Mechanisms and New Space

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Abstract

The objective of this paper is to provide the mechanisms community an understanding of "New Space" applications, giving insight on how to specify, design, produce, and test mechanisms for this emerging paradigm. An in-depth study of how New Space does and does not change the landscape for space mechanisms will be provided. The paper will study these questions generically to provide understand of the adaptation needed but does not intend to specify a recipe for success. The spectrum of applications and programs is very diverse, so the paper will focus on key thought processes, potentially applicable techniques, and the questions to consider for New Space mechanisms. The desired outcome of this paper is to help smart mechanism engineers create wise and unique solutions for specific New Space mechanisms.

Introduction

New Space changes a programmatic paradigm but cannot change physics, nor the space environment, nor the realities of a riding a rocket to space. The most impactful elements of this programmatic change are a very strong emphasis on low cost, usage of volume manufacturing and much tighter schedules than is the norm for current programs. This paper is written from the perspective of learning to thrive in this new paradigm. The author has spent a 30-year career primarily working research and development satellites and their mechanisms within the American space program but has recently refocused his career on the world of New Space. The paper will share the author's growing understanding of the New Space paradigm and its impact on the mechanisms life cycle.

What is New Space?

We must understand the motivations and expectations of New Space enterprises to successfully provide mechanisms for their programs.

New Space Description

The trade magazine *New Space Global* defines New Space well. "New Space is a global industry of private companies and entrepreneurs who primarily target commercial customers, are backed by risk capital seeking a return, and seek to profit from innovative products or services developed in or for space."

New Space will be examined in comparison to the most conventional approach to space, referred to in this paper as 'Big Space.' Big Space is defined for the purposes of this paper as large, very high reliability programs, including major NASA and ESA programs, DoD programs, and long-life Geostationary communication satellites.

The strongest motivation of New Space is simply to use space to make money, which drives a very different approach to satellite design and production than the Big Space motivation of extremely high reliability of each satellite. Low-cost production of satellites is a cornerstone of financial success for New Space enterprises. Programs using the New Space paradigm are endeavoring to build space hardware at a small fraction of the conventional cost by challenging the standard practices of big aerospace programs.

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Proceedings of the 44th Aerospace Mechanisms Symposium, NASA Glenn Research Center, May 16-18, 2018

New Space has emerged in recent years as a sizable business from its roots in the small satellite and CubeSat communities. More than 1000 electro-optical satellites are proposed and more than 10,000 communications satellites are proposed by various companies. Proposals are easy, but it takes a lot of money to become real. Commercial funding for New Space (Figure 2) has grown to an average level of $3 Billion annually from 2015 through 2017. Three of the largest New Space ventures in current production are the SpaceX Falcon rockets, the Planet constellation of imaging satellites and the OneWeb constellation of internet communication satellites (Figure 1). The production programs and funding levels confirm this new paradigm is serious business. Multiple projections show this expenditure level growing in the coming years.

