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Leveraging Cross-Industry Knowledge To Improve the Design of Space Systems

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ABSTRACT

There are valuable satellites that fail early and almost none have been repaired or investigated. Other industries benefit from feedback loops that use failure analysis to accelerate design and manufacturing improvements.[17] Historically the cost of a repair mission would be so high it wouldn't be considered. The cost of space debris mitigation missions can be reduced by leveraging the learning other industries have experienced. Lowering the cost of repair missions will enable more debris mitigation, learn more about why missions failed, and lead to fewer failures and lower costs.

Many space programs rely on outdated processes that increase costs, inflate workforce requirements, and endanger delivery schedules. The techniques proposed enable a paradigm shift revitalizing space system design through cross-industry knowledge and experience sharing. By adopting proven practices from a diverse set of industries, we can enhance performance for spaceborne systems to investigate and recover failed satellites and similar missions.

First, we highlight techniques used in other industries to design for reliability and resilience in harsh environments. We present a framework to determine which established practices can accommodate different space mission profiles and requirements.

Second, we make a data-driven case to leverage more commercial parts and components in future space missions. Analysis of real-world reliability statistics demonstrates commercial hardware often meets or exceeds specifications designed for space. We outline processes already proven successful to qualify commercial parts for the space environment.

This modernization combines the selective incorporation of cross-industry practices and prudent commercial parts adoption. The results are highly reliable space systems that can be utilized in missions with drastically accelerated development timelines at much reduced costs even in missions with low spacecraft counts. We outline actionable next steps for stakeholders to update design and quality assurance standards and acquisition processes to enable this performance transformation through cross-industry knowledge sharing.

INTRODUCTION

Fairchild Semiconductor invented the integrated circuit (IC), while the space industry was the largest consumer of ICs due to the Apollo program in the early 1960s.[1] Other industries only began to adapt these back the highly innovative new devices. In these early days of the semiconductor and space industries, NASA and the US Department of Defense (DOD) spearheaded quality assistance and standardization, and used a part quality philosophy following a bottom up approach for quality and reliability. This is still the case in most space focused related quality assurance standards used today.

However, since Sputnik, Mercury and Apollo, the semiconductor industry's customer base has changed fundamentally. The space industry kept consuming ICs at an increasing rate, while usage in the consumer electronics and automotive industries were exponentially growing for decades. They rapidly overtook the space industry, and today there are several neighboring industrial fields with well established and rigorous testing, validation, and certification systems which were streamlined over decades. These are the product of hard learned lessons, gained through failure and success, based on collectively many millennia of work years of experience present and billions of devices constructed by hundreds of thousands of manufacturers. Today, automotive, biomedical, and even consumer electronics fabrication techniques and standards are highly refined due to this immense wealth of experience, and they have established rigorous feedback based learning systems to improve. The space industry however still follows traditional standards from the golden days of Apollo, which were reduced until to the space shuttle days.

In this paper, we make a case that the space industry in the future must inherit from the deep well of experience and standards from across other industries. We argue that especially the part grading method as used today in aerospace has been obsolete and has limited value. This does not mean it should be completely abandoned. Nor does it mean to completely ignore what makes the space environment challenging, or to ignore the valuable lessons learned by us as a space industry in dealing with this most wonderful of all new frontiers. However, in practice, when a manufacturer is today forced to resort to using expensive space grade parts, development becomes challenging, expensive and slow [23], with many other limitations in regards to project management and testing emerging. In the best case, the reason for this fact is that traditional space grade ICs and passives (capacitors, inductors, resistors, …) are simply less capable or offer reduced performance as compared to space grade parts. This implies that to design a device with certain capabilities, more space grade parts must be used, more functionality has to be added, or necessary functionality must be abandoned. In turn, prototypes are then more complicated to develop and validate, production is delayed, and lead times increase. This today is well known in the industry, but accepted in order to retain a space grade quality assurance label in parts of the industry.

As the traditional space industry continues its shift from military/institutional to commercial projects, and the cost of launch continues to decline, more business cases become possible also there. This paper is intended for those who seek to get better results in less time with a smaller budget per iteration. Some assume low cost is equivalent to cutting corners. Some managers and engineers hold on to this belief, while others due to practical experiences, be it success or failure, realize that a simple system with few well understood parts can be more robust than those constituted by many highly reliable components. However, in management processes, often only raw statistics or heritage and legacy matters, no matter the experience of individuals and their opinion. In this publication, we hope to provide these to help improve reliability of future space systems and success rates in future space programs.

This article starts with problems with old assumptions, explains how volume drives quality, highlights things that can be done to get the benefits of other industries while building on what we know about the space environment, then concludes with three future developments the space industry needs to help catch up with other industries.

Project Management and Improvement, and Feedback Loops

A devious side effect of a slow developing pace is that it delays the ability to learn how to improve design and optimize products, often simply due to brain drain and employee turnover. Today, space standards may be more strict than those of other industries, but those achieve drastically higher product refinement levels, better test coverage, and they can learn from their past mistakes. Inheriting parts of this philosophy has enabled the NewSpace community to rapidly innovate, and successfully conduct more space missions in the past 15 years than in the entire time since Sputnik was deployed in orbit. However, an approach of fail-early-fail-fast is not suitable for the most critical space missions.

