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Advancing Autonomous Operations Technologies for NASA Missions

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Abstract— This paper discusses the importance of implementing advanced autonomous technologies supporting operations of future NASA missions. The ability for crewed, uncrewed and even ground support systems to be capable of mission support without external interaction or control has become essential as space exploration moves further out into the solar system. The push to develop and utilize autonomous technologies for NASA mission operations stems in part from the need to reduce operations cost while improving and increasing capability and safety. This paper will provide examples of autonomous technologies currently in use at NASA and will identify opportunities to advance existing autonomous technologies that will enhance mission success by reducing operations cost, ameliorating inefficiencies, and mitigating catastrophic anomalies. [1] [2]

TABLE OF CONTENTS

1. INTRODUCTION

The Concept and Definition of Autonomy

Automation and space exploration missions have always gone hand-in-hand. From Sputnik to the Apollo missions and even to the most recent Mars rover, Curiosity, there has always been a need for automation of spacecraft functions. As spacecraft functionality has increased with time, so has the complexity of automation, to the point where it is now absolutely essential to understand the different concepts of "Automatic" and "Autonomous." Merriam and Webster [1] define specific differences between these two concepts as they relate to the Aerospace Industry:

Automatic - Operating with minimal human intervention; independent of external control;

Autonomous - Operating without outside control; existing independently;

The difference in these two concepts can be understood easily in these terms: To be automatic is to have human-less operation. To be autonomous is to have (or expect to have) human-like performance. Think of the difference between the functions needed for an unmanned vehicle vs. those needed for a scientific mission to another planet. See Figure 1 below. Both vehicles have the requirement for mobility, to recognize and avoid obstacles and robotic manipulation; but unlike the tracked automated vehicle, to fully support science and exploration missions, the wheeled autonomous vehicle must also be able to identify unexpected hazards, and change its mission parameters as scientific priorities change. Note the concept of autonomous operations can also apply to crews operating without dependence on a ground control facility on Earth.

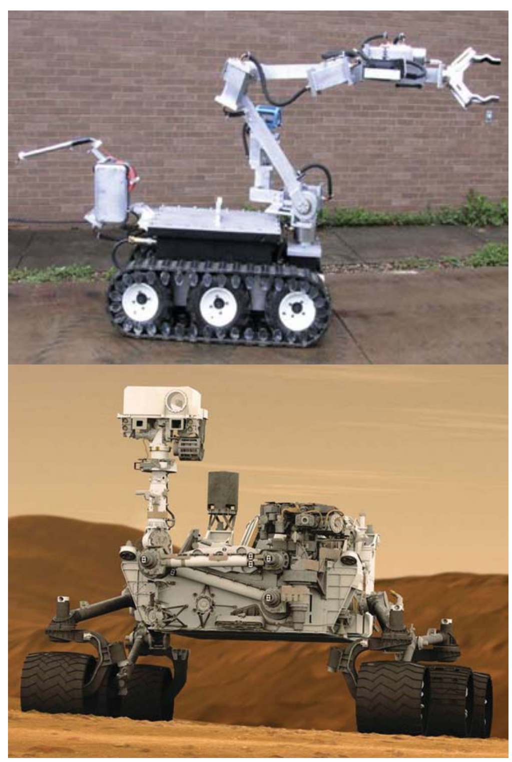

Figure 1: A "simple" automated vehicle (top) and autonomous planetary exploration vehicle (bottom).

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The Importance of Autonomy

Autonomy is absolutely critical in today's space mission environment. For example: a Mars rover must have the ability to recognize obstacles that its controllers did not anticipate, avoid the obstacle if it is out of predefined parameters or stop and wait for instructions before it becomes entrapped or damaged. Important functions for autonomous rovers include: to be able to recognize and move around hazardous terrain, to be intelligent enough to stop if the situation warrants and to have safe modes available if operations do not go as planned.

Here is another key example: imagine if the crew of the International Space Station (ISS) had to wait for instructions from the ground during the first critical minutes of a fire emergency. In this extreme but plausible case, their survival hinges on their ability to quickly understand the situation and take action to mitigate the emergency or in extreme cases, take unilateral action to abandon the ISS for a return to Earth.

