Pathways and Challenges to Innovation in Aerospace

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Abstract—This paper explores impediments to innovation in aerospace and suggests how successful pathways from other industries can be adopted to facilitate greater innovation. Because of its nature, space exploration would seem to be a ripe field of technical innovation. However, engineering can also be a frustratingly conservative endeavor when the realities of cost and risk are included. Impediments like the "find the fault" engineering culture, the treatment of technical risk as almost always evaluated in terms of negative impact, the difficult to account for expansive Moore's Law growth when making predictions, and the stove-piped structural organization of most large aerospace companies and federally funded research laboratories tend to inhibit cross-cutting technical innovation. One successful example of a multi-use cross cutting application that can scale with Moore's Law is the Evolutionary Computational Methods (ECM) technique developed at the Jet Propulsion Lab for automated spectral retrieval. Future innovations like computational engineering and automated design optimization can potentially redefine space exploration, but will require learning lessons from successful innovators.[1][2]

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1. INTRODUCTION

Because of its nature, space exploration would seem to be a ripe field of technical innovation. To build one-of-a-kind exploration machines to "go where no one has gone before" certainly gives the impression of working at the cutting edge of creativity and innovation. However, engineering can also be a frustratingly conservative endeavor when the realities of cost and risk are included.

Impediments to technical innovation exist at every level of space exploration. The "find the fault" culture of most engineering groups tends to be very effective at honing in at robust solutions at the expense of introducing new and innovative ideas. Technical risk is almost always evaluated is terms of negative impact and likelihood, but rarely is it considered in terms of opportunity or advantage. In contrast, a more complete way of managing risk is to consider the risk versus reward ratio in the evaluation. Additionally, the observation of Moore's Law or the Law of Accelerating Returns means that certain processes have been and will continue to advance with exponential growth. Computational power doubles for the same unit cost every 13 months (a factor of 500 every decade). Bandwidth, memory, gene sequencing costs and other processes are advancing even faster. However, it is extremely difficult to account for this unnatural expansive growth when making predictions about future products. Generally, because this growth is not built into aerospace roadmaps, organizations miss the opportunities to fully utilize their potential. Finally, the stove-piped structural organization of most large aerospace companies and federally funded research laboratories tends to only advocate technologies that benefit the sub-field and not the organization as a whole.

Creating and recognizing new innovative ideas is just the first step. Ideas must be embraced by the supporting organization and the applications generated from the new ideas must be infused. This latter step is the most difficult to overcome and the final roadblock for most new ideas. Many of these same impediments to technical innovation also exist in creative fields recognized for their ability to find new ideas. By understanding how innovation is handled in other organizations, the space exploration field may find new paths to increase its performance in the era of Moore's Law.

2. ELEMENTS OF THE BOX

Innovation is often referred to as thinking outside of the box for its quality of finding solutions and pathways in non-traditional areas. For the purpose of getting out of the box, it can be instructive to define the box. Here we define some elements of the environment that can be difficult to account for and may therefore inhibit innovation. We consider two areas that are important in characterizing the working

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[2] IEEEAC paper #1391, Version 6, Updated January 4, 2010

environment. Both are referred to as laws but are, in fact, observations.

Moore's Law

This observation, credited to Gordon Moore [1], states that the performance of computer circuits double in performance about every 18 months. There are many ways to measure performance (instructions per second, transistors per square millimeter, watts per instruction, etc.), but as an illustration let us consider floating point operations per second (FLOPS). Since 1993 the top 500 supercomputers in the world have been consistently compared by the Top 500 web site [1]. Clear criteria are published for testing machines so that comparisons can be established over a wide range of performance and over long periods of time. Data are acquired and published twice a year in June and November and consists of a database of the top 500 fastest computer clusters in the world.

Figure 1 illustrates the performance of the Top 500 Supercomputers from 1993 till the present and shows the fastest machine, the 500th fastest machine and the sum of the 500 fastest machines [2]. The plot is logarithmic in performance and illustrates the consistent exponential growth over time. Many other data sets also indicate similar behavior over a much longer period of time, but this most recent timeframe is particularly illustrative. The doubling time in performance is measured in this database as being only 13 months and is the same for all three components. Also plotted in Figure 1 is the performance of a consumer electronics product. The Sony PlayStation has had three generations of computation engines and also shows a similar 13-month doubling slope. Finally, also illustrated is the performance of the RAD 750 processor that has been the standard for space flight hardware since its introduction in 2004. It is expected that it will be at least two years before a replacement is implemented.