A space mission can generate no revenue during development phases pre-prototype. Hence, the higher that cost and the longer it takes to deliver a spacecraft or subsystem or part, the larger the return on investment is required to be. This means the hardware needs to last longer in space, which will require a more robust system and a more risk averse design. That drives up costs even more. Taking all these aspects into account causes a situation where many opportunities are not worth attempting. And this creates an environment in which more modern parts and concepts do not find their way into future products, missions, and programs, without the capability to objectively consider bottom line reliability unbiased. This has caused a lock in effect.

Alternatively, if more advanced, highly capable, more mature, parts and modern design processes can be adopted for traditional missions, development times can be shorter, subsystems, modules, and parts cost less, prototypes cost less, can be tested sooner, and are less risky to invest in. All making missions more affordable allowing return on investment periods to be shorter and less extreme. More opportunities become worth taking. Shorter, more profitable, and predictable missions mean there is more tolerance for novel parts with lower reliability, further reducing the time to break even.

In Fig 1. is a comparison of the two types of design cycles, rapid and traditional, is provided. Both include a recursive feedback loop with an amplification effect. This feedback loop always exists, unless only on-off instruments are hand-crafted, in which case no learning from failure is possible within a program. This also has a direct impact on prototyping and testing abilities.

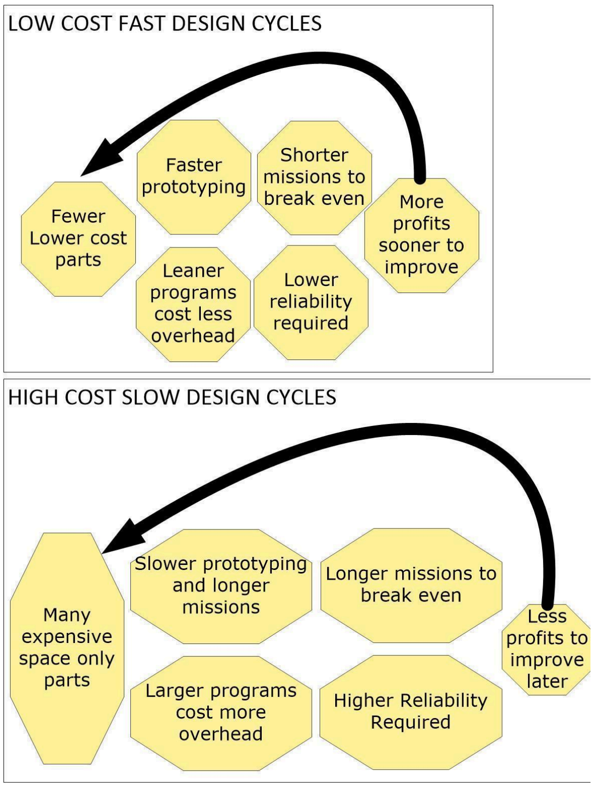

Figure 1: Fast-Low-Cost vs Conservative-High-Maturity Design Cycles

Prototypes, Protoquals, and Finished Products

The more expensive a prototype, the less testing is possible for each prototype generation, and the fewer generations can be iterated over within budget. In some projects, the number of generations or devices manufactured is equal to 1 per TRL level, creating immense pressure on designers and quality assurance to deliver a functional product or fail. Some space industry organizations skip qualifying prototypes and perform a "protoqual", which is delivered instead.

A future flight unit can be tested and overstressed only to a minimal degree in order to maximize its lifetime despite testing. This is due to a lack of units to perform a full systematic and usually, also destructive qualification testing to prove lifespan and environmental margins with flight-suitable units. This leaves little margin for error.

System and part testing using a test sample size of one is more comparable to an environmental screening than systematic validation that could generate statistically viable test data. In this manner, quality assurance may find certain overlooked quality deficits and true mechanical or function-breaking defects, but they can not provide a level of confidence gained in other industries.

Standards, Guidelines and Requirements

US Department of Defense Military Handbook 217F Notice 2.

"THIS HANDBOOK IS FOR GUIDANCE ONLY. DO NOT CITE THIS DOCUMENT AS A REQUIREMENT" - MIL-HDBK-217F NOTICE 2 Published 28 February 1995

Until recently, space industry actors still treated and cited such documents just like actual standards, and derived requirements from them.[25] In certain space projects, this has required constable contortions to brute force them to make sense as standards. Even actors outside the US, who would be unaffected by such documents, and who have much smaller, non-defense contractor budgets are trying to use it. There are at least two much better and affordable alternatives that will be covered later.

The US Department of Defence supported the development of spreadsheet based tools to aid in this process and make decisions more reproducible. The first tool, an MS Excel tool, is still available today, and it has been maintained and improved periodically since its original creation.[2] It also includes software, a key concern that interacts with hardware.