These two examples, one from the robotic perspective the other from human space flight, are just the tip of the iceberg when it comes to the need for autonomy in space operations and exploration. This paper will elaborate on more examples of how autonomous operations have evolved over the relatively short history of NASA space missions, as well as, provide some examples where valuable lessons have been learned through failure or near failure.

The Impact of Successful Autonomy

The importance of having reliable autonomous technologies on spacecraft can literally be the difference between mission success and catastrophic failure. The complexity of space missions today forces the requirement of autonomous systems. The ever increasing demands and unknown environments of exploration missions will only add to these requirements. In the short term, automation certainly adds cost and lengthens development times of new spacecraft systems. However, in every industry from aviation to mining, autonomous technologies that become safer, reliable and accepted standards in fact become less expensive, and just as important, increase capabilities not otherwise possible.

2. Past Autonomous NASA Systems

Successful Past Autonomous NASA Systems

There are too many autonomous systems and technologies involved in past NASA missions to fully explain and do justice to them all in the limited confines of this paper. We have included just a few of examples of how autonomy factored into the success of some prominent and some less prominent NASA missions.

Apollo – Probably the most historic and incredibly successful exploration missions in human history were the Apollo missions to the moon. Given the limited technology of the time, there was a surprising amount of autonomy built into the spacecraft, which in no small measure lead to their success. From having the ability to: manually fly the Saturn V rocket via joy stick in a contingency; update the onboard navigation state without help from mission control; enable man-in-the-loop landings; and to change surface objectives based upon in-situ discoveries. For these reasons and many more, the Apollo astronauts and their spacecraft went down in history as the gold standard of human exploration.

That's not to say they did it totally on their own. The missions never could have succeeded without support from ground controllers back on Earth. The limitations of vehicle technology meant that the crew was nominally reliant on data from the ground, but never the less, they did have the capability to perform most if not all contingency tasks, including return to Earth autonomously. These capabilities have been well documented and analyzed in the years since the crew of Apollo 17 returned [2]. Operationally, the Apollo missions were a huge success, even the near tragedy on Apollo 13. However, the complexity and massive cost of the program ultimately led to its premature conclusion.

Figure 2: An Incredible Integrated Autonomous System: The Apollo Astronauts and their Spacecraft.

NASA's Near Earth Asteroid Rendezvous Mission - The Near Earth Asteroid Rendezvous (NEAR) spacecraft, while maybe not as well known as the Apollo missions, marked a significant improvement in spacecraft autonomy. It was launched in 1997 to study a nearby asteroid and on February 12, 2001, NEAR actually touched down on Eros. Developed and operated for NASA by the Applied Physics Lab (APL) at Johns Hopkins University, the NEAR spacecraft built upon the success of the Advanced Composition Explorer (ACE) mission [3] and other scientific robotic spacecraft. The NEAR spacecraft, considered a second generation autonomous system, helped advance the capability to handle complex mission rules and software-based fault detection and isolation onboard the spacecraft.

When transitioning from the ACE mission to development for NEAR in the early 1990s, APL and NASA realized the spacecraft software autonomy system responsibilities and complexity were growing. This was due in part to the need for rapid onboard responses as the spacecraft had significant time-light communication delays. This along with the tiny operations budget (compared to a mission like Apollo) meant that the small mission ops team back on Earth would have to rely on the spacecraft to manage its operational risks for itself in many situations.

To handle this, APL implemented software autonomy with nested conditional execution statements. This allowed rules to enable or disable other rules. For example, one rule was able to detect a fault and enable a set of rules to respond to the fault. The increase in complexity was also a result of automating more of the onboard fault management and safing. To support the increased responsibilities, multiple levels of command execution responses were needed. In this manner, the response to a higher-priority fault could preempt a lower-priority fault response or automated operations action currently being executed.

Even though the addition of conditional execution and priority responses solved problems faced by developers for the second generation of autonomous spacecraft, the implementation was a double edged sword. APL engineers realized that this was the beginning of the end of the rule-based systems. Their reason for moving away from the rule-based approach was evident in the NEAR mission: "What seemed at first to be a simple rule-based design actually became quite complex when it came to defining the checks and command responses needed to coordinate safing for all spacecraft subsystems [3]." Managing multiple levels of rules to implement system functions also drove the testing time (and cost) necessary to verify the rule implementations. Operationally, it was also very complex and meant that highly trained software support engineers were needed for all phases of the mission. Ultimately the NEAR mission was a success and helped pave the way for more recent exploration missions like NASA's New Horizons mission to Pluto.

