A Review of Spacecraft AI Control Systems

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ABSTRACT

The history of artificial intelligence control systems for use in space is discussed in this paper. The two fields started separately in the 1950s and first merged in the 1970s due to control requirements for a Jet Propulsion Laboratory project. While spacecraft have a special need for AI systems due to communications delays and other factors, much of AI control system development is conducted for earth-based applications. To mitigate risk factors, space-bound AI systems are also tested extensively via simulations. As a result, virtually all AI space control systems get their start on the ground. Additionally, ground support systems are required to facilitate communication with and command of AI controlled and other space craft. Numerous successful missions incorporating or controlled by AI technology have been launched. Further, many more are planned. Examples of ground, space-flown and future AI control missions are all discussed herein. While, spacecraft AI was born out of necessity (due to communication delays and such), it is now becoming desirable for other reasons such as cost savings and mission enhancement.

Keywords: autonomous robotics, autonomous spacecraft, artificial intelligence, robotic control, AI control, control systems

1. INTRODUCTION

To many, space exploration and artificial intelligence just seem to go together. For some, science fiction may be responsible for building the strong association between the two. However, to-date autonomous technology has been deployed in a limited fashion to meet specific mission objectives which in most cases could not be otherwise met. In most instances, autonomy technology has met with success in its limited mission role. Fully autonomous spacecraft control has been demonstrated in a limited capacity and appears to hold promise for reducing mission cost, increasing scientific returns and allowing the operation of more complex multi-vehicle missions. What follows is a look at the history and possible future of artificial intelligence control systems in space.

2. ORIGINS OF AI, SPACE EXPLORATION AND AI FOR SPACE EXPLORATION

Both space exploration and artificial intelligence got their start in the 1950's. One of the first developments in AI was Newell, Shaw and Simon developing IPL-11, the first AI language, in 1955. In 1956, John McCarthy first used the term "artificial intelligence" to state the topic of the Dartmouth conference (which was the first AI conference). Also in 1956, Newell, Shaw and Simon created "The Logic Theorist" which could solve math problems and Ulam developed a chess playing program: Maniac I. On October 4th, 1957 the Sputnik satellite (the first human-built space craft) was launched. Sputnik 2 followed on November 3rd, sending the first mammal in to orbit. On the AI front in 1957, Newell, Shaw and Simon introduced their General Problem Solver. In 1958, McCarthy introduced LISP, the MIT AI lab was established and the National Aeronautics and Space Administration (NASA) was launched. [47, 5, 23]

The two fields, however, would continue to develop separately until 1972 when the Jet Propulsion Laboratory (JPL) started its AI Research on a mars rover vehicle. By 1975, scientists on this project had determined that additional planning capabilities were needed and started construction of an expert system to assist in planning. The DEVISER system was created by the Automated Problem Solving Group at JPL and was used initially to generate commands that would be sent by operators to VOYAGER. VOYAGER program staff expanded the knowledge base of DEVISER and used it to model spacecraft activities. The same group at JPL created a diagnostic expert system, FAITH, which had an initial focus of monitoring telemetry from VOYAGER and other spacecraft. FAITH, based on its monitoring of telemetry streams, could generate alarms if necessary. [18]

In 1979, Carnegie-Mellon University established its' Robotics Institute. This institute was launched with five projects one of which was space construction and exploration. [6, 17]

3. GROUND BASED TESTING & SUPPORTING SYSTEMS

Autonomous spaceflight starts on the ground. For each craft that is sent into space to explore, numerous concepts must be proposed, developed and tested on Earth to ensure a successful mission. Projects and experimental and concept craft such as Carnegie Mellon University's Ambler program, the Self-Mobile Space Manipulator project, the Tessellator robot, Dante I, Dante II, the Automated Scheduling and Planning Environment (ASPEN), the Rocky 7 Rover, Nomad, the Modified Antarctic Mapping Mission, the Distributed Spacecraft Technology (DST) program, Skyworker, TEMPEST, Hyperion, Zoe, the Hetereogeneous Agricultural Research Via Interactive, Scalable Technology (HARVIST) project, the DepthX project, Scarab and MISUS pave the way for future autonomous space exploration. Many of these programs are of a dual-use nature in that they further space exploration goals while providing a (in many cases primary and more immediate) benefit on Earth.

