THE NEW MILLENNIUM PROGRAM: POSITIONING NASA FOR AMBITIOUS SPACE AND EARTH SCIENCE MISSIONS FOR THE 21 st CENTURY

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Abstract

The National Aeronautics ant] Space Administration (NASA) has established the New Millennium Program (NMP) to enable space and Earth science missions to be carried out far more cost-effectively in the 21 st century than they are today. NMP will develop and flight validate the revolutionary technologies that will be needed to carry out NASA's 21 st-century missions, and will also demonstrate methods to drastically reduce mission costs. Advances in technology will enable the reduction of spacecraft and instrument size, an increase in autonomy and reduction of operations costs, and innovation in measurement techniques and mission architectures: all needed for the high-return missions of the future. Because the design space of the technology-valic]ation flights exceeds the available money and scheduling resources, the approach will be to first exhaustively explore mission design space, ant} then evaluate missions for such factors as technological value, scientific capability, cost, and level of public interest. The oversubscribed mission set can then be reduced to a maximum-value set for implementation. Anticipated societal benefits from NMP include stimulated development of advanced technologies and creation of new U.S. industry to meet the demand for capable microspacecraft.

INTRODUCTION

With the approach of the 21st century, and mindful of the public's changing views about the space program and space exploration, the National Aeronautics and Space Administration (NASA) is setting ambitious new challenges for itself. The space program and space exploration techniques, as developed in the 1960s, 1970s, and 1980s, largely completed the initial reconnaissance of the solar system and universe, and have reached a level of maturity in the 1990s that requires a dramatic advance in technology if we are to match or exceed the pace set in the past. So NASA is stepping boldly into the 21st century by using revolutionary spacecraft technology as a springboard to achieving a more cc)st-effective science program for the future.

In past decades, NASA invested heavily in building a strong infrastructure within industry to provide the technology needed to execute NASA space missions, We must now capitalize on this investment, which has developed to a point where implementation of space missions c an be turned over to industry, allowing it to function within the constraints of the free market. Government should back away from the implementation aspects of the space program, concentrating more on the research and development of the technology needed for implementation. Ideally, government and industry should have a working relationship in which the specific strengths of each are combined in such a way that government funds are used most cost-effectively, keeping in mind the public's best interest.

A comprehensive evaluation of how best to enable the 21 st-century science missions we envision found that the best investment we could make would be to concentrate on developing technology. These "leap-ahead" technologies, as we call them, are the focal point of the New Millennium Program (N MP), which is designed to flight validate technologies that will demonstrate both the kinds of capabilities our future missions will need and methods to drastically reduce mission costs.

TECHNOLOGIES

We see a cost revolution being brought about by advances in three major areas. The first is in technologies that enable spacecraft size to be reduced by an order of magnitude or more. Smaller spacecraft can be launched aboard smaller, less costly launch vehicles, ant] typically can be designed, developed, and tested much faster and less expensively than larger vehicles. The second area is autonomy (spacecraft and ground), which can reduce the size of the operations staff needed to operate the spacecraft and execute the mission. Finally, entirely new measurement techniques and mission architectures are emerging that are inherently less expensive than previously used methods to collect scientific information about our planet, the solar system, and the universe around us. With a lower cost per mission and thus a higher possible launch rate for a given funding level, more risk can be taken on each mission because the net impact to the overall program is less in case of a single mission failure. Acceptance of higher risk for individual flights opens the door to the use of more advanced technologies that offer enhanced scientific return.

Spacecraft Size

A number of emerging technologies can contribute to reducing the size of future spacecraft. One of the most far-reaching is the revolution in digital microelectronics. Over the last 20 years, we have witnessed advances that have changed data processing systems from a roomful of exorbitantly expensive electronics requiring massive power supplies, extensive cooling systems, and specially trained operators, to the home computer, which can be plugged into a wall outlet and operated by most teenagers. 1'1 ie trend in microelectronics miniaturization continues today, with functional densities increasing by about a factor of two per year, and with similar advances in speed and circuit complexity.

