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On-Demand Science Missions

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ABSTRACT

Over the last four decades, robotic space explorers have yielded a wealth of scientific discoveries about our solar system and its origins. However, the resources required to design, develop, launch, and operate such missions is enormous. The highly prohibitive nature of established design practices and long development cycles significantly precludes responsive science investigations. Historically, robotic science missions flown in the last forty years have been highly limited in scope and capability. This paper briefly reviews the current practices in use for developing science missions, including; mission design, spacecraft design, and cost estimating. In contrast, today's science missions must be more responsive to changing circumstances. The advances in space related technologies make on-demand science missions even more relevant and desirable. The spacecraft capabilities, capacity, and cost effectiveness are essential deterministic factors enabling successful on-demand science missions. This paper will focus on defining these factors within the context of a responsive space system. This paper discusses the emergence of new space-related technologies that will accelerate the development of on-demand science missions. This discussion includes an overview of current advances in materials, communications, propulsion, and onboard autonomous systems that can play a critical role in the successful design, development, and operation of on-demand science missions. Finally, this paper discusses an on-demand science mission life cycle scenario.

INTRODUCTION

An "on-demand" or responsive science mission comprises a highly flexible mission architecture composed of; responsive launch, robotic spacecraft (bus and scientific instrumentation), and mission operations components, that are *sourced on-demand* and *integrated rapidly* to meet a specific or emerging set of science objectives for space and earth science missions.

As more responsive space systems evolve and grow to meet the needs of a wide variety of science mission end-users (scientists and engineers), so too will the need to incorporate responsively developed robotic spacecraft launched as primary payloads for small and larger science missions.

Every science mission is uniquely different in terms of scope and scale.

To meet changing science mission objectives, a responsive spacecraft design, development, and operations process should incorporate highly integrated, modular and automated manufacturing and processing systems. The enhanced spacecraft development process can facilitate the rapid sourcing and integration of the spacecraft bus with scientific instrumentation while meeting mission end-user requirements for quality, reliability, cost-effectiveness, and higher performance robotic spacecraft.

The concept of a responsive spacecraft for science missions therefore, evolves by way of a more efficient spacecraft development process, as it relates to spacecraft capacity, capability, and cost-effectiveness, which can play a significant role in increasing science mission opportunities.

The desired result gained by developing responsively built spacecraft for science missions is the increased return of science in much shorter time horizons at a lower cost.

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TRADITIONAL SCIENCE MISSIONS

Science mission objectives, in part, drive the scope and scale of the mission and spacecraft design. The project team follows a standard project life cycle methodology for mission and spacecraft design. A series of project phases, each culminating in reviews and certifications, takes place before the spacecraft finds its way to the launch pad. Once launched and on-orbit, the mission operations component manages the flight specific events planned in the mission design. Often, science missions extend well beyond the planned design life of flight hardware. Consequently, small and larger science missions alike developed using the same standard design principles have over decades produced some of the most stunning achievements in space and earth science exploration.

Today, robotic space and earth science programs enjoy unprecedented interest and support. However, the exciting and rewarding benefits of a well-planned and executed science mission often harbor the underlying harsh realities of budget and cost. As is the case in most civil programs, organizations are under constant scrutiny to streamline management processes and lower costs more effectively. Often, the complexity of cost estimating projects and the reallocation of already limited resources of a project shift to meet other organizational priorities producing some cost disparities, resulting in delays or cancellation of important robotic space exploration projects. Consequently, civil space program cost estimating tends to be problematic and less precise.

ON-DEMAND SCIENCE MISSIONS

In contrast to traditional science missions, the "on-demand" science mission approach emphasizes fewer "built-by-hand" subsystem components coupled with a significantly higher level of automated build, test, verify, integration, launch, and mission operations.

The on-demand mission approach utilizes scalable processes that contribute to increased flexibility in meeting the desired spacecraft specifications required for a specific set of science mission objectives. Consequently, the spacecraft bus design can support a more robust suite of scientific instrumentation.