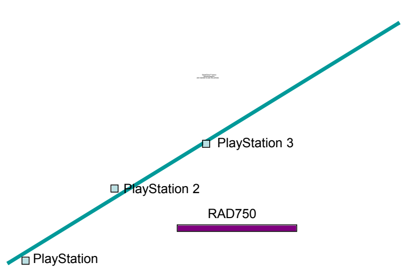

Figure 1 – The performance of the top 500 Supercomputers as a function of time. Plotted are the sum of the 500 fastest machines, the fastest machine and the 500th fastest machine. For comparison, the Sony PlayStations are also shown as well as the RAD750, the current generation of spaceflight processor. Base plot from Top 500 Supercomputer Web site [2] with additional data included.

Computational power doubles for the same unit cost every 13 months (a factor of 500 every decade). Since 1936 when Alan Turing first described a universal computing engine [3] the world has seen a quadrillion fold (million billion or 10^{15}) increase in computational power per dollar. More than 95% of this astonishing increase occurred in the last 5 years and it will double again in the next year. Bandwidth, memory, gene sequencing costs and other processes are even faster. The human brain is not used to this exponential dichotomy between looking back and looking forward. With an expected additional 500-fold increase in available computational resources over the next decade, Moore's Law should play an important part in technology and application planning.

Another factor about Moore's Law is that there has been a constant time factor between supercomputer performance and consumer electronics performance. In the case of the release of the PlayStation 3 in 2006, it took 13 years for a toy to exceed the performance of the fastest supercomputer of 1993. The 13 years was also accompanied by a cost decrease by factor of 100,000 for the same performance.

The Human Genome Project is a good example of building in Moore's Law into advanced planning. Started in 1990 this $3 billion project was expected to take 15 years to complete. Even though in 1990 the cost of mapping the entire genome, with then current technology, exceeded $100 billion it was understood that advances in information technology would bring down the per base cost and accelerate the rate of mapping. Indeed the project was completed in 13 years with a greater than a factor of 1000 increase in efficiency of mapping. Beginning early provided a great advantage of several years of planning, research and policy-making for the assimilation of this valuable database into business, government and society.

Law of Accelerating Returns

Another interesting observation pertaining to the assimilation of new inventions into society is referred to as the law of accelerating returns [4]. This observation of the time-scale to change paradigms can be demonstrated in many ways, where Moore's Law for computer performance is one example. The law states that technological change shows exponential growth and is true over a wide range of technologies including: computation, biology, memory, internet growth, etc. Furthermore, properties like chip speed, cost-effectiveness and energy efficiency also grow exponentially and often contribute to an acceleration of the overall rate of exponential growth.

The general effect of the law of accelerating returns is evident in the time-scale for major shifts in paradigms. The characteristic time for integration and acceptance of new paradigms is progressively shortening. Radio took 38 years to reach 50 million users. TV took 13 years, the Internet 4 years, iPod 3 years and Facebook just over one year. Figure 2 shows a similar representation of this effect by plotting the time it took for a given invention to be in use by one quarter of the U.S. population.

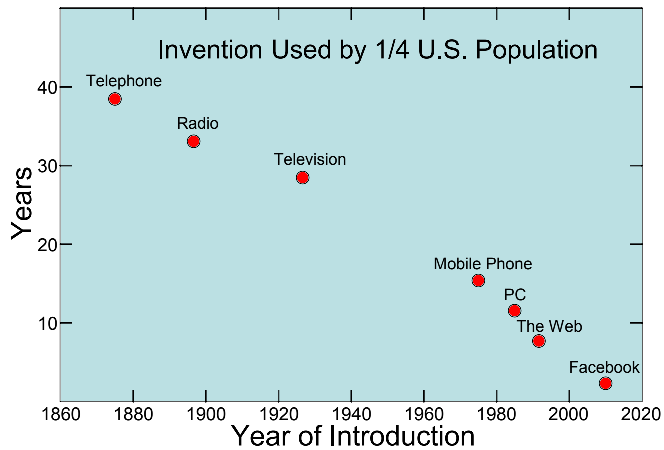

Figure 2 – Time scale for inventions to be in use by one quarter of the U.S. population.

For both sets of Moore's Law and Accelerating Returns observations, it is extremely difficult to account for their unnatural expansive growth when making predictions about future products. Generally, because this growth is not built into roadmaps, companies miss the opportunities to fully utilize the potential. It is with great peril that any organization ignores the reality of current trends in organizing, processing and distributing information.