As an example, under the auspices of the NASA Instrument Incubator Program, the Jet Propulsion Laboratory began development of an autonomous Unmanned Airborne Vehicle (UAV) system for earth sciences use. While this system is, at present, designed only for earth-based use it clearly represents a technology that may have future application for planetary exploration missions. The UAV is designed to carry radar to study earth deformation via repeat passes both over the long term and phenomena which can cause deformation in the short term such as glaciers and earthquakes. The system is currently being developed on a Proteus aircraft, which requires a crew of two to operate it. The researchers believe that the Proteus could be further developed to include UAV capabilities which are necessary due to the fact that human pilots are not able to fly with the precision required to collect the repeat track data. [21, 30]

Important UAV, Unmanned Ground Vehicle (UGV) and Unmanned Surface Vehicle (USV) capabilities are also being developed by a variety of military entities. These include the combined U.S. Army and Navy Mobile Detection Assessment Response System (MDARS) program, the U.S. Army's Future Combat System (FCS) program, the Defense Advanced Research Projects Agency's (DARPA) Perception for Off-Road Robotics (PerceptOR) program, the Cooperative Unmanned Ground Attack Robot (COUGAR) program, and the U.S. Army and Navy SPARTAN Advanced Concept Technology Demonstration (ACTD) program. MDARS and PerceptOR are UGVs which can serve as a mobile launch, landing and support platform for UAV units. SPARTAN is a water-based USV which can similarly serve as a UAV base. The FCS program will incorporate UAVs as part of a network-centric combat system. The COUGAR system involves a command vehicle which carries a control unit, long range weapons robot, and UAV. The UAV is used to survey targets and confirm the missile strike. All of the aforementioned involve various levels of human control, at present. For example, the COUGAR system requires that a human operator pre-program the flight path of the UAV and initiate its launch. SPAWAR Systems Center (SSC), Allied Aerospace and others are working to combine these various technologies to create a system to provide an autonomous response. To this end, testing has been conducted in 2002 regarding the launch of a UAV from a UGV. Additional work regarding landing and refueling of a Allied Aerospace 29" iStar UAV has been conducted and technology from Carnegie Mellon, the Jet Propulsion Laboratory and Geodetics, Inc. is being used to facilitate autonomous landing. [32]

4. AUTONOMOUS SPACE EXPLORATION

A spacecraft encounters a somewhat unique problem as it moves further and further from earth. The increasing distance makes it take longer to receive guidance and ask for help from ground-based controllers. As such, a spacecraft that will be any significant distance from earth must have some autonomy for basic functions such as to be able to take collision-avoidance actions and to reestablish communications with earth should they be lost. The use of autonomous technologies started with meeting these basic requirements and performing actions (such as docking) which required too much precision to be done reliably by a human. They have gone on, however, to be implemented because they can make missions better and less expensive.

The Soviet Union has implemented autonomy technology to dock its spacecraft: first with the IGLA system and later with its replacement, the KURS system. Both the IGLA and KURS systems are radar-based and calculate distance and position based on the relative strength of signals between antennas. The IGLA technology was used by the Soyuz T spacecraft while KURS was used by Soyuz TM and Progress M spacecraft. The MIR space station supported both technologies. The first docking of a Suyuz TM was in 1986; Progress M first docked in 1989. [22]

In 1993, the Jet Propulsion Laboratory started construction on the Mars Pathfinder and its Sojourner rover. The Pathfinder and Sojourner launched on December 4th, 1996 and arrived at Mars on July 4, 1997. Sojourner was the first craft to explore another planet (Viking 1 had landed on Mars in 1976, but wasn't able to move from its landing site). The Sojourner craft was autonomous: while all planning was done on-the-ground and uploaded, the craft was able to respond in a limited fashion to changing conditions and avoid obstacles in the path of its preplanned route. Generally, Sojourner used straight-line navigation to follow the operator go to co-ordinate instruction; however, when an obstacle is detected by the craft's five laser stripe projectors and its two CCD cameras, it can execute one of several condition-specific pre-programmed behaviors in response to the obstacle. If the craft is not able to reach its goal (or not able to reach it within time requirements) it is able to determine what commands from the plan can and should still be run; however, ground operators must decide what the craft should do next. This can, for example, include providing a more specific route (via adding more waypoints), telling the craft to take greater risks to reach its goal, or manually operating the craft remotely. [44, 46]