The anticipated efficiencies gained by the "on-demand" sourcing and rapid integration of subsystem components with the spacecraft bus structure occur within a highly responsive mission process flow (Fig. 1). The on-demand mission process flow represents a model that defines how the major process elements of an on-demand science mission develop from concept to mission operations. The *Level 1 (L1)* design process elements represent a tightly integrated and collaborative information management system that encompasses the collection and analysis of mission science requirements, mission architecture and spacecraft technical specifications seamlessly distributed to the next level. At *Level 2 (L2)*, the design product from L1 drives the build, test, and verify phase of mission development. The rapid sourcing of spacecraft components and integration of the science instrumentation with the spacecraft bus occurs when the application of highly automated manufacturing and assembly processes occur within a very close physical proximity to one another. Therefore, the proximity of the spacecraft to the launch vehicle drives the responsiveness of the mission. At *Level 3 (L3),* the mission operations and support elements of an on-demand science mission, driven by automated mission operations systems and ground support services, contributes to a more efficiently executed science mission.

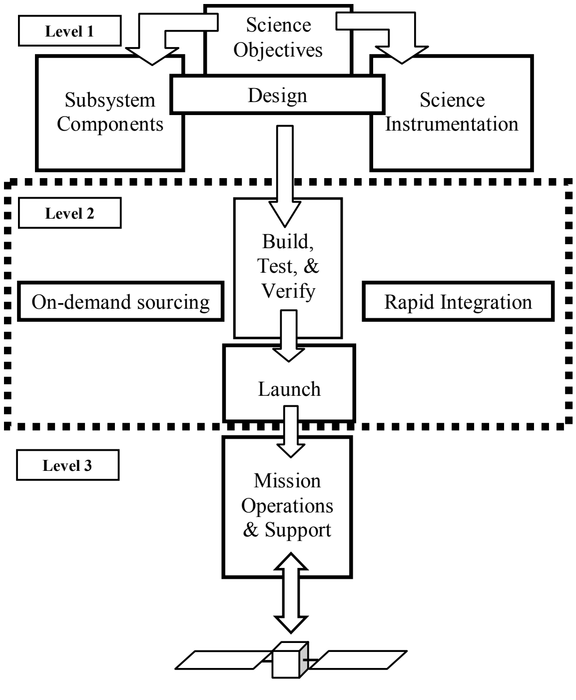

Fig. 1 On-Demand mission process flow.

RESPONSIVE SCIENCE SPACECRAFT

The 3Cs of on-demand science missions

The science spacecraft *capabilities, capacity, and cost effectiveness* are essential deterministic factors enabling successful on-demand science missions. The "3 C's" of on-demand science missions define the science spacecraft in terms of its effectiveness to enable more science. The on-demand approach to science missions not only emphasizes shorter development phases for pre-mission activities (design and development), but also highlights the importance of a responsive science spacecraft that can execute not only its primary science mission objectives but also incorporates flexibly to conduct extended, or ancillary, science investigations.

Capability (Operations)

A responsive science spacecraft comprises robust and highly flexible operational capabilities. As an operational platform, the science spacecraft and its suite of science instruments must operate at peak efficiencies and be capable of analyzing and resolving new or emerging anomalies while recognizing advantageous science opportunities. Therefore, a responsive science spacecraft must be highly capable of full operational autonomy (sub systems and scientific instrumentation) in conjunction with a very high level of hardware redundancy. These mission capabilities reduce the risk of mission operational limitations and to some degree minimize serious hardware anomalies. Within the context of a responsive space mission, these spacecraft capabilities are *critical* to enabling "on-demand" science mission operations.