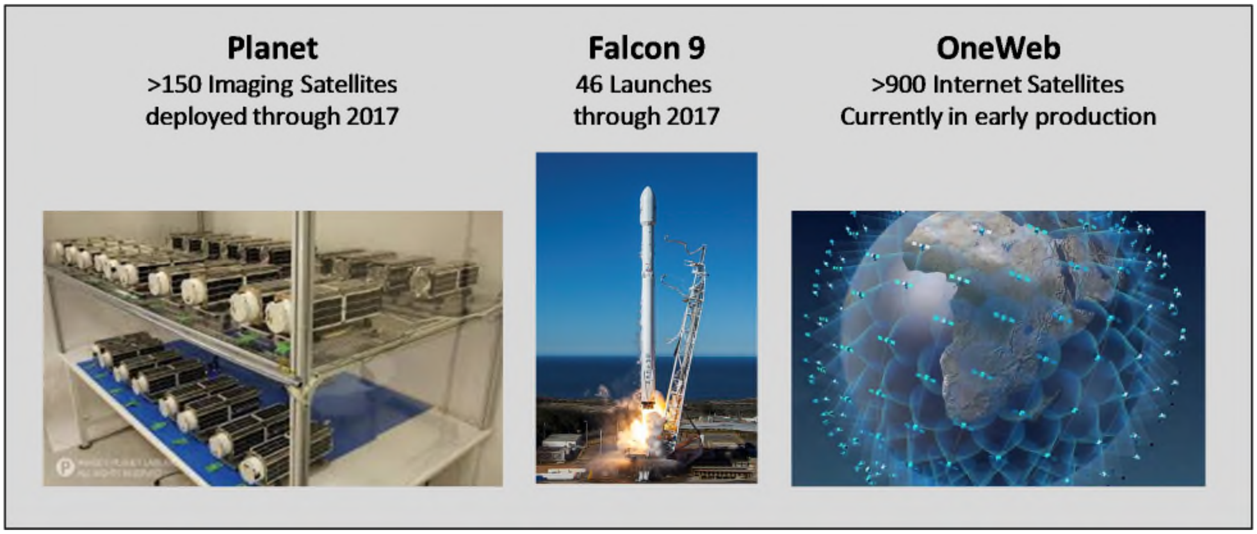

Figure 1. Major New Space Constellations Presently in Production

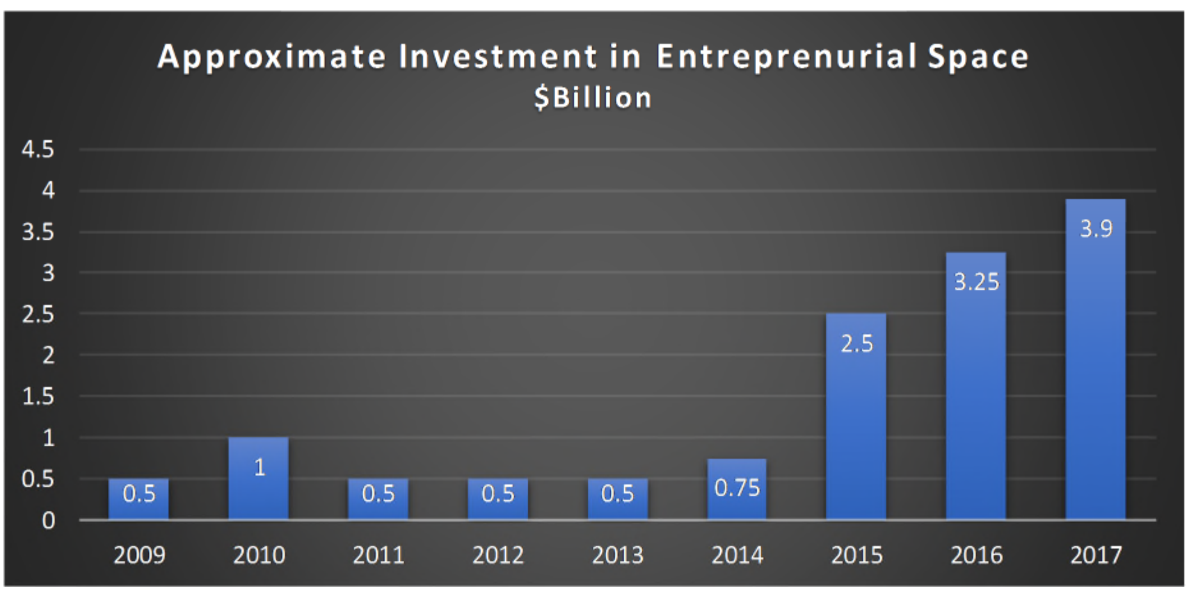

Figure 2. New Space Investment by Year Shows a dramatic increase from 2015 through 2017

New Space Missions

New Space missions can be loosely grouped into five categories. A brief overview of each is intended to provide the reader insight into the driving business cases.

- Internet from space: Satellite constellations of hundreds to thousands in Low Earth Orbit (LEO) are being pursued to provide internet connectivity with high bandwidth and low latency.
- Earth Observation: The purpose is to sell knowledge insights extracted from Earth observations. Constellations of satellites in the tens to hundreds already exist and more are being pursued providing optical imagery, radar imagery, signals monitoring and weather observations to feed new knowledge products.
- Internet of Things (IoT) communication: Satellite constellations of tens to hundreds already exist and more are being pursued to provide low bandwidth connectivity specifically for the IoT.
- Low Cost Launch: SpaceX has been the first to achieve this goal while several other companies are very close to selling low cost launch opportunities.
- Science and Technology demonstrations, typically on CubeSats, are presently being performed with high frequency.

Will New Space Become as Big as Projected?

Cynics will say New Space is just a revisit of the mid 90's when big constellations were successfully built at low cost but were business failures and New Space is doomed to repeat the past. Optimists and advocates will say New Space is the next big thing. The outcome is still uncertain, we will only begin to find out in the year 2020+ time frame as the new constellations materialize or do not materialize and as business plans succeed or fail. In the meantime, there is considerable enthusiasm and money being spent providing many smart and creative entrepreneurs and engineers the opportunity to make it work.

Comparison of New Space and Big Space

It is important to compare and contrast New Space and Big Space; we must understand what changes and what does not change. Table 1 provides a generalized look at this comparison, acknowledging that every space program is unique and there is a wide spectrum between the extremes of each paradigm.

Table 1. General Comparison of New Space and Big Space

#	New Space	Big Space
1	Commercially driven	Customer driven
2	Government is either uninvolved or hands-off	Government sponsored and managed, except commercial GEO communication satellites
3	Profit equation: • High value products derived from space • Using low-cost satellites and launch	Profit equation: • Meet customer requirements at all cost • Cost plus Fixed Fee • Except Geo Communications
4	$100 million satellite is considered very expensive	$100 million satellite is considered very cheap
5	3-year satellite development is considered slow	3-year satellite development is considered fast
6	Moderate capability satellites in high volume	High capability satellites in low volume
7	Reliability of business plan	Reliability of satellites
8	Space Environment	Space Environment
9	Rockets are a rough environment	Rockets are a rough environment
10	Streamlined processes	Very thorough processes
11	Ignore, adapt or use established standards	Mandated use of established standards
12	Why not change?	Why change?

Items 1-3 are the commercial drivers which combine to force New Space satellites to be manufactured at low cost. Items 4 and 5 illustrate the dramatic different in cost and schedule mindset. However, items 8 and 9, the realities of space and the path from earth to space, are two of the fundamental technical drivers and these don't change. New Space is attempting to leverage the philosophy and practices of items 6, 7, 10 and 11 to drive down cost dramatically. It is well known that producing in larger volume (item 6) will drive down cost, but this in and of itself will not drive costs aggressively enough to meet New Space goals.