Starting in 1994, the Jet Propulsion Laboratory was asked by the NASA Office of Space Communications to develop an autonomous unmanned technology for ground control of the Deep Space Network (DSN). DSN is a network of antennas in three locations: California, Spain and Australia which are used to communicate with spacecraft. The Deep Space Station Controller (DSSC) technology was developed in response to this request. The first demonstration of DSSC in 1994 consisted of a test downlink from the SAMPEX and EUVE satellites. In 1995, the ability to uplink was added to the prototype unit. A week long uplink/downlink demonstration was conducted in December. Following the demonstration, the system remained in operation and recorded 3120 hours of tracking during the next 26 months. DS-T followed and demonstrated the feasibility of autonomous uplink/downlink operations with deep space craft. [41]

The DSSC system architecture is a combination of CLEaR (which includes the CASPER and TDL), the Beacon-Based Exception Analysis for Multi-missions (BEAM) system and Spacecraft Health Interface Engine (SHINE). CLEaR, which is a continuous planner based on the CASPER system, determines what should be done. TDL, on the other hand, provides sequencing capabilities and reactive planning. BEAM and SHINE are used for error detection and recovery. BEAM monitors system performance indicators and compares them to a model, identifying any anomalies. SHINE is a knowledge-based expert system which interprets the BEAM information. SHINE uses heuristics to quickly isolate possible fault causes and causal-reasoning to analyze the fault and further refine the possible causes. [41]

NASA has identified a need to transform the Deep Space Network further into the Interplanetary Network to support future mission plans. As part of this transition, it is likely that the existing three site network will expand to encompass additional sites. Some of which may be in remote locations. As such, there is an even greater need for autonomy technology to facilitate the operation of these various stations within budget constraints. [48]

In 1999, the Deep Space One craft was controlled by an autonomous agent called the Remote Agent Experiment (RAX) for a few days. RAX was one of three autonomy technologies tested on Deep Space One. RAX was developed by researchers at the Jet Propulsion Laboratory and the Ames Research Center. It was selected for testing on Deep Space One based on a successful simulator test where it was required to navigate through Saturn's rings and respond to simulated spacecraft failures; it accomplished all of these objectives and also responded to an unplanned simulation failure. Deep Space One was the first spacecraft to use a remote agent for most control. [8, 34, 37]

The remote agent consisted of four parts: an executive, mission manager, planner/scheduler and the Mode ID and Reconfiguration (MIR) system. The executive was the top-level program in the system and executed plan instructions. The mission manager kept track of mission objectives and resource constraints. The planner/scheduler unit was responsible for plan generation based upon high-level goals. The MIR system was responsible for assessing the craft's health and proposing alternates for failed components. The planner unit generates a plan which is implemented by the executive. If the executive is not able to execute the plan due to a failure or other change, the MIR unit can suggest an alternate solution; failing that the executive asks the planner unit to create a new plan. [38]

The first test of RAX was interrupted due the agent failing to shut down the main engine at the expected time. A second test was conducted during which the agent correctly responded to three simulated failures and also correctly avoided use of the main engine due to the previous command failure. These tests validated the use of remote agent technologies on future missions. Unlike previous missions such as Cassini, which required 100 to 300 staff to operate it, Deep Space One required significantly less staff. It also had reduced communications needs, freeing the deep space network for use by more craft simultaneously and allowing more science data to be transmitted instead of control and monitoring data. [33, 35, 39]

Also being tested on Deep Space One was the AutoNav system. AutoNav consisted of five components: navigation executive functions, image processing, orbit determination, maneuver planning and encounter knowledge updates. The executive is responsible for all AutoNav communication to the actual flight control systems. Image processing identifies the objects captured by the craft's cameras. Orbit determination identifies the craft's position; maneuver planning uses the orbit determination information to identify necessary course correction maneuvers. Encounter knowledge updates is a special mode that AutoNav enters after all required pre-encounter course corrections are completed. In this mode, AutoNav provides target position information to the altitude control system to facilitate craft pointing changes. AutoNav started operating on October 24, 1998 and gradually increased the scope of its control as more components were tested through to April 20, 1999 when the craft was placed completely under AutoNav's autonomous control. [2]