Capacity (Performance)

The capacity of a responsive science spacecraft to perform optimally during its mission is relative to the degree of innovative technologies designed into the flight hardware and software. The goal of every science mission is to nominally reach its intended target, collect data, and return the data for analysis. The capacity of the science spacecraft, as a system, to perform its mission successfully by meeting all or more of its science mission objectives is dependent, in part, on the technology designed into the spacecraft. A truly responsive science spacecraft most likely will have many technologies designed into it to substantially enhance and enable the capacity to perform an increased variety of scientific operations. Some of these technologies might include: 1) The structural capacity and thermal protection (light weight and durable) to endure the intensely harsh space environment and protect sensitive scientific instrumentation, 2) A power sub system (self contained) that safely produces and distributes electrical power more efficiently, 3) A propulsion and attitude control system (low volume fuel source) that provides a more reliable and highly sustainable source of energy, and 4) on-board command, data, and communications systems (spacecraft network) that operates at exceptionally high capacity.

When optimized for a higher degree of spacecraft performance the suite of on-board science instruments can operate at peak capacity successfully meeting and exceeding all of the science mission objectives.

Cost Effectiveness (Efficiency)

The cost effectiveness of a responsive science spacecraft correlates to improved efficiencies in the development processes employed to design, build, and operate the spacecraft. Technology again, plays a significant role in the cost-effectiveness of the end-to-end process of developing a responsive spacecraft for an on-demand science mission. It is important to note that the measure for cost effectiveness of the spacecraft performance is not necessarily a function of spacecraft size and scale but more one of capacity and capability. The efficiencies gained by streamlining the development (design, build, test, and verify) process while utilizing more automation can equate to improvements in the production, quality control, mission assurance, and accelerated delivery of the science spacecraft to the customer. Final check out, integration, and launch is accomplished more efficiently where there is close proximity to both the spacecraft production source and the launch vehicle (launch pad). Once the mission is underway, a greater operational autonomy reduces labor costs and technical risk. Ultimately, the quality of the science returned is due primarily to the capacity and capability of the spacecraft, which reflects a significant measure of, cost effectiveness.

SCIENCE ENABLING TECHNOLOGIES

Rapid Spacecraft and Mission Design

The rapid development of on-demand science missions is realistically achievable through the application of rapid spacecraft and mission design and development. The continued emergence of integrated design tools translates to tremendous advantages in terms of time, cost, performance, and quality of science missions. Looking ahead, science missions of all types (scope) and sizes (scale) will require, to yield greater cost-effectiveness and increased efficiencies, completely homogeneous end-to-end automated development processes that are substantially far less complex than the traditional mission spacecraft design regimes with a greater emphasis on integrated collaborative decision-making in the design, development, and operational phases of an on-demand science mission.

As an enabling technology, the rapid design system approach is most effective when connected teams of end-users (scientists, engineers, and technicians) function together in an integrated and collaborative environment that enables and accelerates the mission spacecraft design process by reducing countless life cycle iterations that often delay a project unnecessarily.

Other Advanced Technologies

Advanced space-related technologies continue to play an important role in enabling current and future science missions.[1] For the purpose of this discussion however, the five key technology areas identified and described below attempts to capture the essence of how these current advances in space technologies play a critical role in the operation of on-demand science missions.

Propulsion – *Electric-Ion (EI) propulsion* for science spacecraft is a key enabling technology that embodies many operational characteristics intrinsic to on-demand science mission requirements, such as: affordability, lower spacecraft mass, higher maneuverability, and constant low-thrust output yielding increased velocity over time. For planetary missions EI propulsion eliminates the requirement for gravity-assisted maneuvers, thus accelerating the time-to-arrival at a planetary destination. For outer-planetary and other deep space missions, where there is less sunlight available, *nuclear ion (NI) propulsion* offers some of the same benefits of EI propulsion, including the constant low-thrust output. Both EI and NI propulsion technologies are extremely advantageous for on-demand science missions, because ion propulsion technologies offer excellent operational efficiencies not realized in most of today's science spacecraft utilizing traditional propulsion systems.