By focusing reliability on the success of the business plans, item 7 and using a large quantity of satellites, the occasional random failure of a satellite can be tolerated which leads New Space to an acceptance of risk at the individual satellite level. New Space certainly wants and demands reliable satellites but at a different risk posture. A poorly designed satellite, or unreliable satellite component will lead to frequent satellites failures and will not be acceptable. A well-designed satellite which experiences only a couple failures of individual satellites in a large constellation due to occasional manufacturing glitches is typically an accepted risk. This New Space reliability posture will flow down to mechanism builders as a somewhat increased acceptance of manufacturing / quality assurance risk in exchange for low cost but will not flow down as increased acceptance of poor designs.

The Big Space approach to process described in items 10 and 11 have developed through the decades and do an excellent job of capturing all the best practices to produce super high reliability satellites, however they also drive costs unacceptably for New Space. Thus, New Space programs make choices about which practices to use, which to adapt and which to ignore. Similarly, many New Space programs carry a mentality of 'Why Not?' when addressing the question of 'can we eliminate a certain practice or use a certain unconventional design?' Thus, New Space will consider designs and practices which would be considered unacceptable by Big Space. However, these choices are not always made correctly so this paper will carefully examine these choices and their implications to help the reader make the choices wisely.

Key Point: New Space is using streamlined practices and volume production to reduce cost and schedule

Key Point: There is no change in the space and launch environments for New Space

<u>Can the aggressive cost targets be met?</u>
Many other industries produce reliable items in volume at low cost so there is no reason the space industry cannot. Space will always be a demanding environment requiring sophisticated and rugged designs. Satellite repair for all intents and purposes is not practical and this forces a higher reliability threshold than that for industries in which repair is a tolerable option. It is the author's opinion that significant costs will be driven out of satellite production as the space industry learns how best to streamline the processes of Big Space and creatively leverages the huge advantages of volume production. There will be winners and losers in the transition to New Space, and the author suggests that the winners will be those who wisely make tough decisions and move fast.

Mechanisms Considerations for New Space

The New Space mechanism challenge is:
Continue to design and build great mechanisms – but at a much lower cost than Big Space.

This would be an unfair challenge except for the change in two variables: (i) New Space will be able to build mechanisms in volume and (ii) New Space will entertain options to reduce process and documentation.

The New Space approach will be explored by progressing through the life cycle of a mechanism from concept through flight. A discussion of opportunities to meet the low-cost demands of New Space with good reliability and acceptable performance will be provided. Differences between New Space and Big Space will be brought out in the discussion

Mechanisms Considerations for New Space: Requirements and Design Phase

Requirements

Perhaps the concept of working to minimized requirements is the biggest cost saving of the entire New Space endeavor. New Space programs attempt to pare their technical requirements down to the minimum necessary to satisfy a business case. Additionally, they are paring their mission assurance requirements down to the minimum necessary to produce the reliability necessary to support the business case. The amazingly low cost of cubesats and smallsats relative to Big Space is possibly a direct result of this approach to minimizing requirements.

Selection of appropriate requirements is extremely important to any engineering effort, and mechanisms for New Space is no different. The downward cost pressure and tight schedules of New Space greatly amplifies the importance of minimizing requirements. In contrast, the author has observed requirements development in the world of Big Space stemming from a pervasive mindset of choosing requirements equal to the best that can possibly be done. While this gives engineers fascinating challenges and has produced satellites with amazing capability, this mindset is incompatible with low cost.

Customer and supplier both need to realize that they both will benefit from the easiest acceptable level of requirements. The customer will get the product they need at the low cost they also need. The supplier will have the best chance of success as their task becomes less challenging. A true win – win.

To provide a good low-cost mechanism questions such as the following should be considered jointly by customer and supplier:

- Is this level of performance absolutely necessary?
- Is this required feature / capability absolutely necessary?
- Is this quality / mission assurance requirement going to be cost effective?

A mechanism provider should first assess for themselves, and then enlighten their requirement source about cost savings considerations using questions such as:

- Are you aware that this specific requirement is a significant cost driver for the mechanism?
- We have found that a given quality process has been largely unnecessary and recommend its elimination, can you concur?
- A given quality process is redundant since it is checking for issues that will be uncovered by this other process which we have found to be cost effective, will this be acceptable to you?

A person setting requirements should be asking the mechanism provider questions such as:

- What can I change in my specification to make your cost lower?
- Do you think I am asking for more than I really need?

The eight questions above can be used to identify and eliminate many unnecessary requirements. Time and money must be spent to meet an unnecessary requirement – but only if the requirement has not been eliminated. Elimination of waste is a valuable cost and risk reduction tool and an unnecessary requirement is a prime example of waste that we should be striving to eliminate. There is nothing unique to New Space in this effort to aim for good and minimized requirements. The difference is the critical relationship of minimized requirements to the driving objectives of low cost and fast schedules. Remember the adage ‘Be careful what you ask for, you just might get it.’

Key Point: Reducing and eliminating unnecessary requirements is one of the best ways to reduce cost and schedule for New Space programs and should be a joint effort between provider and customer.

Concept Design

The book Design for Manufacturability, by David M. Anderson (Ref. 3) puts forth that 60% of the total lifecycle cost is decided simply by the concept architecture (Figure 3). This makes a lot of sense simply by thinking about the costs of complexity that can be eliminated by a great concept. Not only does a great concept drive down costs, it drives down schedule and risk simply because there are less opportunities for problems to arise.

When one looks at this chart another way, a new design is the only method to achieve a cost reduction for an existing product to below 80% of the present cost, since reductions greater than 20% are not available by manufacturing improvements alone. Cost reductions to below 60% call for an innovative new concept.