An anecdote in this regard can dispel the part grade myth using the mechanisms behind Wright's law. In a biomedical device manufacturing company, an aging test was conducted to ensure a new design could function correctly over a lifetime of 10+ years. Being a device manufacturer, the main concern in this campaign was to ensure the parts used to manufacture device batches were not just functional and fault-free, but also as reliable as expected across all devices and generations manufactured. However, during the age test units failed prematurely and unexpectedly. The root cause was traced to certain capacitors used. However, this did not mean they were faulty, they functioned correctly as per specifications. The capacitors were military grade and carefully selected following the philosophy that choosing a part of a grade intended for a much more critical application with more stringent standards would certainly mean they were reliable enough to use in a medical device. Initially, it was assumed the parts were sound, but that the assembly, integration, and or test process for the device was flawed, or that the design was overstressing the parts in some manner. Fortunately, the part documentation included traceability per lot, which meant the exact batch could be checked on the source/supplier side. The supplier and manufacturer were contacted, and the testing company's engineers worked with the manufacturer's subject matter experts and materials scientists to pin down exactly what was happening to make the parts fail.

Ultimately the flaw could be associated with a specific flawless rework step for the affected device batch. The testing company could meanwhile exonerate its device design and all manufacturing steps, leaving only the correctly working and validated capacitors to blame, which functioned according to standard and datasheet. However, it turned out that the military-grade capacitors used had been reworked. However, this flaw did not exist in the cheaper, commercial grade parts, because the component manufacturer had streamlined that fabrication process years ago already, as the far higher volumes justified more attention and allowed more automation and added process control steps. For the low volume military grade parts, this was not done.

The part manufacturer decided they would never rework their devices again and scrap batches where this had happened.

This anecdote demonstrates two aspects:

- A large volume of manufactured devices and prototypes can directly reveal even indirectly, subtle flaws in manufacturing processes or designs, and can lead to improvements that can otherwise not be discovered. As one customer did something extra (life testing a random batch of capacitors) they discovered a flaw in the supplier's part system. More customers operating and testing the same parts gives suppliers feedback to make improvements that benefit all customers.
- Low volume can hinder process optimization because older quality levels that were once near the best of what was possible are satisfactory to low volume users that high volume users could not tolerate.

When the DOD switched to reliability predictions based on software, which was based on actual failure rates, they developed that method for 20 years, then in 2006 published a handbook to reflect the updates as cited in Reference 2. This continued to be improved by Quanterion Solutions Incorporated[3].

Figure 2. illustrates the philosophy of "test-in" quality represented by part grades as reflected in 217F.

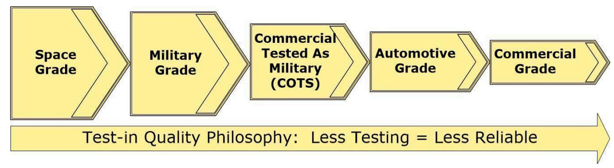

Figure 2: Part Grade Quality Philosophy

This belief that more testing equates to higher quality also makes assumption that higher quality ensures higher reliability. A nuance is reliability includes durability (how long things last when used in real environments) and random failures. For example, a large surface is more likely to be hit by debris or micrometeorites than a small one. This failure mode is part of unreliability but is more about size than manufacturing quality. The durability aspect of reliability accounts for longer duration making it more likely for random events, flexing stress with thermocycles, etc. Reliability is all of the above while quality is mostly about the consistency of the initial process. An uncontrolled process in a garage may get very different results every time while a streamlined process that includes many measurements along the way that ensure every aspect is consistent can have much higher quality.

Commercial Of The Shelf(COTS)

Some companies consider COTS to be directly off the shelf and others consider COTS to be are commercial parts that are tested to Military standards, and pass.[18]

Why does less testing this make high volume commercial parts them a lower quality than lowe volume military grade if they pass the exact same tests? Does testing magically make them better than commercial grade? It is possible that military grade always passes on the first try and commercial grade requires many lots to be discarded before one lot is accepted. However, this brings up a concern with variation and lot of acceptance strategies.

COTS adds a level of confidence that may be a good compromise for those reluctant to abandon space grade. Pratish Shaw explained how Aitech has used this approach to get the best of both worlds with modules on the ISS and other applications.[5]

Low Quantities and the Hand Crafted Grade

Imagine there was such a thing as “hand crafted grade”, ideally imagine a situation where only one device was made of a product. While it would be prudent to test 100% of each item made, the best tests are destructive. Each item will have a tremendous amount of variation due to the lack of experience making them. It would be far more expensive, and domain experts on one of these products would be very rare. They would start fresh with every crafted item, inevitably causing startup mistakes. Each on-off device would have to be reworked as often as possible and re-tested to finally achieve one functionality because the cost of starting over would be prohibitive. Each resulting device incarnation would vary widely, just like early WW1 tanks which all were built individually; Each device would be unique. Even if a destructive test was conducted, it would not be clear how much of the achieved data, or if at all any results, would apply to future incarnations of the same product.

Wright’s Law, The Industrial Learning Curve

The engineer Theodore Paul Wright first formalized the unit cost learning curve for aircraft in the mid 1930s, which he formalized as:

$$C_x = C_1 x^{\log_2(b)} \quad (1)$$

Where C is cost for the x^{th} unit, and 1-b = L is the Learning rate where every doubling in cumulative production halves the cost. It is an approximation and the core concept is that cumulative production is the best prediction for cost improvements. The more units that have been made, the better the industry gets at making those units.

In 2013 a team of scientists studied various technology forecasting methods and found Wright’s law was the best and Moore’s law a close second. Looking closer it turned out Moore’s law was a subset of Wright’s Law. [12]

Even though it is stated in terms of cost it can be applied to other metrics like feature count, longevity, storage size, etc.