The third autonomy technology tested on Deep Space One was beacon software. This represents a new methodology where a spacecraft determines when it needs help from controllers and requests it. The system has two parts. A tone system advises ground controllers of communications needs. The tone can indicate one of four possible contact need timeframes: immediate, within a time period, when convenient or no need. When ground controllers respond to the tone, the second system sends a summary back to controllers. This summary contains high level information, information about sensors that have violated an alarm threshold, snapshot data from all sensors and performance data (which is data that is of known interest to controllers). Alarm thresholds are determined by Envelope Learning and Monitoring using Error Relaxation (ELMER) technology. ELMER uses a neural network to provide faster error detection with fewer false alarms and can be trained either in space or prior to the mission. [2]

In 2003, the Autonomous Sciencecraft Experiment (ASE) onboard Earth Observing-1 was launched. ASE had several AI elements. Its onboard science algorithms were designed to detect phenomena of interest. It used the Spacecraft Command Language to allow it to be event-triggered and to have low-level autonomy. It also made use of the CASPER software which generated and regenerated mission plans based on the aforementioned science algorithms as well as accomplishments on previous orbit-cycles. Its onboard analysis software identified changes and phenomena of interest and CASPER made plans to allow the satellite to observe phenomena of interest and to transmit the most valuable information to earth first. ASE resulted in an increased amount of scientifically important data being transmitted over the fixed-bandwidth radio communications channel through its prioritization. It also allowed the satellite to respond quickly and capture short time span events and it streamlined operations. [25]

Also aboard the EO-1 satellite is the Livingstone Version 2 (LV2) software. Livingstone is an expert system software package developed at NASA's Ames Research Center which detects and diagnoses hardware and software problems on a spacecraft. On EO-1, this is being tested by detecting and diagnosing simulated failures. It also monitors the Autonomous Sciencecraft Experiment software running EO-1's imaging system. It compares actual performance to a model of proper performance. If a difference is noted, the LV2 reasoner attempts to ascertain the cause of the failure and provides human operators with probable causes. LV2's reasoner is independent of the model to allow reuse; software of this type should allow future spacecraft to enjoy longer operating periods by facilitating recovery from errors. [3]

Related to the EO-1 satellite are several sensorweb projects including the volcano sensorweb which started operating in 2004. Sensorwebs are networks of connected nodes which take automated action based on the detection of an event-of-interest by a sensor node. For example, the volcano sensorweb may detect an eruption based on an in or near volcano sensor or a low resolution orbital satellite such as NASA's Terra and Aqua satellites. Based on this event detection, the volcano sensorweb will relay a request for observation to the ASPEN/CASPER based ground planning service which will evaluate it and forward it to the EO-1 satellite which can gather high resolution imagery. The onboard planner on EO-1 will evaluate the request in the context of the current constraints of the satellite and then take the required actions if it is able to action the request. Several sensorwebs have been created including the aforementioned volcano sensorweb as well as sensorwebs related to wildfires, floods and the chryosphere. In all cases, an automated review of sensor data identifies a condition of interest which then triggers a request to EO-1 for further observation to facilitate analysis. Ongoing research includes tasking a uninhabited aerial vehicle to fly-over areas of interest identified by a sensorweb and to act as a trigger-sensor-node. Sensorweb technology has clear applications in the coordination of future space missions containing multiple craft. [9, 42, 43]

In May of 2003, the Japanese Aerospace Exploration Agency (JAXA) launched the Hayabusa spacecraft carrying the Minerva robot. In 2005, Hayabusa made several autonomously controlled landings on an asteroid in an attempt to collect temperature data, images and samples. The November 20, 2005 landing was the first ever controlled landing on an asteroid and the subsequent ascent was the first ever ascent from any body other than the moon and Earth. Despite several hardware failures and a possible chemical fuel leak, controllers hope that the craft collected a sample either due the projectile firing (which is uncertain) or due to the impact kicking up dust in to the collection area. Hayabusa is presently scheduled to return to Earth in June of 2010. [1, 24, 36]

On June 10th and July 7th, 2003 the Jet Propulsion Laboratory's MER-A, known as Spirit, and MER-B, known as Opportunity, rovers were launched. Spirit landed on Mars on January 4th, 2004 and Opportunity landed on January 25th. The two rovers operate autonomously and are given goal-points to navigate to. The Jet Propulsion Laboratory notes that the autonomous driving has allowed the rovers to travel further in a day than they would have been able to if commanded from earth. [26, 27]