Power **-** The lifeblood of any science spacecraft is power. Advances in conventional power generation and storage technology, solar cells and batteries, for satellites and science spacecraft contributes to the improvement of the operational life of science mission spacecraft. However, to support on-demand science operations during longer duration science missions, science spacecraft will require greater power capabilities and improved efficiencies in power distribution and power management. Research and development activities in these areas continue to focus on enhancing *RTG (radioisotope thermoelectric generator)* and other nuclear-electric technologies that will be adaptable and flexible enough to meet the mission requirements of long duration planetary, deep space, and planetary surface explorers and science spacecraft. The application of these enhanced power generation technologies adapted to meet on-demand science mission requirements significantly increases the likelihood of improved science returns from on-demand science operations.

Communications - The application of laser communications for on-demand science spacecraft promises significant improvements in cost, communications reliability, and increased bandwidth not seen in today's science missions. The possibility of 10x or even 100x improvements in transmission of science data may be possible. Generally, laser communications utilizes technology already available today. However, the application of this technology for space exploration poses some challenges (pointing and earth's weather). Challenges not withstanding, when applied as a complete communications system, laser communications for space research and exploration missions may be more affordable, precise and reliable, and power efficient – All beneficial attributes of on-demand science missions.

Software - The development of *autonomous systems* for mission spacecraft operations is a key enabling technology for on-demand science missions. Recent success in deep space and interplanetary missions continues to validate the importance of developing and integrating autonomous systems for use in space research and exploration. Science mission operations, particularly the link between ground systems and the spacecraft subsystems and on-board science instrumentation, becomes less interdependent when on-demand decision-making software systems are incorporated to enable full or near-full spacecraft autonomy. As an enabling technology, full spacecraft autonomy when applied to complex tasks, such as: situational awareness and hazard avoidance, selection and use of appropriate science instruments for in-situ observations and data collection, monitoring and maintaining spacecraft health, and others, can substantially improve science returns while contributing to the overall success of the mission.

Materials – The harsh space environment poses special challenges to protecting on-demand science spacecraft and its highly sensitive science instrumentation from damage caused by long exposure to solar radiation, micrometeorites, and space debris. Therefore, of primary concern is spacecraft survivability. *Nanotechnology* and advancements in the improvement of chemical properties of materials are key enabling technologies contributing to the development of new and innovative protective materials, sensors, and other critical spacecraft components. Protection from damage by long exposure to the space environment is a significant problem addressed by the innovative application of more durable materials built into the spacecraft structure and subsystems. The benefits gained by the application of these materials to the structural integrity of the spacecraft will pay significant dividends, in terms of spacecraft longevity and increased return of science, during the course of an on-demand science mission.

The utilization of lighter and structurally stronger materials in the spacecraft design deliver a more robust spacecraft, which equates to more affordable, reliable, and cost-effective on-demand science missions.

MISSION LIFE CYCLE

Unlike a generic space mission life cycle[2] (~5 phases), a generic on-demand science mission life cycle (Fig. 2) represents an accelerated and tightly integrated hybrid life cycle compressed into three distinct and interdependent phases: Phase 1 (Design), Phase 2 (Development), and Phase 3 (Operations). Three key milestones link these phases together: Final Design Review (Phase 1), Mission Readiness Review (Phase 2), and Final Mission Review (Phase 3).

Phase 1 – Design

The design phase of an on-demand science mission encompasses the mission concept-to-design and the spacecraft requirements driven by the science objectives producing a comprehensive science mission and science spacecraft definition. By way of an integrated and collaborative process, the technical specifications are defined, created, analyzed, tested, and simulated during this phase producing a final design for review and acceptance by mission end-users, for both the mission architecture and the spacecraft design. The major milestone for this phase is the Final Design Review (FDR). During the FDR, all mission stakeholders review the final design products for accuracy, quality, and acceptance.