The reason entire industries improve is that one company will lead and others must follow or fail. They must abandon that product line or go out of business. Also, companies in an industry share suppliers and the leader pushes them to improve and other companies using those parts benefit.

System Level Mitigation

Fault Trees

When human safety is involved it’s better to make systems fault tolerant, and do the extra work of working through fault trees.

For example, if a single capacitor short leads to a crew dying this is not a capacitor problem but a bad system design. If you are sending a crew on a multi year Mars mission then it should consider many such failures and that commercial grade parts may be more reliable than space grade. The grade is not as important as the system design and manufacturing process maturity.

The Quanterion Reliability Handbook reference 3 has an excellent list of failure modes at the part level.

Failure Modes and Effects Analysis(FMEA)

This is closely related to hazard analysis and is sometimes called FMECA with the C added for “Criticality” even though some use that without evaluating criticality. All of these are essentially listing failure modes, considering how bad each one might be, and the probability. For example, a rocket powered by nuclear explosions launching from your city would be a major disaster for many people with 100% probability since that is the intended design. Simply listing this triggers ideas about how to make the severity and probability lower. A team discussing this will have many more ideas. The value of ranking them is to ensure the greatest risks are eliminated by design upfront, and precious engineering time is not spent on trivial risks. As a minimum, this can be done at the system level, at the maximum every failure mode for every part can be considered. This is not as hard as it may first seem since a designer must select parts, find places to mount them, etc. Part of that will be thinking through how to prevent issues so they are already almost there. Part Failure mode probabilities have been estimated as shown in table 1. This shows how different part failure rates can be taken into account. For example, a resistor will almost never fail short, and a performance failure means it has drifted out of spec. All resistors do this with time at different rates, a robust design will not be sensitive to that. You can simplify the analysis to assume the majority of issues will be from resistors going open. The electronic designer can summarize how an open would affect the system.

Table 1: Part Failure Mode Probabilities[3]

Part Type	Short	Open	Notes
Resistor-Film	**10%**	**90%**	**When part of a circuit where drift**

			matters- add to FMEA
Transistor-Bipolar	**75%**	**25%**	
Transistor-FET	**90%**	**10%**	
Capacitor-Tantalum	**65%**	**35%**	
Capacitor-Ceramic	**10 pt**	**Normal**	**When multiples on power so 1 open won't be a failure, treat as 50% functional shorts**
Diode-General	**60%**	**40%**	
Connector-Connection	**20%**	**80%**	**Do per pin - this is why ICs that reduce connectors improve reliability**
IC	**0%**	**100%**	**Put IC performance changes in the FMEA since these might confuse software**

This table assumes derating removes most parametric failures to leave the open and short failure modes to consider. Then recalculated that conditional probability and rounded to the nearest 5%.

The reason derating reduces parametric failures is that the majority of those are due to degradation. For example the speed of an IC or the value of a resistor changes with time. When a design operates near the edge of a part's expected value it is more sensitive to these changes.[26]

In detail every situation is different so consider this a faster first pass to get good enough results to drive your attention where it will do the most good and not get bogged down in minutia. Remember that perfection is the enemy of the good. This is another way figure one drives up costs, the higher the precision and confidence required the longer everything will take, which drives up costs, which makes things take longer and cost more still. Some things do need a lot more attention so you will have to constantly balance this. Start with more generalities and rounding to get closer, and iterate as you learn more and get results.

Shorts are only interesting if there is a spare to switch to when a fuse or circuit breaker is tripped. In a simpler system, it is not worth doing this level of detail since the function is lost. Depending on the part some opens won't necessarily matter. For example, a diode to protect from ESD might mitigate TID charges eventually but are mostly there to survive handling. In general, TID will find another path and once launched the handling risk is gone.

Similarly consider the majority of ceramic capacitors are providing power smoothing for the ICs. A parameter drift won't matter for that role, and even some opens are tolerable. However a short would need to blow a fuse or circuit breaker or burn that capacitor to an open.

ICs rarely fail for performance issues, pushing parts close to ratings increases the chances of this becoming an issue, such as counting on it to be as fast as advertised for decades. As a rule, always use a derating method. There are several and any of them will be much better than none. Parts often have design notes to help you use them as designed with best practices. This may be another way the learning curve helps everyone in an industry. As some customers misuse parts the part providers add notes to teach better ways to use it. They often have application engineers who will help pick the best part for an application and how to ensure it is used better.

A system level FMEA is always worth doing because a little team brainstorming to eliminate failure modes or make them less likely or less severe has a large return on time invested.

Environmental Comparison

The Quaternion 217plus tool superseded the 217F method with US government support and has been periodically improved since. That method takes into account the time assemblies spend at different conditions. Table 2 shows space and four more common challenging environments.

Table 2: Comparison of active operating conditions for three Challenging Environments

Environment	Airborne, Space	Ground, Mobile	Ground, Man Pack
Example Device	**Satellite**	**Automobile**	**Smartphon e**
Temp when Assembly On C	**55**	**55**	**55**
Temp When Assembly Off C	**14**	**14**	**14**

Operating Relative Humidity %	**40**	**40**	**40**
Operating Vibration Grms	**0**	**10**	**1**

Note these are generic temperatures used for reliability estimates during the mission life. In practice, things will go through a wider range of temperatures.

