Closing the TRL gap

In recent years, while accumulating a unique and extensive base of experience in spaceflight, NASA has had to face decreasing budgets. These factors have had a profound impact on new technology development for future space applications, and have resulted in a technology readiness level (TRL) gap in the development of advanced aerospace technologies.

NASA has pioneered the use of the TRL scale for assessing the maturity of a particular technology. The utility of the scale, which consists essentially of nine levels of technology development maturity, has led to its widespread use among other government agencies and in the commercial sector.

The TRL gap is not unique to NASA. Although described using different terminology (funding gap, valley of death, Darwinian sea, the wall between research and product), it exists in all industry sectors. Stated simply, it is the problem of efficiently transitioning a new technology from concept to viable product in the shortest possible time and at least cost. Although the solution proposed here is relevant for space technology development, parallels can be drawn to address similar issues in other sectors of industry.

A close analog of the TRL scale is the "S-curve" commonly used in industry. The S-curve assesses the maturity of a technology either in terms of value to the company or the price a new product can potentially command. It introduces a parameter not explicitly addressed by the TRL scale—the time required to develop the technology (plotted on the X-axis). However, considering development time alone does not adequately describe the technology development process. We propose to modify the X-axis parameter to an as-yet-undefined complex function of time and investment.

Two more terms need introduction in order to fully understand the technology development process: "pull technology development" and "push technology development."

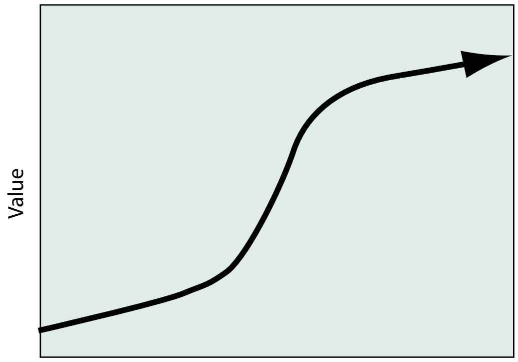
Pull technologies are developed in response to an immediate need. Given this urgency, the tendency is to avoid extensive dependence on innovation but rather to adapt existing, mature technologies by incorporating the minor modifications required for the application niche. By definition, the customer is fully prepared to cover all costs associated with the development, and the outcome has a high probability of success.

Push technologies, on the other hand, are "disruptive," and are based almost exclusively on the innovator's vision of customers' perceived needs. On the plus side, this type of development carries the promise of a pioneering effort. The downside, however, is that most often the outcome has a low probability of success.

In a few cases, this high failure rate could be attributed to unforeseen, technical "fatal flaws." Most of the failures, however, are due to the inability of the technology development to cross the "TRL gap" to become a pull technology. The causes for failure are peculiar to each case but, in general, are a combination of unenthusiastic customer perception, "impedance mismatch" with customer needs, subcritical investment, bad timing, insufficient niche development, and a lack of necessary technological support infrastructure, among others.

The end result of the TRL gap is that the infusion of advanced technology is slowed, and in some cases stopped. In light of this, the TRL gap problem can be reformulated as the challenge of how to efficiently transition push technologies into pull technologies.

The S-curve for technology development shows the value of a new product for a company plotted as a function of development.



Doing things the old way

Two historical technology developments, both of which have had an enormous impact on aerospace, were the result of long, painful development. One is electric ion propulsion, a revolutionary concept conceived in the 1930s but not fully implemented until 1998; another is GPS, which underwent many stops and starts in its three-decade development.

An ion propulsion system generates thrust by accelerating electrically charged atoms out of an engine. Despite the tremendous potential savings in fuel mass and the greater specific thrust ion propulsion provides over chemical propulsion, the development of ion drives underwent a series of stops and starts throughout the 1950s and into the early 1990s.

A major demotivator was the fact that chemical propulsion already existed as a proven technology, and in the race to get a man on the Moon, electrical propulsion development was perceived as a distraction from the goal at hand. It was not until the Deep Space-1 mission in 1998 that ion propulsion became truly operational for space missions. Now, it has been baselined as the critical technology for rapid flights to Mars and beyond.

The Global Positioning System, considered one of the greatest inventions of humankind, is another technology with a long development history. The concept arose from pioneering work done in the

1960s on three-dimensional positioning, when the DOD developed the idea of global all-weather satellite positioning (the Transit and Timation programs). From these beginnings, however, GPS did not achieve full operation until 1995. Among the challenges holding back its rapid development were the lack of coordination among the various DOD agencies, competing initiatives, low and unstable funding, and the lack of a well-defined cost/benefit argument.