Phase 2 – Development

Once a final design is accepted, the development phase of the on-demand science mission begins. This phase relies on the final design products to build, test, and verify the science spacecraft. The manufacturing and assembly process, directed by highly automated systems, accelerates spacecraft component and science instrumentation integration with the spacecraft bus. Prior to launch vehicle integration, a Mission Readiness Review (MRR) convenes. This review fully accesses the overall integrity of the final design with the completed spacecraft. Upon acceptance, the launch vehicle team can receive the completed spacecraft for integration and final testing.

Phase 3 – Operations

In Phase 3, the integration and testing of the science spacecraft with the launch vehicle occurs after MRR. The launch vehicle integration and test phase completes a significant milestone, culminating with the Final Mission Review (FMR). Before launch, the FMR encompasses an all-inclusive comprehensive review, by the complete mission team and key mission stakeholders, to determine the state of mission readiness, quality, consistency, and adherence to the mission design plan. Upon final acceptance, a "go" for launch results and mission operations can begin.

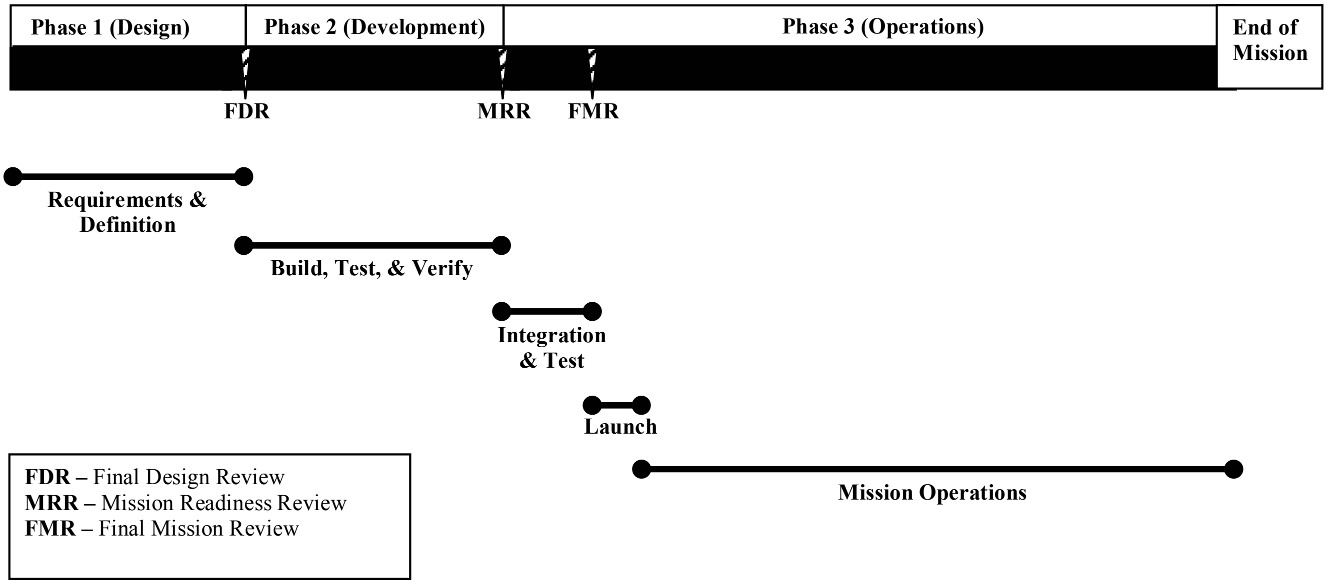

Fig. 2 Generic On-Demand Science Mission Life Cycle.

CONCLUSIONS

Within the context of a fully responsive space system (spacecraft, launch vehicle, and mission operations), on-demand science missions are far more likely to deliver a higher capability, capacity, and cost-effectiveness that meet the needs of key mission stakeholders (scientists and engineers) than traditional science missions.

With the institution of improved efficiencies, greater flexibility and scalability, and an overall reduction in complexity, on-demand science missions most certainly can contribute to a far greater return of science by utilizing fewer resources more efficiently in conjunction with improved mission design and development processes that accelerate the time-to-delivery of science spacecraft on their voyages of discovery.

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