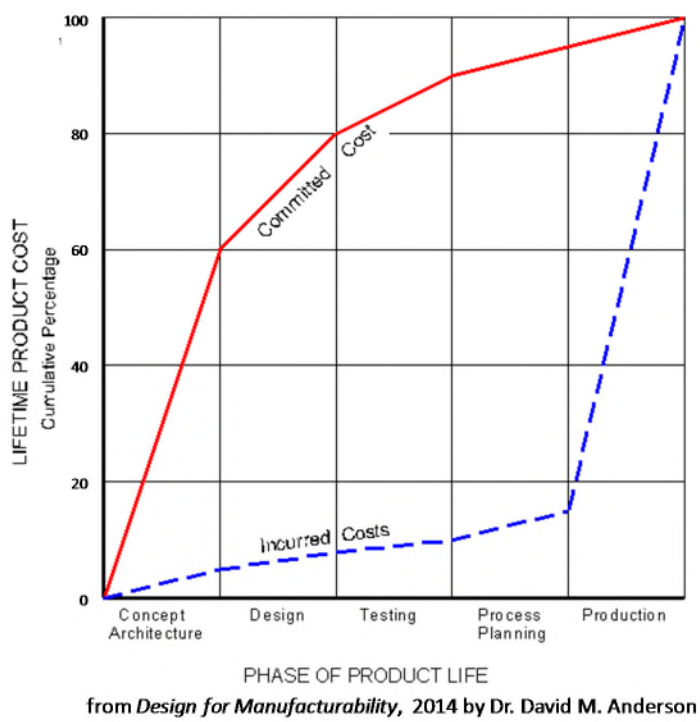

Figure 3. Costs Committed and Costs Incurred vs. Life Cycle. This figure shows the majority of total life cycle costs are committed by the completion of the concept architecture plus design phases even though these costs are not realized until the production phase. Plot courtesy of Dr. David Anderson

Many lessons from the referenced text and from the world of production emphasize a rapid cycle of conceive, test, iterate, and repeat as one of the best methods to evolve to a great concept. The speed at which this rapid design iteration can now be accomplished is greatly improved by leveraging additive manufacturing for rapid prototyping. It is also taught that extra time spent in the search for a great concept can ultimately save a program time when the benefits of the great concept are realized in development and production schedules.

One concept often seen in New Space is usage of mass-produced industrial components for flight even though they were not designed for space applications. With proper testing many industrial items can be found to work for space applications either as-is or with minor modification. The use of industrial components, in our case, mechanisms, provides a great cost savings opportunity – but only if the mechanism is properly qualified for the application and the environment and the supplier's approach to quality is found acceptable. In contrast, the use of industrial components with industrial quality practices is virtually inconceivable in Big Space.

When considering a mechanism conceptual design, it is important to keep in mind that the goal is lowest overall system cost. For example, if a low-cost mechanism requires high-cost drive electronics then it may not provide the lowest overall cost to the satellite system.

Key Point: Concept design, including requirements definition, is the biggest driver of cost and schedule in a production program.

<u>Detail Design</u>

There is an entire engineering discipline of design-for-manufacturing which is beyond the scope of this paper. Some highlights providing the most potential benefit for mechanisms will, however, be discussed.

The Design for Manufacturability text points out that 80% of the total lifecycle cost is dictated by the combination of the concept architecture plus the detail design. Once an unnecessary feature has been designed in, there is no amount of manufacturing brilliance that can make it cost less than to never have had to manufacture it in the first place. Thus, the detail design phase is of crucial importance for the success of any mechanism, which, for New Space, includes performance, cost and schedule.

Low production cost must be an important design consideration from day one. This low cost emphasis requires a very different mindset than what is common in Big Space. Production cost can and should be traded against the typical design goals of performance and mass. The design considerations of low cost must include the full life cycle costs; parts manufacturing, assembly, testability, electrical interface costs, spacecraft interface and integration costs.

A powerful cost savings in design is simply a minimization of parts count. Every part in an assembly invokes all the following tasks at a minimum: design effort, a drawing, analysis, manufacturing, a vendor to manage, an opportunity for manufacturing problems, inspection, storage, and assembly.

Discussions with manufacturers during the part design process can prove extremely valuable as the manufacturers can provide unique feedback on features which either drive manufacturing costs into the part or, conversely, save manufacturing difficulties. Design engineers are often unaware of subtle design selections which accidentally drive manufacturing difficulty and cost.

A significant cost savings can be found by clever designs that leverage modern manufacturing methods to combine multiple parts into one. When multiple parts are combined, assembly costs and risks are eliminated, and the savings associated with reduced parts count are realized. The question becomes *'are the lifecycle costs of this single complex part, in fact, cheaper than an assembly of several simpler parts?'*

Designers must look at tolerancing as a source of cost savings because poor tolerancing will result in cost increases. Manufacturing costs rise exponentially with tighter tolerances. For example, studies have shown a 3.5X manufacturing cost increase simply by changing a tolerance from 0.005 inch (0.12 mm) to 0.001 inch (0.025 mm). Cost growth rates are even larger as one tolerance become even tighter. However, if tolerances are too loose then improper mechanism performance will sometimes result producing costly test failures. A good designer will carefully choose the loosest acceptable tolerances while carefully performing worst case tolerance analyses to avoid mechanism faults if tolerances are too loose.

Key Point: Detail design is the second biggest driver of cost and schedule in a production program.