In November, 2006, new software developed by Carnegie Mellon was tested on the rovers which produced planned paths for the rovers to follow. On February 7th, 2007 this software was placed in control of the rover. This new software expands on the rover's previous ability to avoid obstacles or hazards and now allows the rover to navigate based on a wide-area terrain map. This software was based on Field D*, which was created for the Army research laboratory and had previously been used to control other robots such as Carnegie Mellon's Crusher unmanned ground combat vehicle. [7]

Both rovers use imagery from stereo camera pairs and generate three dimensional terrain maps which are then evaluated for traversability and cost. The lowest cost path is selected, the rover advances by between one-half and two meters and then recalculates available paths. Additionally, the imagery is used to determine how far the rover has traveled and correct for slippage in the sand. Opportunity has driven over 230 meters and Sprit had driven over 1250 meters, autonomously. [26]

Planning for the rovers on the ground is done using MAPGEN software created at the Ames Research Center. A human controller uses MAPGEN to generate an activity plan to be sent to the rovers. MAPGEN, which is based on the EUROPA framework (developed for Deep Space 1's Remote Agent Experiment), is a mixed-initiative planning system which uses a simple temporal constraint network to model the plan that it is developing. The system can operate at a variety of levels of autonomy ranging from a completely autonomous mode, where the system attempts to generate a full plan inclusive of all requested activities and obeying all constraints, to a more limited autonomous mode where it places selected activities in to the schedule. [4]

On March 2, 2004 the European Space Agency (ESA) launched the Rosetta spacecraft. Rosetta was originally planned to rendezvous with the comet 46 P/Wirtanen, but due to a launch date postponement it will instead rendezvous with comet 67 P/Churyumov-Gerasimenko; in route, it has flown by the Steins asteroid and will fly by the Lutetia asteroid in 2010. Rosetta is a fully autonomous craft as necessitated by the communications delay (which may be as much as an hour), long periods of time where communication with earth is not possible, and long periods of hibernation to save power. The Rosetta architecture includes a command and data management unit, attitude and orbit control system, image processor, mode manager, TC manager, TM manager, science payload manager, mass memory controller, on-board maintenance module and Rosetta basic software (which provides low level services). [12, 15]

In 2005, NASA's Demonstrator to Test Future Autonomous Rendezvous Technologies in Orbit (DART) mission attempted an autonomous rendezvous. This mission resulted in the loss of both satellites due to a navigation system problem which caused the satellites to collide. [31, 50]

On July 4, 2005 the Deep Impact Spacecraft's impactor spacecraft successfully and autonomously guided itself to impact with the Tempel I comet. The mission yielded the highest resolution images of a comet nucleus and resulted in a successful illuminated impact. The mission also gave scientists the first look ever at the inside of a comet via the impact crater. The impactor craft was released from Deep Impact approximately 24 hours prior to the time of impact. The final two hours were the critical autonomous portion of the mission. During this time, the craft was under the control of the AutoNav system which commanded three maneuvers to align the craft with the comet nucleus. AutoNav is the same navigation system created for the Deep Space One mission. While issues arose with the Attitude Determination and Control System due to large reported discontinuities in attitude quanternion data, these were resolved through the use of attitude filter parameters. All mission objectives were achieved without reliance on the use of contingency plans. [10, 29]

In 2007, the US Defense Advanced Research Projects Agency's (DARPA) ASTRO and NextSat satellites demonstrated the first US in-space autonomous docking and separation. Despite a mechanical issue requiring a change to how NextSat was released, the mission was successful and demonstrated a technology that could be used in the future to allow autonomous attachment to repair or refuel satellites. Autonomy, in this situation, is important as intermittent communications failures could make the precision maneuvers required for docking problematic if performed by ground controllers. [50]

5. THE FUTURE OF AUTONOMY IN SPACE

It seems that, for autonomous craft in space, the best is yet to come. Research, mission concepts and planned missions promise to deploy autonomous technology in to space with progressively greater mission importance. Far from being just a mission-enabler, autonomous technology looks to become the mission commander both on earth and on-craft.