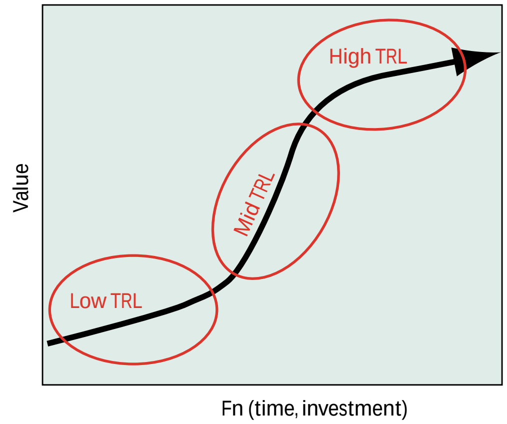
Ultimately, the successful development of the GPS system required the establishment of a joint initiative among the Navy, the Army, and the Applied Physics Laboratory. Even then, it took several years for the group to establish the specifications for the system. Today, although the GPS system was developed to satisfy specific DOD positioning requirements, there has been an explosion in the number and diversity of its scientific and commercial applications, many probably not imagined by the original developers.

Why a new approach now?

It is recognized within the aerospace sector that a combination of risk-averse conservatism and lack of sufficient technology development funding has reduced the insertion of new technologies to a trickle. NASA and the U.S. aerospace industry at large are suffering from a broken technology development pipeline, which threatens to eliminate our competitive edge and with it our leadership in the aerospace sector. Clearly, the existing technology development process is unsuitable for the realities of today's environment and the constraints imposed on the infusion of new technologies.

NASA's technology development process is similar to that employed by most commercial firms, in which a Darwinian selection approach is applied to technology development and infusion. At the low TRL development stage, an attempt is made to increase the number of innovative ideas in hopes that there will ultimately be one or two productive concepts. The implicit assumption is that overcoming the low probability of success for push technologies requires the "seeding" of multiple concepts. It is questionable whether this is an efficient technology development paradigm. There are two key problems with this approach:

- The overall resources allocated to low TRL development are severely limited. Therefore, by increasing one's initial portfolio, one has further stretched these resources over an increased number of projects, driving each to be further subcritically funded and thereby raising the probability of failure for each.
- There is no one to "pick up the ball" once a technology has reached a mid-TRL stage. The link has not been made with potential customers and sponsors, who can carry the technology forward across the TRL gap.



With this modified S-curve, the new product value is plotted as a function of both time and investment. Also seen are the equivalences with NASA's TRL scale.

Crossing the TRL divide

Among the root causes of the TRL gap is the major divide in the mindsets of developers working in the high and low TRL areas. Individuals in the high TRL arena are accustomed to a relatively well-defined work environment in which the objective is to construct and demonstrate the technology at a system level. Technology development is generally straightforward, with few surprises. Low TRL folks, on the other hand, excel in an environment in which very little is precise. Chaos, serendipity, and ingenuity are woven intimately into the fabric of their work day.

The primary challenge for NASA sponsors seeking to increase the efficiency of the technology "harvesting" process is to bring these communities together and create the most continuous technology development pipeline possible. The answer may lie in the creation of a TRL Maturation Team (TMT), composed of representatives from the high and low TRL communities. Given the current divide between the two, this may only happen via a NASA-inspired "shotgun marriage," with strong management oversight, at least in the early stages.

The TMT concept is not original—the commercial sector has adopted "technology champion" and "transition team" concepts in an attempt to improve the efficiency of the technology maturation process. Ideally, the proposed TMT would be composed of the inventor of the technology, the high TRL system developer, reliability and testing personnel, and the end user. From an implementation per-

TRL SCALE

TRL	Basic principles observed and reported
TRL2	Technology concept and/or application formulated
TRL3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL4	Component and/or breadboard validation in the laboratory environment
TRL5	Component and/or breadboard validation in the relevant environment
TRL6	System/subsystem model or prototype demonstration in the relevant environment (ground or space)
TRL7	System prototype demonstration in a space environment
TRL8	Actual system completed and flight-qualified through test and demonstration (ground or flight)
TRL9	Actual system "flight-proven" through successful mission operations

spective, the team should be formed at the early stages of low TRL development, essentially immediately after a new concept has been selected for funding.