Development Process

Development of New Space mechanisms varies from development for Big Space in two key ways; (i) New Space will have tighter timelines and more schedule pressure and (ii) The development phase needs to drive cost out of the design concept as well as validate and improve the design.

Most engineers will agree that multiple iterations continue to improve designs. This is very important considering the premise that 80% of the lifecycle cost is dictated by the concept and design. The leverage of design improvements in the concept phase is huge. Iteration early and often can be very cost effective even if early models are quite crude. A crude breadboard level prototype in-hand can often show a creative engineer design options not yet conceived or problems to be designed out.

A hardware-rich development period is a very powerful method of working within tighter timelines and enabling cost reduction. A hardware-rich development means that multiple prototypes of each design are built rather than just a single unit. The author has found this to be extremely valuable and cost effective in practice. The cost of the multiple prototypes is more than recovered in the flexibility it provides. Plus, it typically does not cost much more to make multiple prototypes than a single unit. For example, the hardware-rich approach of building four engineering models instead of one allows the following allocations and parallel efforts:

- Unit 1 - Test for functionality and performance
- Unit 2 - Test for environments
- Unit 3 – Test interfaces with electronics or with prototype spacecraft
- Unit 4 – Held in reserve for use in response to unforeseen occurrences or troubleshooting

Another aspect of a hardware-rich development can be the parallel production of multiple design options. In some cases, a trade between two or more options can be best made after being informed by prototype hardware evaluation. For example, one could prototype Design A offering lower cost with higher performance risks and Design B with better performance and higher production costs. This way the development program can hold schedule if the low-cost option fails to meet performance, but, does not give up the chance to hit a low cost, adequate performance mechanism home run.

Key Point: Fast paced, iterative, hardware-rich development is a powerful tool for improving the concept and detail design quickly.

In a development effort for a mechanism intended to enter volume production, working out all the bugs is of high importance before entering production. Minor design errors will be extremely costly if they are found during volume manufacturing. Imagine the pain of finding a design flaw that can cause intermittent failures after already having shipped 100 units to customers. Similarly, minor inconsistencies in manufacturing will make a mess of production schedules in volume production. For volume production, manufacturing and design are effectively indistinguishable, the design of the manufacturing process is part of the design of the mechanism. Thus, both manufacturing and design must be perfected in the development phase is one is to have smooth, cost effective volume production.

Mechanisms Considerations for New Space: Manufacturing Phase

There is a tremendous knowledge base available on volume production, both for volume production in general and specifically for space. The author has found significant value from the following references:

- Reference 1, a paper in the 29th Aerospace Mechanisms Symposium about the high-volume production of release mechanisms for the first Iridium program by Daryl Maus provides a powerful look an early usage of volume production for space.

- Reference 2, a paper in the 2017 European Space Mechanisms and Tribology Symposium about volume production of pointing mechanisms in volume production for several space programs by Jean-Nicholas Lajoie, provides good insight into current volume production for space.
- Reference 3 the book Design for Manufacturability: How to Use Concurrent Engineering to Rapidly Develop Low-Cost, High-Quality Products for Lean Production by Dr. David Anderson shows methods to develop manufacturable products with the lowest cost in the least time and provided the author good insight into cost savings in general.
- Reference 4. The book Toyota Production System by Taiichi Ohno is considered one of the fundamental texts of lean manufacturing.
- Reference 7, The Goal: A Process of Ongoing Improvement, serves as a good introduction to the value of and methodologies for streamlining manufacturing told as a story.
- Personal observations of a certain burrito restaurant showed the author lean manufacturing in action.

The field of lean manufacturing provides many techniques for us to leverage to reduce the effort and costs of all aspects of the mechanism build and test cycle. These principles are best suited for volume production but several of the principles are valuable for build quantities of a few units. The engineering in the field of lean manufacturing is well developed and is well outside the scope of this paper. This paper will illustrate a few key principles that will provide extremely valuable to inspire readers to learn more.

One of the key philosophies that has provided the author immediate benefit is a 'relentless search for waste.' Continually questioning any production, test or for that matter any design element with the question of 'Is this necessary?' will tend to expose a wide variety of improvements by simplification.

A second key philosophy of value to the author has been a strong mindset in constantly thinking about the manufacturing cycle while designing. Questions such as (i) 'How will this be built?', (ii) 'How will this be tested?' (iii) 'Can this be simplified?' (iv) 'Is there a way to change the design to allow more efficient manufacturing?' should be continually asked of oneself.

Part Manufacturing

Many New Space mechanisms will now be manufactured in quantities of hundreds if not thousands per year. There are considerable advantages to volume production in and of itself, but more so with a search for ways to best utilize its advantages.

There is nothing unique about volume manufacturing of parts for space relative to industry. This is good news because there is tremendous existing knowledge and capability for us to leverage. A trip to a manufacturing show was enlightening for the author and is highly recommended to readers. Tremendous manufacturing capability exists to manufacture parts and assemblies in volume at low cost. The key for those of us who've spent a career building in low volume is to find and utilize this existing volume manufacturing capability base.

The emerging field of additive manufacturing (AM) is receiving a lot of excitement these days and can certainly be valuable for mechanisms. However, it is not a panacea, nor is it one-size-fits-all. The author has found four key points to understand about additive manufacturing:

1. AM is not a simple as sending the CAD file to the printer. The part to be printed must be designed to work within the parameters of the additive manufacturing technology chosen.
2. Additive manufacturing is very valuable for use in accelerating the prototyping phase. This can greatly enhance the critical concept development process. Even if the production parts will not be made by AM, AM can often be used to produce prototype parts faster than any other method.
3. AM enables the creation of shapes not possible by any other method. A classic example is embedding curved internal passages in an otherwise solid part. Creative designers can utilize this capability to improve or simplify their designs.
4. AM can be leveraged to make a single part which otherwise would have required many individual parts. It should be noted that 5-axis CNC machining can also offer this advantage.

