half-life of the isotopes can be in the order of decades, a dedicated power source can be designed to last for generational periods (greater than 20 years), which makes it attractive for deep-space or planetary missions. However, in the case of Pu this material comes a high price tag as well as strict handling and safety regulations.

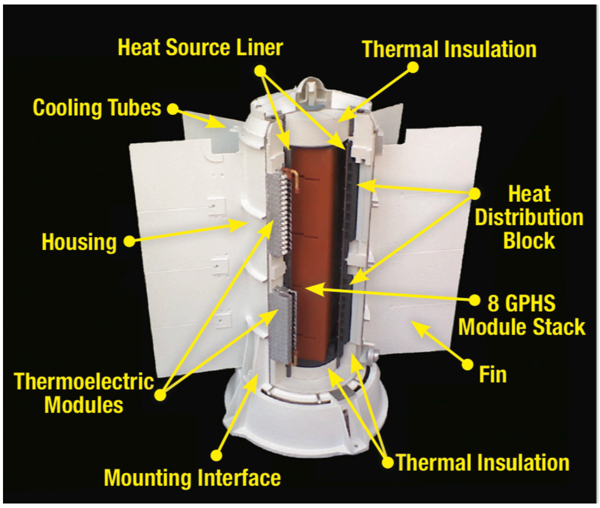

Figure 6 - A model of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) from [33] (Credit NASA)

In a 2015 study [35], the cost of development of an RTG for NASA space missions was investigated. The cost was just less that \$2000/g of Pu. Manufacture and qualification of an RTG using Pu and weighing even a few kilograms would involve *millions* of dollars of investment. This would be enough to stop any small satellites mission development. An alternative would be to use cheaper radioisotopes and to break generators into modules.

On paper, a Sr-based system has a power density of approximately 2W/kg when compared to Pu. It has a half-life of 28 years and is easily available as it is a common fission-fuel waste product. Sr has β-decay rather than α as is the case for Pu and Am. The disadvantage of Sr is that if the pellets have sufficient material, the x-rays generated from the shield need to be further shielded for. A secondary shield can be orders of magnitude thicker than that for Pu and typically consists of lead or stainless steel [36].

To mitigate this, a series of smaller generators could be linked together so that the overall power comes from a combination of electrical components rather than a series of radioisotope pellets in one unit. Sr-based Micro-RTGs designs have been studied recently [37] with promising results. Making smaller modular devices would mean a quicker time to launch as well as building flight heritage.

Current thinking however is to increase the efficiency of devices in order to get higher W/Kg values. There are programs dedicated to creating piston-type Sterling

Generators [38, 39] though as large-scale rather than miniature-modular devices. A larger scale RTG is being developed in Europe using Am [38] but taking a monolithic approach.

The Am-based device is yet to be flown and is still in phases of development.

DOCKSAT

A concept called "DockSat" is proposed as an example of a modular mission with redundant infrastructure. This idea borrows from recent activities into investigating and developing docking spacecraft such as the CubeSat Proximity Operations Demonstration (CPOD) [40] and DARPA Phoenix program [41].

The idea is that instead of launching large single satellites, infrastructure is assembled from component satellites piece by piece. The satellites dock with each other and create various structures depending on their design.

Like in Phoenix, a "satellite stack" can be created out of such component satellites. However unlike Phoenix, each component satellite is not limited to a fixed form factor, nor does it need to be fully autonomous. This means that in the most marked example, each component satellite would have a main payload making up the majority of the satellite, and which plays a part of the satellite stack system. There would then only be minimum capability for other major spacecraft functions on the satellite.

It practice that would mean that a component satellite would need to have docking capability, using a common docking port and control protocol, and a minimised attitude and orbital control (AOCS), in order to exhibit some basic space debris mitigation capability. The size and shape of a component satellite would be variable allowing greater flexibility for builders and suppliers, provided the basic common functionalities were still present. Therefore stack architectures would not be limited to being built out of a narrow band of fixed components.

The initial stages of such an endeavour would be testing the minimum satellite capability as well as a suitable nominal satellite size range. At the same time a coupled technology demonstration would be performed to exhibit feasibility and scalability of the architecture.