It might seem odd for a space to have humidity above 0. In fact rapid decompression is a risk to test before launch to ensure that quickly going from a normal, humid atmosphere to the vacuum of space won't pop things apart. In practice assemblies destined for space will be in lab environments with controlled humidity. Consider the first assembly will wait until the last assembly has been installed. Then there are integration steps and tests. It is important to consider how corrosion can be introduced during these phases without easy detection. Once started removing moisture on orbit is too late.

Vibration shown for space is 0, which reflects that a space device is off when surviving the short launch then turned on later. There may typically be station short occasional station keeping maneuvers. For the ISS this is about once a month.

There are six things smartphones, automobiles, and other earth based industries don't need to worry about as much as space does. These are explosive decompression, micrometeorites, magnetic moments, outgassing, tin whiskers, and radiation.

Mitigating Temperature Ranges at the System Level

The temperature ranges of commercial parts may not be as high as space grade as shown in Table 3.

Table 3: Operating Temperature Ranges in C

Part Grade	Low	High
Commercial	-40	85
Auto	-40	125
Military and Space	-55	125

Heat is considered the driving cause of part failure rates so lower is better as a rule.[2] Rather than require all parts to operate at higher temperatures consider ways to make the whole system cooler. Notice in the table that at the low end space grade parts can only tolerate 15C less than automotive and commercial grades, can the system be heated more before turning on? At the high end of the temperature range, the space grade parts are the same as automotive. Cooling more to accommodate commercial grade parts has the added benefit of higher reliability overall.

Longer missions can also minimize thermal cycling that stresses connections. This is a larger concern for LEO orbits compared to earth bases systems because they will have about 14 days of hot and cold compared to something outside that only sees one day cycle. A Geostationary mission sees the same day/night cycle as earth. A longer mission will make this a larger concern and more, longer tests will be required to validate it, which will increase costs (see figure 1).

Mitigating Single Event Effects at the System Level

Computers can use redundancy to compare results and ignore noise or reboot after a latchup event. This means that condition needs to be detected fast enough to reboot before ICs are damaged. Memory can be stored multiple times in multiple places so comparing copies will reveal the corruption to be fixed. The sensitivity and frequency of these need to be considered. A frequent upset event that causes a lengthy reboot process could render a system almost useless. A best practice is a local boot and a watchdog to trigger if silence is too long. Software improvements could be uploaded to one chip at a time so no there is no downtime.

Mitigating Tin Whiskers at the System Level

When most industries adopted lead-free parts and processes there were tin whisker concerns for space applications.

Tin Whiskers refer to the tendency for tin-based solder to gradually grow dendrites. In most cases, they will clear themselves by vaporizing because they are too small to carry much current, though even this vapor can still carry currents briefly. In some cases a fuse may blow first, causing the same system level effect as a hard short because the fuse reacted to it faster than it could clear.

Conformally coating the assembly with Arathane 5750 uniformly to a nominal 2 to 3 mils thickness (55-80 microns) provides significant benefits.[7] It not only reduces whisker growth speed but if they penetrate the coating and break off, floating whiskers are unlikely to penetrate the coating in other locations. This is especially relevant for maneuvering spacecraft.

Mitigating Outgassing

The automotive industry calls this off gassing. The plastics are still curing.[16].

Epoxies and plastics contain softeners and curing agents due to thermal cycling and accelerated material aging This can reduce the life of a mission. Just as this takes years to become an issue for automobiles it is only a concern for long missions. Shorter missions will not have this concern and any extra costs associated with it (see Figure 1).

NASA recommends minimizing this risk with part selection and providing an online material catalog to help. However, the faster and easier mitigation is adding the Thermal Vacuum Bake Out step they also recommend.[6]

But before imposing extra steps consider if the mission life can be short enough to skip it. Even if the mission ends a little early because it was needed after all that may be a lower risk than an abundance of caution that drives up mitigating everything that might be an issue someday. See Figure 1 for how additional delays and costs cause more delays and costs.

Mitigating Radiation at the System Level

Finally the big concern is radiation and it is not trivial. Earth is truly blessed with a magnetic field that intercepts the majority of cosmic and electron energy before it reaches the surface devices. The two types of radiation are Single Event Effects (SEE) and Total Ionizing Dose (TID).

A lone automotive or commercial part in space will see far worse radiation than it would on Earth. In practice, parts are surrounded by metal shields. Consider the copper planes in power supplies, thermal management, and other metals act as free shielding. Tantalum has been commonly used to spot shield sensitive parts since it is relatively light and dense.

Bottom Up Reliability Analysis beyond 217F

The two newer methods for this are the 217plus[3] and Telcordia workbooks.[10] These workbooks are very affordable and include user friendly MS excel based tools. The advantage of Telcordia is it has more newer parts. Using both is better than just one or the other but they get similar results so either one will work well.

Wrights Law for Commercial Parts

The commercial electronics industry includes personal computers, smartphones, Televisions, and far more devices. Of these, the most demanding may be smartphones. People drop them, they must fit in a small package and do a lot of demanding tasks with a limited battery.