Unsuccessful Past Autonomous Systems

DART - NASA's Demonstration of Autonomous Rendezvous Technologies (DART) flight experiment, in 2005, was an example of a technology demonstration that did not end in success but helped to teach valuable operations lessons for autonomous space systems. DART was a small robotic spacecraft designed to rendezvous with and perform maneuvers in close proximity to the Multiple Paths, Beyond Line of Sight Communications (MUBLCOM) satellite, without any assistance from ground personnel. Its prime objective was to test new rendezvous and proximity operations techniques, sensors and operations capabilities for future exploration missions. See Figure 3.

DART was launched from Vandenberg, California on April 15, 2005. It performed as planned during the early orbit, and rendezvous phases of the mission, accomplishing all objectives up to that time. However 8 hours into the mission, ground personnel noticed anomalies with the navigation system but were unable to command to the spacecraft because command uplink was not a requirement! During proximity operations, DART began using significantly more propellant than expected. Approximately 11 hours into a planned 24-hour mission, DART detected that its propellant supply was depleted, and it began a series of maneuvers for departure and retirement. It was not known at the time, DART had actually collided with MUBLCOM just before initiating retirement.

Because DART failed to achieve its primary mission objectives, NASA convened a Mishap Investigation Board. In DART's case, none of the 14 requirements related to proximity operations − the critical technology objectives of the mission − were met. However, other portions of the mission, including the launch, early orbit, rendezvous, and retirement, were successful. Out of a total 27 defined mission objectives, DART fully or partially met 11 of those objectives [4].

In the case of DART, the technology implemented as well as the operational concepts were probably not mature as they could have been. It was later discovered that onboard navigation software caused erroneous solutions thereby causing inaccurate thruster firings. Additionally, the concept of a totally autonomous rendezvous and close approach without any command uplink capability, in Low Earth Orbit was not an effective strategy. Even though one of the key goals was to demonstrate autonomous proximity maneuvers, the DART operations team would have been well served to include a few critical commands in minimize their risks. In this case, perhaps a software update or even a navigation filter reset could have saved the mission.

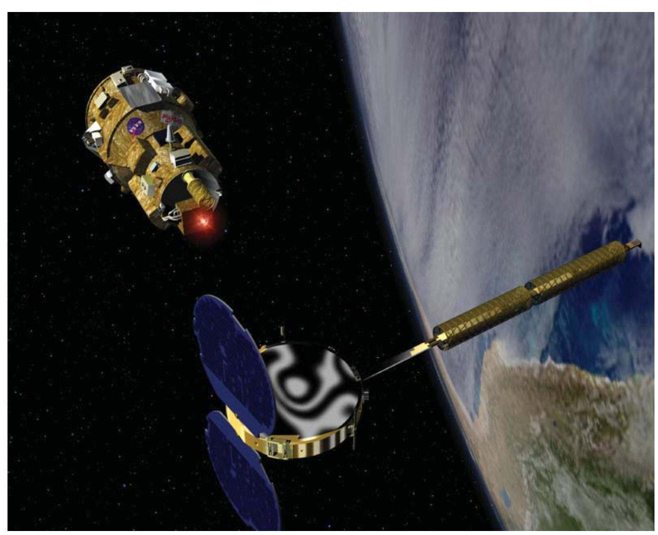

Figure 3: NASA's DART Flight Experiment.

Through successes or failures, NASA has always gathered and analyzed lessons learned. Autonomous spacecraft rendezvous, proximity operations, and capture capabilities will continue to be critically important to successful space exploration. In the case of DART, the prime lesson is that a command uplink and the ability to upload software updates for autonomous systems are critical, especially in technology demonstration missions.