For example, a satellite could include a series of antenna - AntennaSat - with high bandwidth capability but and suitable attitude and orbital control (AOCS) and power. This would be coupled with a satellite containing a scientific payload that did not have high bandwidth communications capability. Joining the two together would create an enhanced satellite (Figure 7).

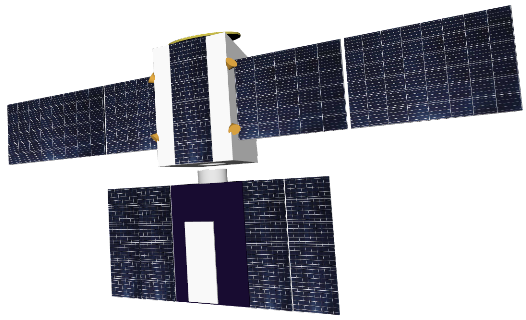

Figure 7 - A simple two satellite stack with different form factors

Initially the AOCS on both satellites would allow safe manoeuvring and docking, after which another satellite could be added: PropulsionSat. This would have more power and greater impulse capability, thus making it the satellite that could 'fetch' or reposition the whole stack. It would not contain any other payload. If the stack assembly was unsuccessful, all satellites would still have basic debris mitigation capability in that they would have more than basic manoeuvrability. However, if there were progress with stacks the amount of this capability could be dependent on other parts of the system, and hence not be as complex.

One of the drivers behind the concept is that the satellite stacks grow incrementally and demonstrate increasing complexity of capability based on success and feedback rather than a preplanned detailed roadmap. Hence the modular nature would drive the specification process, and the lack of a singular satellite form factor would allow a range of designs to be tested.

Disadvantages of the Architecture

The initial stacks in DockSat could be small and use current technology. The docking mechanism would have to be developed though this can borrow from experience already in the field of machine vision and docking techniques. Docking can also be demonstrated on ground using drones. The development time of such capability is a risk, though the docking protocols do not need to be autonomous at first attempt.

As the idea of self-assembling satellite stacks is not an original one, DockSat would need to provide a unique selling point. It may also need a key advantage over other infrastructure. This could be rapid deployment, being available to commercial industry (i.e. non-military) or that the power does not come solely from solar panels. The use of smaller RTGs as discussed or adding something as simple as a large battery satellite (BatterySat) could mean the possibility of positioning stacks in exotic orbits such as those that experience high eclipse periods. Another key issue is that initially the satellites would be deployed from one launcher so that close proximity could be maintained as the propulsion capabilities would not be enough to orbit raise. This launch risk would have to be factored in to the mission design. As stacks progressed, satellites with greater range could be used so that they could be deployed separately.

Space Debris - Motivate to Mitigate

Creating satellite stacks from docking components is going to increase the risk of collisions and debris. Failed dockings and stranded satellites could offer potential problems without some sort of mitigation, especially if a minimal AOCS for some component satellite is used.

The International Academy of Astronautics (IAA) recommended space debris mitigation includes having the capability to remove non-operational satellites and launch components (i.e. stages) from orbit after 25 years [42]. In addition, the satellite should not operate in a manner that would increase the likelihood of generating debris. By this measure a satellite manufacturer either has to create a system that will have de-orbiting capability, either actively or passively; or it has the same number of years to find another means to remove the item i,e: by going and moving it with another satellite.

There are two streams of thought that can be summarised as:

- Build the capability for the worst case debris mitigation after 25 years into the satellite
- Plan to fetch the satellite and move it to be disposed safely within 25 years

Building in capability on a satellite will depend on the size and weight, as small de-orbit thruster systems are readily available that have a relatively small footprint for a large metre-scale satellite. However for small satellites (i.e. CubeSat size) the capability has to be included in the design from the start. This may be limited by satellite power and size and the nature of that component satellites function. Hence the de-orbit capability may not be there, which is a primary concern for satellites placed in Low Earth Orbit (LEO) [43].

The other option is to wait for the ability to fetch and move the satellites as the convention allows up to 25 years. This may change with the growing traffic due to LEO constellations. Conversely, satellite design may not need de-orbit or mitigation capability as there will be satellites that perform these tasks.