Smartphones are similar to satellites in that they store power, have computation, communication, and sensors, all in a small integrated package where changing any one feature means changing everything.

The iPhone

The first smartphone as we know it today was introduced by Apple in mid 2007. At that time there were only two choices, the low end had 4GB of storage and cost $499 USD. They also offered a more expensive 8GB version that was otherwise the same.[4] Over the years they improved every aspect and by 2022 the lowest version offered was the 64GB SE3 for $429 USD. The other 25 offerings still available that year were better in various ways and more expensive. Considering inflation most of those fall in the “regular line” range. From 2007 to 2022 inflation made the USD drop about 45% so $429 in 2022 would be about $296 in 2007. This is a 41% drop in real cost. Even more dramatic is the increase in features and quality. Table 2. highlights the feature improvement from building more iPhones every year and learning.

Table 2: Feature growth from building 2.6B iPhones[15]

Features	2007 Lowest = 1st Gen	2022 Lowest = SE 3rd gen	15 Year Change
Screen	**3.5in, 480x320 pixel**	**4.7in, 1334x750 pixel**	**1.8x larger screen, 6.5x better resolution**
Storage	**4GB**	**64GB**	**16x more memory**
Compute	**412MHz CPU with 128MB RAM**	**3.22Ghz CPU with 4GB RAM**	**7.8x faster and 31x more memory**

Sensors	**2MP camera, accelerometer, proximity sensor, ambient light sensor, microphone**	**12MP rear camera, 7MP front camera, fingerprint scanner, accelerometer, proximity sensor, GPS, gyroscope, compass, barometer**	**Rear camera 6x better and 1.8 more sensors**
Comm	**Cell Provider specific, Wifi, Bluetooth 2**	**NanoSim and eSIM, Qualcomm X57 modem, Near field comm(NFC), Bluetooth 5, Wifi 6, Voice over LTE**	**2.3x more and upgraded options**
Power	**1400 mAh Battery, USB2 Apple charger**	**2000 mAh battery, Apple lightning charger, Wireless charger**	**1.4x larger battery and 2x more charging methods**
Price (2007 USD)	**$499**	**$296**	**Cost 41% lower**

Over this time the smartphone industry has built almost as many since Apple started with 100% market share and drifted to 60%. This is complementary to the computer, digital camera, flatscreen TV, and related industries since they are all improving, and parts and processes used for one can be used in another.

Quality is implied by cost reduction despite adding features. Consider every time a larger or new chip is added or a new sensor, not only is that one more thing that might fail, but it also must have all those other interfaces to the other chips. Every connection is an opportunity for failure. When these are in production they cause more assembly rework and scrap, which adds to the cost. The sold units must pay for these costs. Quality defects follow the infant mortality curve. Warranty claims on defective units that either escaped tests or had latent defects are a higher expense because an entire finished unit has to be replaced. More features raise expectations, by providing more ways to have a warranty claim and increase the possibility of a failed device due to those features and all the additional interfaces required to support them. This means the defect rate must decline relentlessly to allow adding more features while maintaining or lowering the prices as demonstrated in Table 2.

Durability versus Upgradability

For the smartphone industry, durability is of limited interest since within a few years customers often want to upgrade to new devices with new features. The cost of replacing a worn battery to salvage a now obsolete device has limited appeal. For the Automotive industry reliability and durability are of great interest.

Wrights law for Automotive

The iPhone was the top selling smartphone in 2007 (by creating the category) and that year the world's top selling vehicle was the Toyota Camry. By then a mature "device" given the first year of this model was 1979 (28 years) and Toyota first started making automobiles in 1936(71 years). Table 3. shows the price and features of the lowest model available between 15 years.

Table 3: Feature growth from building Over 12M Camrys[14]

Features	2007 Lowest = CE	2022 Lowest = LE	15 Year Change
Power System	**158 HP, 34 MPG, Manual Transmission**	**203 HP, 39 MPG, Automatic Transmission**	**1.3 more power and 1.1 better mileage**
Controls	**Cruise control, Power locks, Power windows**	**Cruise control, Power locks, Power windows, Fob controls cargo/fuel access and windows**	**1 more feature standard**
Electric	**Variable wipers**	**Variable wipers, Trip computer, 2 LCD monitors, Amazon Alexa, Voice recognition**	**4 more**
Audio	**6 Speakers, CD player, MP3/WMA**	**6 Speakers, Android and Apple carplay, USB media, Bluetooth**	**5 more**

		wireless, XM satellite, Wi-Fi 2GB, Speed compensated volume	
Safety	**Tire pressure monitor, Anti lock brakes, Driver and passenger airbags, Side airbags**	**Tire pressure monitor, Anti lock brakes, Dual Stage Driver and passenger airbags, Side airbags, Toyota safety sense 2.5+,Perimeter alarm, Evasion assist, Auto headlights,**	**6 more**
Driving	**Variable assist steering**	**Electric Assist Steering, Electronic stability control, Lane tracing assist, Lane departure alert, Driveline traction control**	**4 more**
Price (2007 USD)	**$18,470**	**$17,824**	**Cost about the same**

Note that in 2007 the LE model was the next better model above the CE, eventually, they dropped the CE level, making the LE model the lowest level. In real dollar terms the 2022 LE is 97% of the 2007 CE price. Considering the inflation adjustment isn't perfect this is essentially the same price. In return a buyer gets an automatic instead of manual transmission, 30% more horsepower, 15% more miles per gallon, far more electronics, many more safety features, and a better driving experience.