3. Autonomous NASA Spacecraft Currently in Operation

Autonomous Surface Systems

Since Apollo, the most important examples autonomous exploration systems NASA has had are the series of robotic rovers that have been sent to Mars. In no other case in human history has man sent exploration craft so far away and expected such complex equipment to fend for its own "survival" with little direct help from Earth. In these cases especially, autonomous operations were required for essential functions such as cruise stage health monitoring, entry, descent and landing as well as surface operations. Some examples and insights to autonomous operations on another planet are given below:

NASA's first Martian rover, named Sojourner, landed on Mars in 1997. It was a relatively small 23 lb, 6 wheeled rover that lasted 84 days on the surface and was a "proof-of-concept" for various technologies, such as airbag landings and automated obstacle avoidance, used by later rover designs. NASA has two active rovers on Mars, Opportunity (Figure 4) and Curiosity (Figure 5). Both rovers were designed to provide scientist on Earth with knowledge about the elemental properties that make up the planet, the harsh environment, surface terrain, and potential microbial life that may have existed.

Opportunity and its twin, Spirit began operations after landing on the Martian surface in January 2004. Both were second generation rover designs: 374 pound, six-wheeled robots powered by rechargeable lithium ion batteries. Their initial design mission life was only 90 sols (1 Martian day or Sol ≅ 24 hr, 39 min), however, over eight years later Opportunity is still collecting data and providing imagery to scientists. Spirit unfortunately became stuck in soft soil in May 2009 but continued performing stationary science observations until March 2010 when all contact was lost [5].

A program goal for each rover was to drive up to 40 meters a day, for a total of up to one 1 kilometer and both goals were exceeded. The extensive lifetime of Opportunity has allowed scientist to gain a better understanding of the planet's surface. It has also been an extraordinary tool for robotic engineers to test and verify autonomous sensors and software algorithms. There have been occasions where the rover had to conduct precise maneuvers to free itself from becoming completely immobilized. While not completely autonomous, Opportunity is able to manage its own operational risks through a combination of onboard sensor monitoring, mission rules with predefined parameters, safe modes and feedback from the mission controllers on Earth. For example, onboard sensors allow the rover to detect when its wheels are slipping and perform alternative maneuvering to prevent the rover from becoming stuck [5].

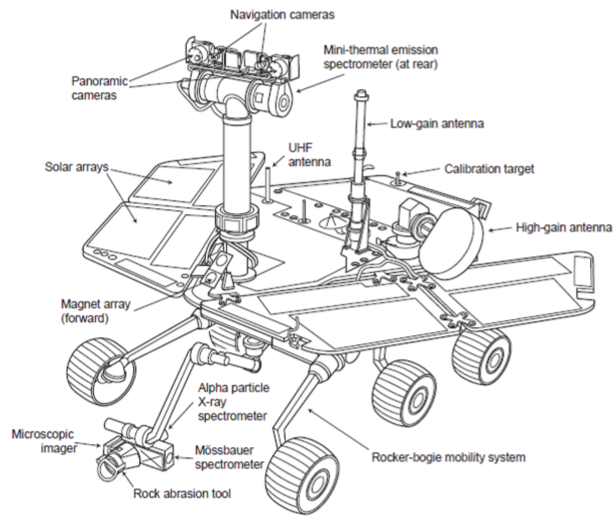

Figure 4: NASA's Opportunity Rover.

The Mars Science Laboratory, or Curiosity, is NASA's latest rover to journey to the Martian surface. Curiosity is a 1,982 pound six-wheeled robot powered by a radioisotope thermoelectric generator (RTG). When comparing the Sojourner, Opportunity and Curiosity rovers, it is clear that the designers have made substantial improvements to the Curiosity based on capabilities and knowledge gained from its predecessors. There are similarities between the rovers such as the 6 wheel design, camera imagery/navigation, Alpha Particle X-ray Spectrometer, etc. However, Curiosity brings a whole suite of new capabilities along with significant upgrades to the previously existing capabilities. See Tables 1 and 2 for comparisons of Opportunity and Curiosity's major systems and scientific instruments. With this increase in instrumentation, operations for the Curiosity are even more complex than the previous rovers and were [6]. [*ADD ADDITIONAL DETAILS HERE*]