For DockSat, the initial demonstration satellites would be sized to include some de-orbit capability, either with propulsion systems or by the natural decay at EOL. As satellite stacks grow and the component satellites diversify, mitigation could handled by having satellite capability to move satellites. In addition, depending on how successful development of batteries or RTGs, the use of more exotic orbits lessens the issue of collision events with current satellite populations. In the extreme case, DockSat stacks may rarely cross or interact with conventional orbits.

Would it save the UK Space Industry?

Perhaps this is a bold claim as the UK Space Industry is currently expanding and growing in terms of income (£13.7 billion in 2015/2016 [44] and £14.2 billion in 2017/2018 [45]). However as this paper deals with the thinking behind mission planning and success, using a modular approach which adapts and is used in other industries would be prudent.

Compared to the vertical business approach for Phoenix, DockSat offers a more horizontal business opportunity. The “satlet” form factor of Phoenix, as a building block, may limit the growth possibilities that the satellite system could enjoy, as companies are forced into making a complete satellite system within tight constraints.

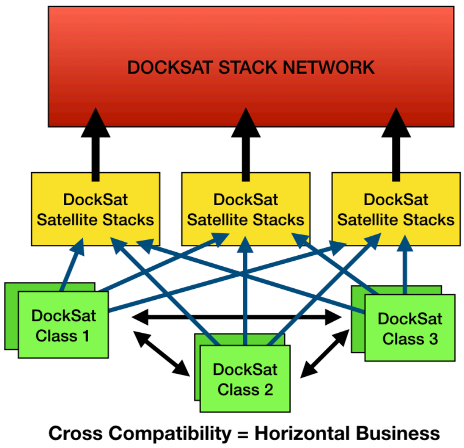

Figure 8 - Horizontal business alignment. Modular but different satellite classes can be used to build a network

Compare this to CubeSats which have a basic unit size but come in different volumes and shapes, creating a degree of horizontal business alignment. DockSat has commonalities in docking protocols and interfaces and could have similar inter-satellite communication standards if needed. However, the size, mass and shape are dictated by the mission need, which is in itself a functionality need. DockSat has a looser requirement set than CubeSats.

Due to the nature of these component satellites, companies, especially in the U.K. would not need to compete on the satellite level all the time. Companies would lend themselves to creating a certain type of satellite based on current competence e.g. communications infrastructure, propulsion-based satellites, or multi-payload imaging satellites. The qualification specification of the satellites would not be as stringent and time-intensive initially, as iterative improvement is a key element in the DockSat approach. It is designed to be modular promoting a results-based leaner approach. This would also further solidify and broaden niche markets in successful technologies as well as absorb the impact of mission failures. Figure 8 shows the difference in business alignment that DockSat could offer.

If modular thinking took precedence over monolithic thinking, it could have impacts on industries such as space insurance. The premiums on cheaper elements would either be lower or be better understood due to the feedback from the progress of missions using modular approaches. A significant factor would be having more data and a greater sample size to model risk, leading to better risk models and pricing. In the current environment, dominated by large monolithic projects, it was reported that one large insurer had decided to withdraw from the market [46] in large part due to not being able to afford failure payouts. This can reduce choice and force smaller companies out of the market as they cannot afford the premiums of companies that remain.

DockSat represents only one type of modular space mission, with its primary goal of creating infrastructure satellites. Constellations, space habitats, and even probe missions can all benefit from the MVP approach and modular architecture so that the risk of LEOP failure is handled and costed rather than gambled with.

However, no real progress can be made without changing the thought process in planning missions, whether privately funded or by publicly funded.

CONCLUSIONS

The main points of this paper can be summarised as:

- The initial overall failure risk is the same for both highly-specified and lowly-specified missions, but the highly specified missions carries the greater cost with much less contingency. It is advisable to try and design in modularity.
- The redundancy of modular missions is much greater, hence contingency costs are more manageable and that should be *at least as important as* mission performance goals.
- When accounting for risk and contingency, more progress and adaptability is created using a modular based approach (the Minimum Viable Product model)
- If a strict monolithic approach is maintained it is just a matter of time before a competitor organisation will make the monolithic approach, hence that business model, redundant. This is already taking place.

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