While the lowest new iPhone type price stayed about the same, a real drop with inflation, the Camry price rose to keep up with inflation resulting in almost the same real cost. About 20 new features were added for that price, mostly attributed to improvements in other technologies like ICs. Even the higher Horsepower with better mileage is likely to be at least partially due to improved engine controls.

Consider that all additional features provide more ways a car can fail. Every new feature also needs new power and control interfaces, which may also fail. If quality wasn't improving dramatically the rework and warranty costs would make it impossible for them to make a profit at the same price as the much simpler vehicle.

Toyota Camry Quality and Durability

Toyota was rated the highest reliability by consumer reports customer reliability survey.[19]

Consumer reports noted that at one time 100,000 miles was about time to scrap a car. Now 200,000 is a reasonable expectation.20 Note that Toyota and the others are not using space grade, military grade, or COTS. They have been using automotive grade, the second worst quality grade if the part testing philosophy was the main driver of quality. Also note this is a harsher vibration environment as seen in table 2.

Wright's law may seem like magic. As a company makes more of the same thing it gets better and can sell it at a lower price. Customers will prefer the better things at the lower price and buy more from that brand, creating a virtuous cycle. This is how Toyota's reputation for quality and reliability translates to resale value as shown in Figure 3.

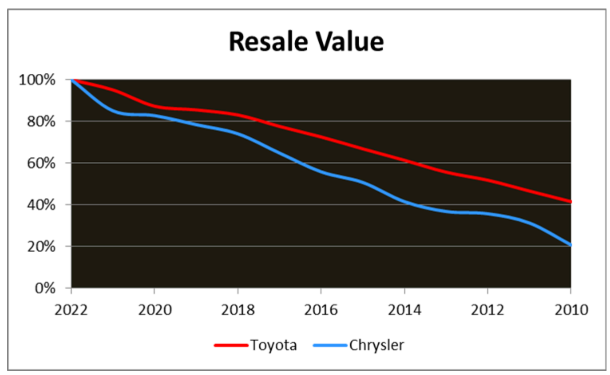

Figure 3: Toyota and Values Over Time[11]

Since many people know when buying a new one they will have a lower cost for repairs and a higher trade in value they will pay a little more upfront than a comparable vehicle from a low reputation brand like Chrysler[11].

Wright's Law for the Space Industry

Traditional space and defense solutions upgrade cycles tend to exist in the decade range due to the reasons outlined in the earlier sections. Until StarLink and PlanetLabs, Iridium satellites were the largest contributors of active spacecraft in orbit by count. And even the total of all spacecraft launched into space back then is dwarfed by the number of objects placed in space in the past 15 years, since the emergence of the new space industry, for visual comparison, see Figure 3.

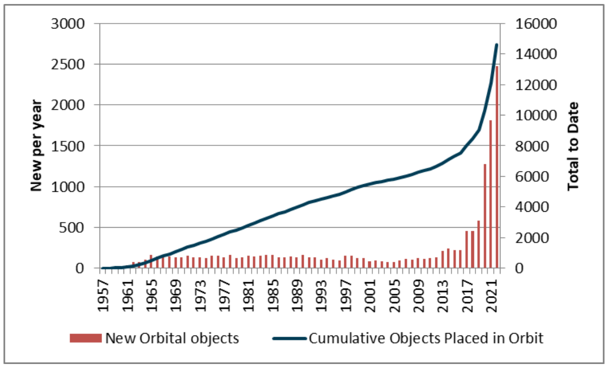

Figure 3: 65 Years of Objects Placed in Earth Orbit

From 1965-2012 the annual average was 131, with 163 in 1965 and 134 in 2012(ref 8). This was essentially flat until 2013. In over 65 years less than 16,000 objects were put in orbit. The lessons learned by ESA, NASA, JAX, Roscosmos, and others do not automatically reach each other for many reasons. The less shared technologies are used the slower each learns.

Compare this volume to the manufacturing count of a single first generation cellphone. When the iPhone was released mid 2007, in the first week alone 300,000 were sold.[13] To do so, Apple had worked on fabrication process optimization for three years and spent about $200M(2022 USD), this included software, hardware, and quality assurance processes, as well as the requirement for setting up a distribution and servicing network.[27] After a year 122 million devices had not only been manufactured but sold, a number that would increase in subsequent years.[9] The fabrication process established allowed manufacturing about 400,000 devices each day, or about 20,000 per hour. This means that by 2007, Apple alone had made more iPhones in one hour than the sum total of all satellites the entire space industry has ever produced in 65 years. This comfortably also accounts not just for launched satellites, flight models, but also for ground models produced.

SpaceX spent about $1 Billion to develop reusable rockets20, for comparison as of 2020 NASA was charged over $14 Billion[21] to redevelop the one-time-use rockets despite using Reusable Space Shuttle technology as a head start.[22] The difference can attributed to the lean startup business mindset versus using legacy space approaches that maximize spending.