Table 1: Opportunity and Curiosity Comparisons

Prime Design Comparisons		
Rovers	Opportunity	Curiosity
Design mission life on Mars	90 Mars sols (13 weeks)	1 Martian year (98 weeks)
Rover mass	170 kg	900 kg
Rover size (excluding arm)	Length 1.6 m Width 2.3 m Height 1.5 m	Length 3 m Width 2.7 m Height 2.2 m
Robotic arm	0.8 meters	2.1 meters
Entry, Descent and Landing	Ballistic entry, air bags	Guided entry, sky crane
Computer(s)	Single, 20 MHz 128 MB of RAM 256 MB of flash memory	Redundant pair, 200 MHz, 250 MB of RAM, 2 GB of flash memory

Table 2: Rover Scientific Instrument Comparisons

Opportunity	Curiosity
Panoramic Cameras	Mast Camera (Mastcams)
Miniature Thermal Emission Spectrometer	Mars Hand Lens Imager
Mössbauer Spectrometer	Mars Descent Imager (MARDI)
Alpha Particle X-ray Spectrometer	Alpha Particle X-Ray Spectrometer (APXS)
Microscopic Imager	Chem Camera - laser for vaporizing surfaces, and a remote micro-imager.
Rock Abrasion Tool	Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument
Magnet Arrays for airborne dust	Sample Analysis Instruments
	Radiation Assessment Detector
	Dynamic Albedo of Neutrons
	Rover Environmental Monitoring Station

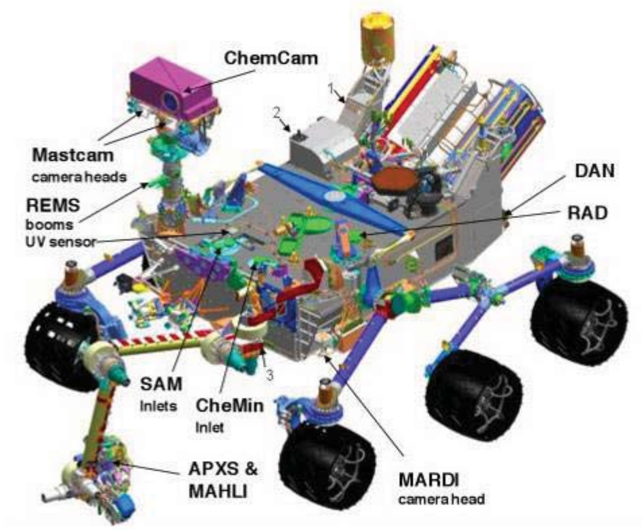

Figure 5: NASA's Curiosity Rover.

Autonomous Entry and Landing Systems

Of all the autonomous and automated technologies required for landing rovers on Mars, the most challenging is the discipline of Entry, Descent and Landing (EDL). From the precise astro-navigation required for an accurate atmospheric entry, to planning aero braking maneuvers, to the complex sequence of events for touchdown and landing, all must go exactly right or the vehicle and mission are doomed. Some of these events are timed but others, such as trim burns, or component separations, must in fact be commanded solely by the vehicle, again without input from the engineers back on Earth.

The Curiosity landing was the most complicated landing since Apollo 11 landed on the Moon. Due to its large weight, the rover was designed to be soft landed on the surface by a combination of aero braking, parachute deceleration and finally propulsively with a new concept called a "sky crane [7]." The sky crane's ability to autonomously and precisely land a large payload on the surface had never been tried before. Shown in Figure 6, it used sensors to detect the surface, identify a safe place to land the rover, descend to within 20 meters of the surface, hover and lower the rover before flying away to dispose of itself a safe distance away. All of the maneuvers had to occur autonomously without any chance of interaction from the operations team on Earth due to the light-time delay between Earth and Mars. For all these reasons, Curiosity's EDL phase earned the nickname "the 7 minutes of terror."

Figure 6: The Sky Crane Lowers Curiosity to the Martian Surface While Hovering with Rocket Engines.

And with the whole world watching, it all happened successfully on August 5, 2012. There have been many technical papers and articles documenting the details of Curiosities EDL system, but at a high level, it was another amazing technical and operational first. It proved that critical and complex spacecraft soft landing operations were possible even with the total lack of human direct control.