Inspection and Quality Assurance

Considerable schedule and cost efficiency is available from modern computerized inspection equipment. When one thinks about the time involved to inspect a single part and then multiplies that time by a thousand parts it is easy to see the large cost savings available from quick and accurate automated inspection. Camera based inspection systems and automated Coordinate Measurement Machines (CMM) are available with associated software to streamline the inspection process. Simple parts can be inspected in a couple minutes and complex parts in a half hour with very little operator effort. This quick inspection also results in a published inspection report against required tolerances.

There are multiple vendors offering camera based systems producing inspection accuracy on the order of 0.002 inch / 0.05 mm. These systems are available at a modest cost. The automated photographic inspection process is:

1. An operator puts a part on a stand.
2. A pair of cameras on a motion control platform move around the part accumulating stereo photos.
3. The part is flipped over and then more photos are accumulated.
4. The photos are then processed in image analysis software to produce a point cloud. The point cloud is then mapped onto the dimensioned CAD file and an inspection report is produced. The inspection report will include pass-fail assessment against every required dimension and will show margin against tolerances.
5. The whole process typically takes a couple minutes per part and all the operator must do is put the part on a table, flip it over, then remove it.

Automated CMM inspection provides much greater accuracy than the camera systems and is available at a higher investment cost. An automated CMM works comparably to a manual CMM except the CMM axes are motor driven and follow a programmed measurement path. Here an operator needs to put the part into a jig setting the part datums for inspection. The CMM then drives through its inspection path. Ultimately this process produces an automated inspection report comparable to that described above, but at better accuracy than the camera process. A complex part with many features to inspect at both high and low precision might take about 30 minutes for a full inspection.

Key Point: Modern automated inspection methods can provide accurate inspection very quickly while minimizing the documentation burden.

Big Space programs invoke considerable costs with extensive quality assurance requirements. Every deliverable document costs time and money. Every requirement flowed to subtier vendors adds to the cost of each part. New Space programs are re-evaluating how much of this existing quality assurance process is necessary. The right answer is neither (i) none of it nor (ii) all of it.

It is far less expensive to stop problems before mechanism test than to troubleshoot and resolve mechanism failures and anomalies. New Space programs have the philosophy to drive costs out of process control and quality assurance by re-evaluating what is truly necessary. However, New Space programs cannot afford failures any more than Big Space programs. So, the mechanisms programs for New Space can and must carefully address which process controls ultimately save more cost than they add, and conversely, which processes add more cost than they save. This decision process will be driven by judgments unique to each provider and program. It is crucial to perform this re-evaluation of quality assurance process controls, but this paper will not attempt to address the relative merits of each.

Key Point: Done right, significant portions of conventional mission assurance can be simplified to reduce cost and schedule with minimal increase is risk.

Assembly

Efficiency in assembly is always valuable and becomes crucial for keeping costs low in volume manufacturing. An example from the restaurant industry illustrates key principles clearly. Most readers have the opportunity to view very good lean manufacturing in action at a popular chain of burrito restaurants. These restaurants manufacture custom burritos in an assembly line with remarkable efficiency. The author observed one of these outlets finding the following truly impressive statistics:

- It took only one minute twelve seconds from “Hi may I take your order” to “thank you for paying” for the author to receive a burrito custom ordered with nine individually selected ingredients.
- 28 burritos were made in a 10 minute period – 2.8 burritos per minute.
- There were 8 workers involved in burrito production, including the cashier.
- This works out to just 2.8 man-minutes labor per assembled burrito.