TMTs are created after funding decisions for low TRL concepts have been made to avoid coloring the initial technology selection process in any way with high TRL pragmatism. Instead, the selection process should be left pretty much in its current form, wherein a competitive process is employed in which revolutionary or breakthrough concepts are selected by a panel of low TRL developers. Maintaining the status quo ensures that "diamonds in the rough" are not rejected.

Even as a selection process can be expected to gather truly innovative concepts, the subsequent investment can also be made more efficient. By funding each project at the level required for a successful outcome, we can ensure that we are getting the best "bang" for our limited new technology development dollars.

The shotgun marriage of the low and high TRL points of view within the TMT could prove to be mutually beneficial. During the low TRL development phase, high TRL teammembers play essentially an advisory role, guiding the inventor away from technological dead ends that could stop the technology from transitioning to the system level. Design changes are far cheaper and more cost-effective at low TRL than after the technology has matured in a direction that is not well aligned with the end application.

In return, the high TRL members become intimately acquainted with the emerging technology and its various nuances, so that they can anticipate the challenges they will have to face during high TRL development. The TMT's role becomes increasingly important once the proof-of-concept for the technology has been successfully demonstrated.

The TMT assumes a critical role during the mid-TRL phase of the technology development. This is the crucial juncture in the development cycle—the point at which the TRL gap manifests itself. The reason mid-TRL development is such a dreaded phase is that a successful transition to high TRL depends on factors coming together in the correct order. The ultimate objective here is to change the character of the technology from "push" to "pull"—to create a customer demand.

BENEFITS OF THE TMT APPROACH

- **Creates a smoothly functioning "technology development pipeline."**
- **Minimizes the inefficiencies that currently exist in the transitioning of new technologies to mission applications by:**
    - **Reducing waste of low TRL investment, (increasing the probability of successful development outcomes)**
    - **Enabling low-cost design changes at the low TRL development stage to make the technology more compatible with the ultimate system implementation**
    - **Reducing "impedance mismatch" between low TRL technologies and high TRL end applications**
    - **Shortening the total life cycle for new technology development, including avoiding stops and starts**
    - **Avoiding additional investment and loss of infusion time at the high TRL stage by cash-strapped flight projects attempting to adapt the technology to fit within the mission constraints.**
- **Establishes effective advocacy for the technology, beginning at the low TRL development stage.**
- **Informs high TRL systems developers well in advance of specific technologies that will be transitioned to systems. This allows them to hit the ground running because they are intimately familiar with the characteristics of the new technologies.**
- **Ultimately increases flexibility in the types of space missions that are doable, as a direct consequence of the much larger portfolio of "mature" technologies.**

Technologies often have a potential far greater than that which might be developed by a specific program. The TMT paradigm allows for the effective development and exploitation of significantly enhanced capabilities of new technologies.

In NASA terms, this means convincing mission managers or principal investigators that the technology has significant advantages over the state-of-the-art. Just as in the commercial sector, the conversion process involves first adapting the technology to a sequential series of niche applications and technology demonstrations (as in the electric ion propulsion case) until the demonstrated successes combine to create a demand for the technology. Successful transition to high TRL is achieved when new missions are designed around the technology rather than the other way around. This is an expensive, time-consuming process and one in which the skills of the high TRL members of the team come to the forefront.

Selling the customers

A TMT-like mechanism may prove to be a significant improvement over the status quo and offers program managers, and ultimately the agency, a means to efficiently transition a larger number of new technologies within the same budgetary constraints. In the current technology development environment, it is incumbent on the inventor to develop the necessary skills to transition a technology across the TRL gap. With the proposed TMT approach, the burden of maturing the technology is shared by the TMT as a whole.

Quite often, the hardest task the inventor faces is convincing potential customers and high TRL developers that the new technology will provide significant benefits over the state-of-the-art. The vicious cycle—inadequate results to attract funding for further development, resulting from inadequate funding to generate the necessary results—is an all-too-common occurrence in the low TRL world.

The TMT-based technology development process, if implemented well, should result in a smooth transition through the various TRL levels. The success of the process rests primarily on the higher TRL "champions" for the technology. By making them an integral part of the TMT from the beginning, they will need no further convincing on the merits of the new technology. Within the TMT mechanism a smooth transition in "leading roles" is assured. During the low TRL development phase, the inventor's role is ascendant; as the technology achieves higher maturity, members possessing the appropriate level of marketing and customer interface skills required for the further advancement assume leadership roles.

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