Even as Curiosity's mission is just beginning, it is obvious that the return in terms of the knowledge obtained of a totally new planet will be the most since Apollo. Thanks to the advances in autonomy, this science return comes at only a fraction of the cost of Apollo. What's next? Many engineers and scientists believe it is a robotic sample Mars return mission - which has been under study for many years.

4. AUTONOMOUS SYSTEMS IN DEVELOPMENT

Leveraging Past & Current Technologies

NASA's persistence to demonstrating new concepts of autonomous operations was again demonstrated with the development and successful flight test of the "Mighty Eagle" robotic lander (see figure 7). The Mighty Eagle is a 4' tall by 8' wide, 700 pound three-legged prototype that uses 90% pure hydrogen peroxide as propellant [8]. The lander consist of 16 onboard thrusters - 15 pulsed and one gravity cancelling thruster - all controlled by commands set from the onboard computer. The robotic lander and the pre-programmed automated flight profile serves as a platform to develop and test algorithms, sensors, avionics, software, landing legs, and integrated system elements to support future autonomous landings on airless planetary bodies, where aero-braking and parachutes are not options.

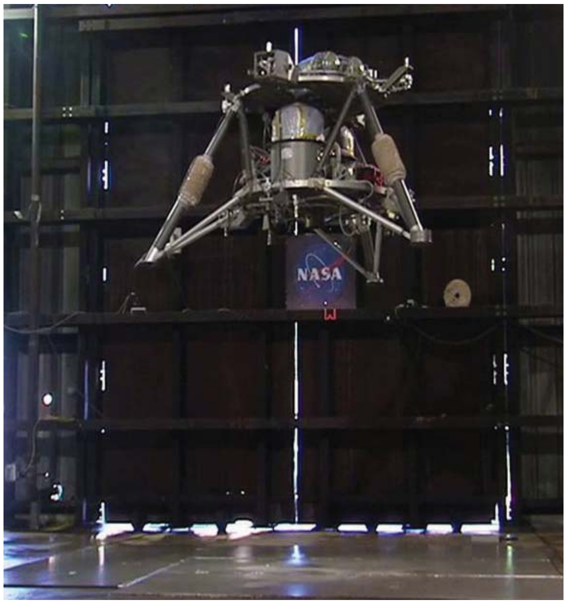

Figure 7: NASA's Mighty Eagle Robotic Lander Prototype during an Initial Indoor Test Flight.

In 2010-2011 project goals were vehicle design, construction, integration, and short flight tests (less than 15 sec) that showed NASA and its contractor team had the ability to design a prototype lander on an accelerated schedule and with minimal cost. The vehicle was designed with a path-to-flight and was a risk reduction activity for the potential international lunar mission. The project demonstrated NASA's capability to quickly and efficiently perform vehicle design (dynamics modeling, thermal analysis, propulsion analysis, fault analysis, software architecture, etc), vehicle assembly and integration (mechanical, propulsion, avionics), vehicle functional testing (avionics, software), and ground operations (ground support command and telemetry software, and flight software testing). Its flight tests were designed to perform progressively more difficult controls maneuvers. They began with strap down testing, progressed to low altitude indoor flights, and finished with high altitude outdoor flights. This test series was successful in demonstrating the capabilities of the vehicle to perform final descent and landing, the main objective of the risk reduction activity.

The 2012 test series continued vehicle operations with software enhancements, ongoing vehicle maintenance and characterization. It also demonstrated the ability to perform simple autonomous rendezvous and capture maneuvers using the existing capabilities of the vehicle. NASA MSFC and SAIC developed software to detect a target placed in the field of view of the onboard camera and to command itself to land on the target. The vehicle successfully demonstrated both open and closed loop operation of the software at an altitude of 10 and 30 m. This test series also extended the vehicle's maximum altitude and flight duration to 50 m and 45 seconds respectively (see figure 8).

Figure 8: The Mighty Eagle Robotic Lander in Stable Flight, 50m above the Ground.

Data from the flight tests of the Mighty Eagle will aid in the design and development of a new generation of small, smart, (and much cheaper) robotic landers capable of performing science and exploration research on the surface of the moon or other airless bodies in the solar system. Lander development programs like the Mighty Eagle and others will no doubt save development time and money in the future.