Additional elements of the innovation environment come from consequences of Moore's Law and the Law of Accelerating Returns. An example of this compounding effect is illustrated by the increasing loss of traditional privacy in everyday interactions due to technical innovations. Technology advances in information processing, increased imaging sensor placement, ease of automated facial identification, creation of social networked databases of identified photos, cell phone location tracking, credit card electronic signatures, and other information technology advances have created a trade between security, convenience and privacy. The assimilation of this trade into society and business will be necessarily very rapid. This current rate of technological change is so rapid that traditional timescales for debate, public acceptance and introduction of legislation will fall short of anticipating the social consequences.

3. IMPEDIMENTS TO INNOVATION

Aerospace engineering has the challenging task of delivering unique solutions to one-of-a-kind problems within constrained budgets and often with high visibility and adverse political consequences for failure. Beyond the popular belief of a highly innovative and flexible nature, space exploration is a conservative and risk averse business. There are several clear impediments to innovation.

Engineering Culture

Culture is a difficult concept to pin down and often interpreted differently by different observers. A high level manager may see corporate culture as "implementation is king". Meaning that the path to success is to gain managerial control of a flight project. At the individual engineering level, however, the culture is often that of "find the fault". The conservative nature of risk identification and mitigation pervades engineering implementation and often leads to choosing well established methods and solutions over newer and perhaps more innovative ones. It is easier to "find the fault" in less proven methods by virtue of the fact that less proven is in itself a fault.

It is recognized that generating new ideas and developing the technical details of creative ideas are the easy part. The difficulty comes from trying to infuse the new technology into a culture that can be skeptical, constrained, fearful, biased or unprepared. It is easier to "find the fault" than to "make it happen". Unfortunately, changing the culture is extremely difficult. It requires either determined leadership or high degrees of stress.

Risk Identification and Mitigation

The identification of risk is an important component of managing a complex flight system development. Technical risk is almost always evaluated in terms of negative impact and likelihood, but rarely is it considered in terms of opportunity or advantage. In contrast, a more complete way of managing risk is to consider the risk versus reward ratio in the evaluation. The opportunity component of risk taking is always necessary for deciding to invest in stocks and should likewise be a required evaluator for risk management. Often the original reason for considering a more risky path is because it offers a cost, performance or schedule advantage over conventional means. This advantage is sometimes not evaluated against more conventional risk metrics as likelihood and consequence.

Compartmentalization

Aerospace organizations tend to be high compartmentalized and not prone to advocate cross cutting ideas. Advocacy of technology is usually based on immediate need to enable or solve a problem. It is also often viewed from a specialized perspective of an implementing department and not from the perspective of the broader program or organization as a whole. Technological implementations with limited local impact, but high general value or multi-use value often fail to gain advocacy. Championing technological solutions for the general good could sacrifice getting your local highest priority technology. Funding for new technology is also often prioritized and allocated at a local level.

Predicting the Future from Extrapolating the Past

The asymmetry of the exponential growth of Moore's Law and the Law of Accelerating Returns creates a more conservative prediction of the future if based on past experience. Exponential growth in the information technology field in computation, memory, bandwidth and other resources can also factor in similar advances in analytical areas like testing, validation and design. These are often overlooked in planning and in business roadmaps.

4. SOLUTIONS FROM INNOVATORS

Over the course of the last year, the author interviewed the CEOs, CIOs, managers and heads of several large companies known for their reputations for innovation. They included Activision, Electronic Arts, ImageMovers Digital, Lightstorm Entertainment, DreamWorks, EON Reality and Disney. The following are some examples of how some organizations outside of aerospace handle innovation.

Leadership

Strong leadership is a hallmark for highly flexible and innovative companies. If Jeffery Katzenberg (of DreamWorks) or James Cameron (of Lightstorm) wants 3D movies, their organizations will make it happen. Leadership sets the tone for the entire organization and hands-on leadership (like Cameron developing his own hardware) seals the deal. A clear mandate to foster, value and incentivize creative thinking and creative infusion is required to seed the expectation of innovation. Successful innovation comes from leaders creating a vision and setting high goals.

Culture

The basic culture of an organization generally grows more conservative with time, but nevertheless can be influenced by the leadership and corporate values. In innovative companies new ideas are valued, examined and evaluated not shot down prematurely. Even in companies that have strict bottom lines and require delivering high quality products, cultures that foster creative thinking abound. Anxiety comes from fearing the missed opportunity rather than from fearing change.