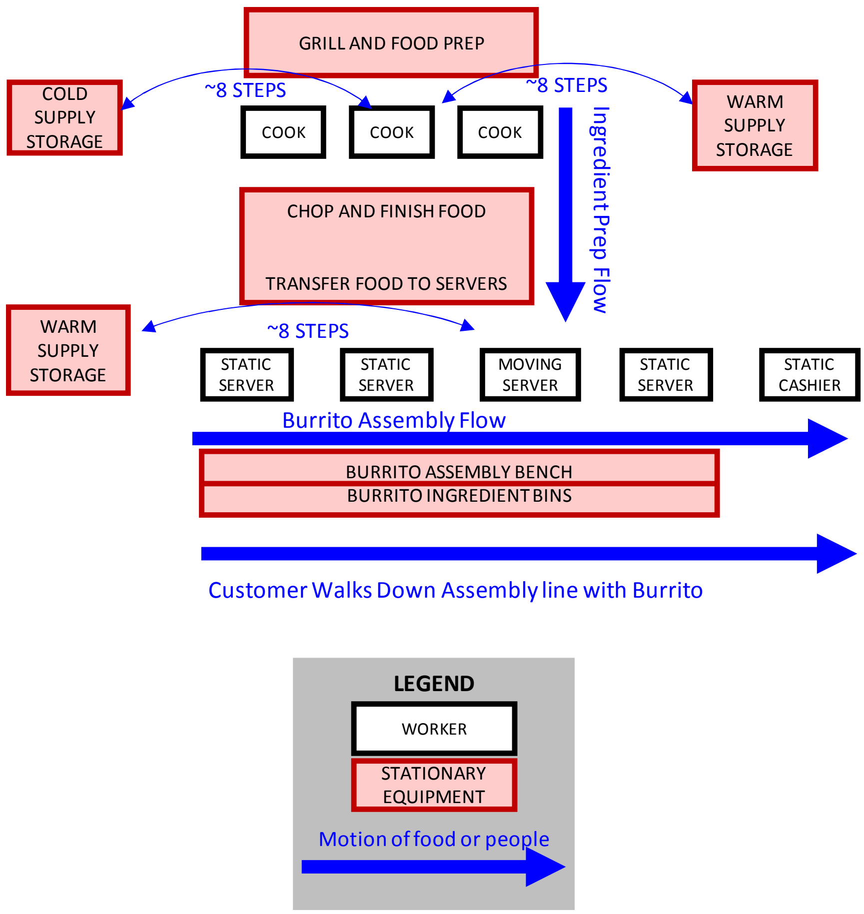

Figure 3. Efficient Burrito Assembly Diagram serves as an example for efficient mechanism assembly

One will see many principles of lean manufacturing of which two will be described. The basic burrito production line and key features is shown in Figure 3.

- Principle one – eliminate waste. The burrito manufacturing employees spend very little time walking from their work station. The principle is that walking around is waste and to be minimized. Four of the eight employees, identified as ‘static’ in the figure*Figure 3* never took more than three steps from their work station. Four of the employees had tasks to replenish supplies and their walk was typically only eight steps from work station to supply location.
- Principle two – excess inventory is waste. In any assembly line, if worker A gets ahead of worker B and keeps piling up inventory, there is waste in building the inventory pile, waste in the floor space for the inventory and waste in pulling material off the inventory pile. At the restaurant, the burrito ingredient supplies for the servers are only replenished when they fall below half full. The servers communicate to the cooks when it is time for the cooks to make more supplies. The communication is timed so that the server’s supplies will be replenished at some point between

half full and empty. There is no inventory piling up between the cooks (worker A) and the servers (worker B), yet the servers never run out of ingredients.

Just imaging if a nine-part mechanism could be assembled with only 2.8 man-minutes of labor. While this may be extreme for the space mechanism field it is illustrative of the incredible power of efficient design of an assembly process.

Key Point: The principles of lean manufacturing are very applicable to volume production of mechanisms.

Key Point: A relentless search for waste will prove valuable in any aspect of any mechanism program.

There are some opportunities to improve mechanism assembly with automation. Most engineers immediately think of the rapidly growing field of robotics. Robotics have been found effective for pick and place type tasks. In some cases, pick and place machines common in electronic card manufacturing can be designed to support mechanism assembly tasks. Robots are not a panacea but can provide good value in the right applications. The best applications for robotics seem to be repetitive tasks and those tasks that could be performed 24 hours a day without supervision.

One can look for labor intensive tasks which can be automated, one example being parts washing. Systems that automate multi-stage cleaning processes are available and will save cost given sufficient manufacturing volume. The conclusion is that there are many automation tools and processes available from industry to investigate leveraging to reduce assembly costs.

Mechanisms Considerations for New Space: Integration and Test Phase

Test. Big Space programs generally start test planning from a perspective of ‘what can be tested?’. New Space programs generally start test planning from a perspective of ‘what absolutely must be tested?’. The nature of mechanisms is that test is often the only true method of validating performance and reliability. Reducing the amount of testing goes against the author’s comfort zone, yet it can and must be done for volume production of space mechanisms as it is done successfully in other manufacturing fields.

Most mechanisms engineers would agree that the nature of mechanisms is that testing is crucial to proving performance and reliability. Verification by analysis and inspection of mechanisms without a test has historically proven inadequate. This is a particular challenge for mechanism production where testing is very expensive, and we are looking to drive cost out of the program. There is no easy answer – extensive testing is great for proving reliability. Limited testing is great for cost reduction but exposes the risk of the severe pain of an on-orbit failure.

Each testing program is unique, so the following is a discussion of options for the reader to consider for their unique mechanism effort. Each mechanism team must make their own tough choices regarding the balance of testing versus cost.

Development testing: The goal of development testing is to expose all flaws in a design so that they will be removed prior to going into production because design flaws found while in a production run are extremely damaging. Extensive development testing is key to eliminating flaws and benefits considerably from the hardware rich approach described above. When time is short, one can also find value by finishing development testing in parallel with early production. While it is ideal to finish development before starting production, continuing development can serve useful to expose a remaining flaw while still early in production instead of building the flaw into a large quantity of delivered mechanisms. Life testing of development units is a prime example of the value in finishing development in parallel with early production since it takes so much time to complete.

Environmental Testing: Launch environments are driven by the choice of launch vehicle. Satellites built for New Space typically want to be compatible with many different launch vehicles for maximum access to space and for flexibility to adapt to launch delays. In addition, new launch vehicles coming on the market will not yet have well characterized launch environments. This scenario results in considerable uncertainty in the vibration, acoustics and loads environment to test against. Testing against an envelope of all launch vehicles is conservative but can result in a significant overtest. Some programs elect to use the generalized environments from the NASA GEVS (General Environmental Verification Standard) or comparable specifications to address this uncertainty. Using generic environments such as these certainly carries some risk that specific environments from specific launch vehicles will exceed the tested limit. There is no easy answer to address environments uncertainty, so the answer becomes a judgment call balancing the risk of undertest versus the risk of false failures from overtest.