While these advances have gradually been incorporated into scientific space missions, .spacecraft electronics have typically lagged behind emerging consumer products by a decade or more, corresponding to greater than three orders of magnitude in capability. One NMP goal is to close this gap by developing space-qualifiable electronics systems that are closer to the sta[c-of-the-ar[commercial products. Civilian and Department of Defense government-supported research and development are also leading the way toward higher integration densities and lower-power systems, which are performance parameters particularly important for space applications. Higher-density electronics are envisioned through extending the design space out of two-dimensional planar circuits into the third dimension by stacking chips anti moving toward the realization of fully three-dimensional, very large-scale integration. The goal is to achieve fully integrated spacecraft avionics systems by incorporating not only the processor and memory electronics, but also engineering sensors, spacecraft power management systems, and digital communications electronics.

Efficient power generation and storage are also required elements of a microspacecraft. NMP is considering the use of lithium ion batteries capable of storing three times more power per kilogram than nickel cadmium batteries, as a first step towards more efficient power storage. High-efficiency solar concentrator arrays capable of generating sufficient power for an all-solar craft beyond the orbit of Jupiter are also under consideration. Large apertures are also necessary for deep space solar power collection, as well as for other spacecraft functions such as large photon buckets for collecting weak science signals, ancl transmission of telemetry far from Earth. However, the use of small, less expensive launch vehicles precludes systems that are massive or are large in scale in their configuration during launch. This leads to the consideration of gossamer structures that are deployed to their full dimensions in space. Structures that expand, inflate, unfurl, or unfold are options, and the challenge is to achieve the required accuracy of shape and smoothness after deployment. For example, a Ka-band telemetry antenna requires better than 1 millimeter RMS surface roughness and deformation. One approach to improving the effective figure of the system is to use an adaptive secondary reflector, which can be relatively small in scale, that compensates for unavoidable irregularities in the large primary.

Another approach to r-educing spacecraft mass is through multiplexing functions. In a discrete implementation, this can be as straightforward as using the same reflector for- telemetry and solar power collection, or sharing input optics for multiple sensor arrays operating in different wavelength regimes. On a more fundamental level, spacecraft structural elements can be designed to build in multiple functional capabilities, such as thermal control ant] signal and power distribution. Using the interior and exterior surfaces to mount processing electronics and sensors, respectively, multifunctional building blocks can be realized that snap together to form the spacecraft structure. The ensuing modularity can significantly reduce design and fabrication times and costs,

Science instruments and certain engineering sensors must also be miniaturized. Part of the solution lies in full system integration, using emerging low-mass structural materials such as SiC; shared optics; highly sensitive, large-area focal-plane arrays; and low-noise readout electronics. New array technologies that enable flexible, pixel-by-pixel readout architectures can be manufactured on standard microelectronics fabrication lines and operate with simplified control electronics, which will further lower the cost, complexity, ant] mass of imaging systems. Emerging on-chip integration technologies dubbed MEMS (microelectromechanical systems) arc the basis of further breakthroughs in instrument miniaturization. MEMS technology enables the chip-level integration of sensors with control, readout, and processing electronics. The technology is also of value for the automobile and medical industries in particular, and for manufacturing automation in general.

Autonomy

The second major area for cost reduction is autonomy, primarily on the spacecraft but also on the ground. Current spacecraft operations approaches require sizable ground staff, and deep space missions are already close to saturating much of the telemetry bandwidth available through NASA's Deep Space Network (DSN). As we envision much higher- launch rates in the 2 1st century, both operations costs and DSN bandwidth limitations arc pushing towards more onboard autonomy. In particular, it is desirable to remove the reliance on ground staff for functions that can be performed on the spacecraft, and reserve the precious telemetry resources for the return of high-quality science data. In the past, the design philosophy was "don't do anything on the spacecraft that can be done on the ground"; now the philosophy is "don't do anything on the ground that can be done on the spacecraft ."