Environment

Some companies go great distances to create environments that bring people and ideas together. Creative, interactive environments are fostered at the innovating companies. DreamWorks has a campus where many gathering places are set up. Ping Pong and Foosball tables populate many outdoor lounges. Lunch and snacks are free (included as a salary benefit) and as a result the dining area is alive as a congregation and meeting arena. Co-location is recognized in aerospace and is certainly a benefit. Meetings can also be venues for relaxed exchange and evaluation of ideas. This IEEE Aerospace meeting, with its intermixing of sessions, with plenary talks, group dinners, gathering and social events is often exemplified as a venue for surprising exchanges of information, often by members from the same organization.

Stress – Investment in the face of adversity

An important motivator for innovation is stress. It is not a recommended attribute for a company, but its importance must be recognized. Often the only time large companies, armies or countries innovate (change their cultures) is after a near death experience. Anecdotally, inventors often admit to their best ideas coming after they were fired or financially stressed. The current economic downturn is perceived in two ways depending on the outlook of the company. Some companies (like Electronic Arts) will say it is a terrible time to spend precious resources on research and development. They will hunker down and stick to what they know. Others (like DreamWorks and Activison) will recognize that this is an environment that forces companies to reinvent themselves. The motivating fear is that if a large company does not do it, a small start-up will take away their market or create new ones.

5. CROSS-CUTTING EXAMPLES

One successful example of a multi-use cross cutting application that can scale with Moore's Law is the Evolutionary Computational Methods (ECM) technique developed at the Jet Propulsion Lab. Although, originally developed for automated spectral retrieval [5], ECM was found to have may other implementations over a wide range of fields.

ECM is based on evolutionary computational optimizers developed by the Center for Evolutionary Computational and Automated Design (CECAD) at the Jet Propulsion Lab [6,7]. It is a framework (see Figure 3) that enables a population of computational models or simulators to be run using initial random inputs. Stochastic optimizers (genetic algorithms, differential evolution, etc.) [8,9] are used to compete solutions satisfying an objective function (fitness function) and to create a new generation of models populated by improved inputs. The process is repeated until a global optimum is found. Two additional components have been added to this framework and make up the performance analyzer. A performance trade tool examines the population of best solutions and bins them into useful trade study comparisons and a cluster analyzer identifies solutions that deviate from conventional parameter values.

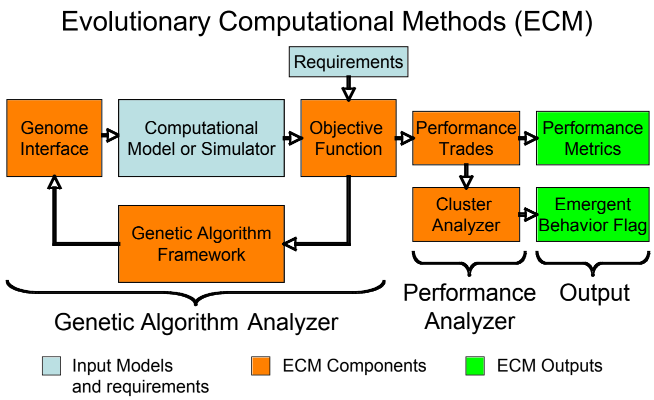

Figure 3 – Block diagram of structure of the Evolutionary Computational Method (ECM) for optimizing performance of computer models or simulators. Blue components are model and requirement inputs and green are performance outputs.

ECM is best used to find solutions to computational problems that are well modeled but very difficult to solve. Solutions are found by forward running the models and have the following advantages:

- Best solutions are found automatically with very efficient use of computer time.
- No expert initial guesses or knowledge of the environment is required.
- Genetic searches are very opportunistic and will explore non-traditional uses of resources to accomplish a goal (maximize objective fitness).
- Optimum solutions are found for varying conditions, allowing the simple visualization of trade-offs for a range of requirements.
- ECM returned solutions provide a best-case standard that can be used to test against actual performance in computer or field environments.
- Unexpected solutions can be identified and characterized as emergent behaviors.

The Moore's Law scalability of ECM comes from the property that problems can be divided up into parallel paths that can be addressed asynchronously on multiple processors. Additionally, performance comes from the size of the population competing and the number of generations run. Therefore, performance of ECM generally scales with computational resources. We have seen this progression to more capable machines by now using desktop multiple core workstations to solve problems that used to require small, dedicated cluster computers only 5 years ago. Supercomputer problems have similarly been migrated to smaller clusters.