Qualification Testing: Formal qualification testing of one or more mechanisms never intended to fly prior to completion of the flight articles was prevalent in the early days of the space program. In recent times, most programs have moved to protoqual (or protoflight) testing in a quest to save the time and money associated with testing units that will never fly.

As New Space moves into volume production, qualification testing becomes a much more viable and valuable option. The premise of qualification testing is to test flight equivalent units to demonstrate high margins. For example, vibration testing would be to levels twice as high for three times the flight duration. Testing to these high margin levels is not smart for units intended to fly but is a great tool for showing the robustness of a design. A plan to build hundreds or thousands of mechanisms draws two large benefits from qualification testing; (i) high margin testing exposes flaws prior to the commitment to major production and (ii) provides confidence that streamlined acceptance testing will be adequate to assure reliability.

Acceptance Testing: There are significant costs of mechanism testing which provides an opportunity for considerable savings during a flight production run if the risks of reduced testing are well managed. Given that a mechanism has been through a formal qualification program, the objective of the acceptance test program becomes a verification that each flight unit performs the same as the qualification units. Once tests demonstrate that an individual unit has performance in-family with the qualification units, it follows that the individual units are ready for flight. Paring a mechanisms acceptance test down to only those tests necessary to prove manufacturing and performance consistent with qualification is key to realizing the cost savings.

Sampling Tests: Consideration should be given to pulling one or more units off a production line on a regular basis for more extensive testing to verify that inconsistencies have not crept into the production process. This approach is quite common in non-space industries. This sampling testing could be a subset of the qualification test to perform more extensive and insightful testing to ensure that small flaws are not hiding from the simplified acceptance test. The periodic nature of the sampling tests acts to reduce exposure to the misery of finding a problem after a very large quantity of mechanisms have already been delivered. The sampling tests can be a powerful complement to an acceptance approach with very limited testing on each unit.

Automation of Testing: As we move into testing of larger quantities of mechanisms there are many test automation systems on the market which we can use to reduce the hand labor typically associated with mechanisms test. Electrical pinout verification is made much easier with automated harness testers. These automated testers make harness testing as simple as plugging the harness into the tester which uses a computer driven electronic tester to very rapidly perform all the resistance, continuity, dielectric and HiPot type measurements needed. Motor testing can be performed by all-in-one motor test stands in which the motor is mechanically and electrically connected to a test stand including both a dynamometer and harness tester. One can easily see how these automated testers can change a series of tests that might take hours per unit into a couple automated tests that takes only minutes per unit and produce a finished electronic test report. Reference 2 presents an approach for thermal testing of many gimbal drives concurrently on a single fixture. This is an example of creatively driving testing costs out of a volume production mechanism.

Key Point: Modern automated testing methods can provide accurate testing very quickly while minimizing the documentation burden.

Test architecture Design: The author proposes that a mechanism engineer consider the following questions in designing a low-cost test program:

- What type of performance test provides great insight into mechanism performance yet is easy to perform?
- What combination of qualification, acceptance and sampling tests will be best?
- Do I need to test each individual mechanism for:
  - Vibration?
  - Thermal?
  - Vacuum?
- How can I automate the tests performed on each unit?
- How can I automate the test reporting and deliverable documentation?
- What testing will provide me confidence that problems have not crept into the production line?
- How much does this test really cost? And what is its true value?
- Can I create a single test that provides confidence in multiple aspects of performance?

Key Point: A wide variety of opportunities for streamlining during acceptance testing of volume produced mechanisms are available but need tailoring for the unique aspects of each mechanism production program.

Spacecraft Integration and Test

New Space programs are looking to simplify the satellite level integration and test process for recurring production. The testing for qualification satellites and early prototype satellites will tend to be extensive, much like Big Space programs. Once a new satellite design and its production processes have been qualified, however, the integration and test emphasis shifts towards confirming that each satellite has been built and performs the same as those units qualified. The biggest difference is that New Space will consider satellite level environmental testing as a choice to be made rather than something that simply must be done.

Mechanisms for New Space satellites may receive requirements to be compatible with streamlined satellite assembly processes. For example, satellite builders may ask for certain features to enable automated handling, and, will certainly desire mechanisms interfaces that make for fast and easy installation.

Flight Operations

There should be no fundamental differences in the flight operations of mechanisms between Big Space and New Space. In both cases mechanism operations are typically performed with very little intervention by human operators. New Space constellations will desire even more automation of satellite operations, so they will certainly not want any mechanisms that require complex operations with intensive human intervention. Any space program will benefit from an analysis of flight operations to either (i) simplify mechanism requirements or (ii) expose mechanism requirements which had inadvertently been missed.

Conclusions

1. The New Space effort is presently very active with significant continuing commercial funding.
2. Done right, the New Space objective of satellites produced in volume at low cost is achievable although it adds some risk of individual satellite failures.
3. New Space requires mechanisms very similar to Big Space but at greatly reduced cost and schedule.
4. New Space programs will tend to be accepting of simplifications in mechanism performance and mission assurance requirements in support of cost and schedule targets.
5. Design excellence is a far more powerful cost saver than manufacturing engineering.
6. No amount of manufacturing brilliance can make a poor design cheaper than a great and simple design.
7. The move into volume production of mechanisms needs to leverage the tremendous knowledge base for lean manufacturing.
8. Readily available equipment for the automation of inspection and testing offers significant advantages over more labor intensive manual efforts presently common in mechanism production.

There is no reason the space mechanisms community cannot produce reliable products at low cost, many other industries do.

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