Future prospective autonomous crafts in space include NASA's Snakebots which are to be autonomous snake-like robots which can be used to explore planets. Unlike traditional wheel-based robots, the Snakebots will be able to disembark the lander without a ramp and climb, dig and crawl into cracks in the surface of the planet. The Snakebots are to be autonomous and incorporate obstacle avoidance and decision making facilities. [28]

NASA's Autonomic Nano Technology Swarm (ANTS) is an architecture for the development of autonomous clusters of robots. ANTS clusters are patterned after the insect world which has demonstrated that a group of specialists will outperform a group of generalists and be able to perform tasks which a single individual could not. ANTS researchers are working to create a software neural basis function which will act as a bridge between the lower level neural system which deals with basic functions and safety and the higher level neural system which engages in problem solving and other goal-oriented computation such as scheduling and planning. The Prospecting ANTS Mission, which could launch in the 2020's, would involve investigating the asteroid belt within the solar system using nine hundred approximately one kilogram craft. The fleet would include various specialty craft such as several types of worker units (each of which has a different instrument onboard) and communications and leader units. The craft would function autonomously, and have the capability to change mission goals based on information that was collected. They would aim to categorize one thousand or more asteroids in each year. Other uses for ANTS technology include the Autonomous Lunar Investigator mission which seeks to explore the polar regions of the moon. [11, 19]

JPL mission concepts for missions to Titan and Europa also involve autonomous operation. A Europa submersible would likely have limited contact with its mission satellite and no direct contact with earth due to operating under a layer of ice. Due to this (as well as distance delay limitations), this vehicle would need to be completely autonomous and would not be able to rely on real-time teleoperation via earth-based controllers. A submersible concept could be part of a 2020 NASA mission to Europa. The Titan Aerobot concept involves an airship-like robot which would use various sensors and directional radio frequencies such as those from the deep space network, the sun and the mission orbital satellite to navigate. It is projected that the Aerobot would encounter numerous environmental conditions and would, thus, need the capacity to adapt to the situation. The Aerobot would include an autonomous planning, execution, health monitoring and recovery system components. Test flights have been conducted in California's Mojave Desert which have included limited tests of the autonomous control system. [13, 20, 40]

The Google Lunar X Prize is encouraging significant interest in autonomous exploration. The competition requires a winning team to land a robot on the moon, travel 500 meters and transmit pictures, video and other data back to earth before 2014 (or before 2012 for a larger cash prize). [49]

The Swedish Space Corporation plans to launch its Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) spacecraft before February, 2010. PRISMA will be highly autonomous and demonstrate (from a guidance, navigation and control perspective) autonomous formation flying, homing and rendezvous, and proximity operations. The craft will also test several types of sensor technology. [14, 45]

A group of researchers at CalTech, the University of Arizona and the US Geologic Survey argue that more autonomy is needed. They note (as at 2005) that most space craft are not truly autonomous, which they define as including complete mission control such as goal identification, prioritization, navigation and other elements. Instead, they propose a new paradigm of multi-tier exploration craft. Under this model, a single or multiple satellites would deploy and command a set of airborne balloons or blimps which would deploy (deployment might also be direct from the satellite) and command a set of ground-tier rovers or other craft. The ground craft would pass observations to the airborne units which would pass this data, along with the data that they collect, to the satellites which would forward this, along with data collected by the satellite, back to earth. [16]

This approach, the researchers argue, would allow a more thorough exploration of the subject planet or moon as it would allow multiple areas to be studied in detail instead of the current model which generally studies only one area in detail or a wide area with limited detail. The researchers note that the understanding of the natural world is based on inferences, which are not made from a single observation but rather from numerous ones which are in many cases made at locations distant from each other. The new multi-tier approach, they argue, would allow more observations, covering more area. It would also create redundancy, prolonging the mission and allowing the investigation of areas which are of interest but would be too dangerous for a sole-craft (whose loss would end the mission) to explore. [16]

6. CONCLUSION

There is little doubt that artificial intelligence will continue to play a large role in spacecraft operations. With limited budgets, space exploration agencies and future private space operators will likely want to obtain the maximum benefit for their expenditure. Research and actual missions indicate that autonomous spacecraft are able to provide a higher level of return than a human operated one. They are able to go places where humans can not yet (due to life-support constraints), they are able to react faster using on-board AI than they could if they had to contact the ground for instructions and they are able to operate with a precision and redundancy that human operators would be hard-pressed to meet. Even for manned exploration, autonomous technologies will clearly have a role in preparing for these missions as well as supporting and assisting the humans who go on them. As such, the future of AI in space looks bright.

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