5. Future Needs for Autonomous Systems in Space Exploration Missions

New Autonomous Systems to Enable Future Mission

As is usually the case in technology, what is "cutting edge" one day quickly becomes "old tech." While this process is a little slower in the conservative discipline of space system development and operation, more capable autonomous systems are in demand such as:

- Autonomous sample return vehicles
- Robotic crew assistants
- Spacecraft fault detection and recovery
- Control center automation
- Prelaunch vehicle testing

A sample return missions from Mars appears to be the next major first in space exploration. Operations and design concepts have been on the books for years but cost and mission risks remain high due to the extreme mission complexity. Systems that will reduce both include ascent vehicles, rendezvous and capture, in space navigation and Earth entry and landing.

[*NEED ADDITIONAL DETAILS HERE*]

Onboard Crew Assistants

Onboard crew robotic assistants are another technology area that is being studied. A crew's time is one of the most limited resources during a human spaceflight mission. Anything that can be done to make their job more efficient or ease their always full timelines, is seen as a benefit and potentially a way to increase the probability of mission sucess.

One example of how robotics is attempting to help the ISS crew is the current payload called Robonaut. It is a 300-pound robot with a head and a torso with two arms and hands (See figure 8). Robonaut arrived on the ISS in February 2011. Since then, Engineers have been monitoring how the robot operates in weightlessness. For its first trials, it will be confined to operations in the station's Destiny laboratory. However, future enhancements and modifications will allow it to move around the station's interior or outside the complex [9].

Figure 9: Robonaut - Robotic Assistant Payload Onboard ISS

Autonomous Spacecraft Fault Detection and Recovery

There are a whole host of subsystems that will potentially help to automate spacecraft in ways that haven't even been considered yet. Fault detection, isolation and recovery sensors, and logic have been used on launch vehicles and spacecraft since the beginning of space exploration, but recent advanced in nano-technology, high speed space hardened circuitry and an increased confidence in on-board scripting languages like Timeliner and others are being used to prototype vehicles that can not only detect and isolate a failure, but predict future failures based upon real-time telemetry and recommend replacement to the ground or onboard crew. [10]
[ADDTIONAL DETAILS PENDING]

Control Center and Ground Facility Automation

- Lights out operations for current LEO satellites as well as deep space probes.
- Automation that enables non-expert operators to manage missions
- Delay Tolerant Network (DTN)

An important aspect of any operational system and a key cost driver is the training and certification of a highly specialized operations team whether it is the crew onboard or the ground support team. Traditionally, and usually successfully, NASA has relied on a team of experts to operate its space assets. In the future, it may become more cost effective to rely on an experience team of non-expert operators or mission managers who know the key parameters and objectives of a mission, but rely on the autonomous systems on the spacecraft or ground to do the detailed analysis of fault detection, and/or resource requirement planning [11].
[ADDTIONAL DETAILS PENDING]

Prelaunch Vehicle Testing Operations

- Automated verification of software and hardware prior to final vehicle integration
- Automated vehicle checkout and prelaunch testing

[12]

[MORE DETAILS NEEDED]

6. CONCLUSION

This paper has illustrated operational examples of the development of autonomous technologies at NASA for missions including crew autonomy on Apollo, uncrewed vehicles including spacecraft and surface rovers. The paper also covered successful and unsuccessful, technology demonstrators which no matter the outcome helped NASA to learn how better to employ autonomous systems. Ultimately, autonomous technologies enhance mission success by reducing long term operations cost, but there can be significant initial systems development and verification costs.

NASA's future exploration missions will require autonomy to limit the effects on time delay, increase safety and mission success as well as to reduce inefficiencies, and mitigating catastrophic anomalies. They will increase operational flexibility by helping non-expert operators and mission managers to have good situational awareness of system status' and constraints. Autonomy will eventually enable more capable onboard crew assistance technology that will be able to perform mundane and repetitive tasks in order to free up crew time for more important duties. The ISS payload Robonaut is just one example of how this starting to become reality.

Through successful and unsuccessful missions, NASA continues to grow and leverage knowledge to ensure that future exploration endeavors are provided with the latest technology while utilizing the most cost effective approach.

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BIOGRAPHY

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