Wright's law requires high volumes to drive down costs, as poor quality becomes the largest cost as volumes go up.[24]

Hand Crafted Part Grade resembles space grade parts and assemblies much more than commercial or automotive. Volume is a kind of magic. As a company makes more of the same thing it gets better and can sell it at a lower price. Customers will prefer the better things at the lower price and buy more from that brand, creating a virtuous cycle. This is how Toyota's reputation for quality and reliability translate to resale value. Since people know when buying a new one they will have a lower cost for repairs and a higher trade in value they will pay a little more up front than a comparable vehicle from a low reputation brand like Chrysler. [[

A final system-level policy is to buy as much as possible and invent as little as possible.

The Space Industry Misses Out On Feedback Loops

The automotive, consumer electronics, and medical industry participants benefit from several feedback loops that allow them to increase maturity and accelerate learning. The traditional space industry has no access to these. Figure 4 illustrates these gaps.

Figure 4: Five Failure Analysis Feedback Loops

Space performs environmental testing and different destructive and nondestructive qualification tests to capture quality issues of parts and processes, as do all other industries. Quality escapes that then fail when first turned on in space have limited feedback. People can review intermediate photos and see a washer in the wrong place or something, but even then they don't know for sure that is the root cause of a unit not turning on or failing shortly afterward. The pattern of infant mortalities like this is exponential decline, the majority should be seen very early, then decline with time. A good rule of thumb is it's the warranty period, 3 years for most cars, and 1 year for many consumer products.

Random failures such as a satellite hitting a micrometeorite, a car getting a flat tire, or an iPhone screen getting cracked are equally likely the 1st year as the 4th year. In the earliest days of cars, they carried many spares even for short trips because tires were frequently punctured. Today a tire is a masterpiece of engineering that fails far less often. The major innovation for the iPhone was gorilla glass, a collaboration between Apple and Corning to solve the fragility problem seen on similar devices up to that point. Space lacks this feedback loop. When something fails there are guesses, and a major collision is observable, but the majority get no failure analysis.

When there is a warranty claim or accident on Earth, failure analysis can find the root cause and ensure it never happens again or happens less often, or isn't catastrophic. The extra testing for space systems provides some failure data so this is not completely missing. ISS modules that fail have been analyzed. Generally, space failures are mysteries. For example, if a fuse is blown in a system odds are good it is due to a short somewhere, but which part shorted? Was it a washer drifting in the system that finally landed in the wrong place?

The final category is wear out failures. For a car the tires lose tread every drive and eventually become too bald to drive safely in the rain and need to be replaced. Their life span is measured in miles and has had over a century of iterative improvements based on tremendous real world and life test data. The battery in a smartphone has a charge/discharge life span. These have also been improving from tremendous amounts of real world and life tests in laboratories. These batteries also have cross industry benefits since similar batteries are used in electric toothbrushes and electric cars. An improvement in any industry can find its way into others just as IC chips have. The space industry can take credit for pioneering batteries like this decades ago, and now can benefit from the other industries.

CONCLUSIONS

There may be failure modes that are still poorly understood about the space environment which makes issues with commercial and automotive parts and processes unique.

1. Propper Failure Analysis

Other industries have the ability to study every failure to figure out the root cause. In many cases, failures occur when a combination of conditions exist. The part variation, process variation, and transient environmental conditions may contribute to reliability problems. . This is where good data collection will pay for itself. There is very little of this for space. Telemetry can give hints but ultimately no one is doing the failure analysis. In fact according to international law Low Earth Orbiting satellites must be sent to burn up in the atmosphere, destroying the evidence. So the first missing need is failure analysis on orbit.

We need something like remote operated drones to disassemble, inspect, and perform failure analysis in orbit. That capability enables a second need.

2. Capture, Control, and repair

The cost to access space has been dropping and adopting best practices from mature industries will drop the cost of payloads also. This will increase the volume of objects in space dramatically. From a Wright's law point of view this larger volume, combined with failure analysis to accelerate learning will exponentially improve the industry and enable even more to be done with even less. But this exacerbates the current debris risk.

The main concern with space debris is the out-of-control objects. When the risk of a collision is detected one or both will maneuver to miss by a safe margin. Nothing can be done when neither is under control. With the ability to do failure analysis on failed satellites, we are a few steps from repairing them. Another option would be to take one derelict under control with the same method used to move the repair robot. Once under control, it can be moved as needed to avoid a collision.

3. Upcycle, Reuse, repurpose, and Recycle

The third need is to put obsolete hardware to good use.

Reusing mass already in orbit can lower the cost of new, repairing otherwise good satellites will lower costs, and providing space specific failure analysis data to improve designs will lower costs again. Table

Final Conclusion

The main problem for the space industry has been low volumes. More, faster, smaller, cheaper iterations will enable faster learning to do even more with even less.

Consider how Apple, Toyota, and others started with a prototype and relentlessly improved features while driving down costs to become world-class. Designing systems for the new space industry will benefit from adopting best practices while keeping in mind the space environment has its own challenges.

This paper has explained how the part grade approach has been replaced with better methods, how the highest volumes lead to the most maturity, and provided several methods for engineers to make the most of high volume, high quality, highly capable low cost parts for applications in space. It concluded with three next steps for the space industry to enable failure analysis as useful as other industries.

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