ECM for automated spectral retrieval was initially applied to astrophysics for the Terrestrial Planet Finder (TPF) mission and used to analyze Earthshine spectra and predict the performance of TPF. Earth Science data was used in the analysis and soon stand-alone applications of ECM to these data were found [10] along with similar applications to Mars atmospheric data. Later, ECM was applied to instrument design requirements definition [5] and to non-NASA work for the identification of emergent behavior in complex systems [11]. Additionally, ECM has been applied to Deep Space Network scheduling and to optimization of critical events scheduling [12,13]. As more experience is gained with EMC applications additional implementations are anticipated in assisted design optimizations of spacecraft systems.

Even though the aggregate value of ECM is high because of the multi-use potential, it remains a difficult technology to infuse. This is because of its non-traditional methodology and the difficulty of gaining broad advocacy in any environment where highly specialized departments compete for technology funds. Future innovations like computational engineering and automated design optimization can potentially redefine space exploration, but will require learning lessons from successful innovators before successful infusion can take place.

6. METHODS

By addressing the lessons from other innovators and from the successful examples of infusion of cross-cutting innovative technologies there are several techniques that can defined and applied to space exploration.

Innovate within the culture

If the conservative nature of the engineering culture is to "find the fault", then innovate better ways of finding the fault. Several examples of this are improved methods to automatically test complex systems over large design volumes, or developing methods to measure cost and schedule robustness. In the ECM example, the development of the original methodology was applied to multiple problems after demonstrating feasibility, applicability and measured advantage in initial implementations. Even though ECM had many cross cutting uses, only implementations that addressed conservative cultural concerns were initially considered. Initial funded applications were for automated testing of complex systems for the identification of faults [14].

Find IT-Based Solutions

Many processes in the information technology sector benefit from Moore's Law increases in available and affordable computational resources. Finding innovative solutions and applications that can capitalize on similar processes can position an organization to be more competitive. The next decade should deliver a factor of 500 increase in computational capabilities for a very small replenishment investment. Careful selection of applications that can take advantage of these gains (scalability with Moore's Law increases in computational power) and the development of more realistic roadmaps can lead to a significant innovative advantage (as it was in the example of the mapping of the human genome).

Identify Cross Cutting Technologies

The compartmentalized nature of aerospace engineering imposes limitations on the ability to identify and foster cross cutting technologies and innovative applications. Efforts must be undertaken to evaluate broad potential and multi-use for solutions at a general level before special interests reduce advocacy. This requires attention to technological value at an early stage with a broad view of the total landscape and with sequestered funding allocations for implementation.

Examine Broader Implications of Risk

Treat risk as an equation by considering the opportunity opened by incurring risk. When assuming a risky element it is necessary to evaluate the reward for success with respect to the likelihood and consequence of failure. Bookkeeping risk advantage can open conservative postures to a wider range of options.

Redefine Old Problems

Traditional methods in a conservative organization are difficult to change. This is particularly true for ongoing processes that may be inefficient but need to continue operation. One technique often cited by innovators is to solve a new problem that is similar to the old one, demonstrate the advantage, and then apply the solution to the old problem. Transition to a proven solution is faster and less risky than possibly corrupting a required process while trying to improve it.

7. CONCLUSIONS

There are important lessons that can be applied to aerospace organizations by benchmarking external innovative organizations. The conservative nature of cutting edge engineering in space exploration tends to stifle non-traditional solutions. Additionally, the compartmentalized nature of technology advocacy tends to deter applications with multi-use or cross cutting features.

Successful innovating organizations have several characteristics that can be applied to aerospace. First, innovation starts at the leadership with recognition of the value and the setting of high goals and expectations of infusion. Ideas are the seeds of innovation, but useless unless they can be infused. Second is recognition of the culture and if the culture cannot be changed then innovation can be structured to the culture. In a find the fault culture, find innovative ways to find the fault. Finally, environment for innovation is important. By creating opportunities and environments to explore cooperative ideas with the right mix of people innovation can flourish.

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Biography

Richard J. Terrile created and directs the Center for Evolutionary Computation and Automated Design at NASA's Jet Propulsion Laboratory. His group has developed genetic algorithm based tools to improve on human design of space systems and has demonstrated that computer aided design tools can also be used for automated innovation and design of complex systems. He is a planetary astronomer and the co-discoverer of the Beta Pictoris circumstellar disk. Dr. Terrile has B.S. degrees in Physics and Astronomy from the State University of New York at Stony Brook and an M.S. and a Ph.D. in Planetary Science from the California Institute of Technology in 1978.