The first step along the path to autonomy is to reconfigure the ground and spacecraft operations software architecture into a unified, modular system that permits migration of functions from the ground to the spacecraft. Functions that will be migrated to the spacecraft include anomaly detection and fault recovery; resource management; sequence generation; autonomous navigation, guidance and control; and onboard target detection and science data processing, Much of this functionality exists in theoretical models ant] simulations, and NMP expects to validate many of these capabilities in early flights,

For deep space missions, onboard optical navigation using known asteroids will enable a spacecraft to carry out precise trajectory determination without any groLlnd-based tracking. By car rying the planetary ephemerides, the spacecraft will then calculate and execute the needed trajectory correction maneuvers to arrive at the target body. When it is in the vicinity of the target body, the spacecraft will point one or more of its imaging sensors at that target and commence taking pictures. Onboard analysis of these pictures will provide pointing error data that, when combined with onboard trajectory-generated information, will be used to update the camera pointing angles. This closed-loop target body tracking will be completely carried out without any ground intervention. In addition to autonomous guidance and navigation, the spacecraft will also perform comprehensive fault protection and correction and onboard mission planning and execution to further reduce ground control dependency.

Measurement Techniques and Mission Architectures

The final area for innovation to enhance the capability per cost of future missions is that of new measurement techniques and mission architectures. A major component is the development of microsensors based on MEMS technology. Micromachined structures are the basis of a wide variety of chif~-level sensors, including chemical, geophysical, meteorological, nlass/energy analysis, and seismological sensors. MEMS sensors offer the potential for low-cost in situ measurements as an alternative to costly sample return for many scientific investigations of our solar system. Advances in chip-level photonics also enable a range of miniature active sensor systems, such as lidars and synthetic aperture radars, that can be used to image solar system bodies, including planet Earth, from space. Constellations of miniature "sensorcraft" designed and fabricated around the microsensors can be envisioned as an approach to investigate dynamic and complex systems that cannot be well characterized by single probes. This extreme miniaturization also underlies the possibility of free-flying instruments that could map out the three-dimensional character of solar and planetary fields.

MISSION PLANS

The first block of NMP missions includes three deep space missions and two or three Earth-orbiting missions. As currently planned, all will be launched during the three-year period 1998–2000. Each mission is designed to validate a suite of the advanced technologies judged to be important enabling elements of NASA's future lower-cost, yet ambitious, space and Earth science program, as described above.

Formulating the overall plan for these validation missions, including the logical ordering of them, involved the simultaneous investigation and evaluation of several architectural issues. These issues included the nature of the candidate advanced technologies and their potential benefits to future NASA science missions, the definition of candidate mission types that could serve as a "test track" for the technologies, the launch dates and duration of the missions, concepts for mission operations, techniques for validating the technologies during the missions, prospects for science during the missions, launch vehicle options, synergies between the various NMP missions, synergies between the NMP and ongoing NASA science programs, and various funding profile and costing issues.

Key trade-offs addressed include technology content for each mission, target spacecraft mass and launch vehicle selection, nature of the primary and extended mission phases for each mission, and the assessment of various factors related to mission reliability and resiliency. To illustrate how this process was used and what it produces, the first three planned NMP deep space missions are described below (NMP Earth-orbiting missions are not addressed in this paper).

First NMP Deep Space Mission

The first planned deep space mission --- and the first NMP mission — will validate a complement of advanced technologies needed by a broad mix of future NASA science missions: advanced miniaturized avionics; miniaturized deep space telecommunications equipment; advanced batteries and solar array technology; one or more prototypes of advanced miniaturized science instruments, such as imaging spectrometers; and various types of onboard autonomy, such as one that enables autonomous guidance, navigation, and control. Also slated for validation on this mission is solar electric propulsion (SEP). One 30-centimeter-diameter ion thruster will supply the primary source of thrust for the vehicle, generating thrust levels of 10 to 100 millinewtons depending on the commanded setting. Xenon gas is the propellant.

To prove out these technologies, four mission types were investigated as candidates: a SEP-propelled spiral from Earth to the Moon, followed by a lunar gravity assist and a flyby of a near-Earth asteroid; a rendezvous with a near-Earth asteroid; a multiple flyby sequence of a near-Earth asteroid and a comet; and a comet rendezvous. For several reasons, the asteroid/comet flyby profile was ultimately selected. At least two launch opportunities in 1998 allow both targets to be visited within a year to 18 months from launch, using an 11V-2-class launch vehicle. Extended mission opportunities exist, including one or more additional small-body flybys.

Second NMP Deep Space Mission

The second planned NMP deep space advanced technology-validation mission seeks to demonstrate prototypical terrestrial planet micropenetrator [technologies. A wide variety of future science missions require this capability One or two of these microprobe, consisting of a very low-mass aeroshell and very low-mass penetrator system, will be carried to Mars by the cruise stage of the Mars '98 lander mission, one of two launches planned (this one in early 1999) during the 1998--99 Mars window by NASA's Mars Exploration Program.

Following a 6- to 10-month cruise, the small systems, approximately 2 kilograms each, will be separated from the cruise stage about 10 days from Mars entry. They are designed to self-orient into the proper atmospheric entry angle regardless of entry interface attitude. They then ballistically enter and descend without parachutes or any other mechanical or propulsive devices, and ultimately impact the surface of Mars at approximately 150 meters per second. The small, 1-kilogram micropenetrator punches through the aeroshell and finally comes to a stop about 0.5 meter below the surface. A small aftbody with a communicant ions antenna remains on the surface, connected to the subsurface package by a coaxial cable. The elements of the penetrator system include a suite of highly miniaturized components needed by most future micropenetrator systems: batteries, power electronics, control and data handling microelectronics, telecommunications equipment and antenna, etc. For the NMP demonstration, various options have been identified for the inclusion of a prototype microinstrument into the design to demonstrate that the micropenetrator technology indeed has the capability to acquire and relay a meaningful measurement to an orbiting craft, assumed to be the Mars '96 orbiter.

Third NMP Deep Space Mission

The third planned deep space technology-validation mission is a three-spacecraft, free-flying interferometer placed in solar orbit by a single launch. Owing to employment of kilometer-long (or longer) baselines, separated-spacecraft, free-flying interferometers hold the potential for enabling dramatic breakthroughs in astrophysics by virtue of their unparalleled capability for resolving distant astronomical objects. The first demonstration of this observing technique in space by NMP will place NASA on a path toward using larger, more sophisticated versions of such instruments to detect, image, and characterize Earth-like planets around other stars in our galaxy. Technical challenges to be taken on by NMP with this six-month mission include faint starlight detection (down to 14th magnitude) with two spacecraft; use of actively controlled optics to manipulate and combine the starlight from the two collector spacecraft in the combiner spacecraft with 10-nanometer control; use of a laser metrology system to precisely measure the starlight path lengths and optical baselines between the three spacecraft; use of a laser-based "kilometric optical gym" to measure the overall rotation rates of the three-spacecraft constellation during operations; precise stationkeeping for all three spacecraft with control to the centimeter level; and techniques for initializing the configuration of the constellation following launch vehicle separation.

PATH TO THE FUTURE

NASA's New Millennium Program will spur the development of the revolutionary technologies needed for the high-return, lower-cost space and Earth science missions envisioned for the 21st century. These "leap-ahead" technologies, implemented in validation flights, will demonstrate the capabilities needed for future missions. The NMP technology-validation flights are also science missions, selected according to a series of assessment criteria designed to maximize the science return and at the same time thoroughly prove the technologies as they perform in spaceflight conditions. Societal benefits will be both immediate and ongoing: in the stimulation of technological development, the creation of new U.S. industry through the requirement for capable microspacecraft, and the acceleration of academic work from research to application.

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