ADVANCING THE SCIENTIFIC FRONTIER WITH INCREASINGLY AUTONOMOUS SYSTEMS. R. B. Amini1, J. Castillo-Rogez and J. Day, 1Jet Propulsion Laboratory, California Institute of Technology, rashied.amini@jpl.nasa.gov.

Introduction: A close partnership between people and semi-autonomous machines has enabled decades of space exploration, but to continue to expand our horizons, our systems must become more capable. Increasing the nature and degree of autonomy - allowing our systems to make and act on internal decisions - enables new science capabilities. In the current Planetary Science Decadal (Vision and Voyages), increased autonomy was identified as one of eight core multi-mission technologies required for future missions. Both scientific and technological progress over the last decade has reinforced the necessity and demonstrated the feasibility of autonomous systems for planetary exploration. Specifically, autonomy is poised to enable new planetary missions and access to new environments, increase science return, increase resilience of mission systems, and reduce mission cost.

Six of the pre-decadal studies recently selected by NASA explicitly call for surface exploration at a wide range of planetary bodies as the natural next step in the exploration of targets whose scientific value was demonstrated by reconnaissance missions over the past decades. These missions require operating in challenging environments (e.g., Mercury, Enceladus, Triton) and/or require long-range mobility (e.g., Ceres, Moon). Other selected concepts, like the Pluto Orbiter and Kuiper Belt exploration missions must address the challenges of operation at an extreme distance. Over the longer term, NASA’s vision includes accessing the subsurface oceans of known ocean worlds. Successful accomplishment of these missions will require deployment of increasingly autonomous systems.

Continued technology development, both internal to NASA and strategically selected external investments, provides a rich field of solutions and capabilities to advance the use of autonomy in NASA missions. Advances in goal-directed operation, model-based reasoning, and situational awareness allows operators and scientists to focus on objectives and oversight, while the deployed system determines how to safely perform its assigned objectives. Progress in development of systems engineering processes, system and environmental models, and formal behavior specifications enable more rigorous analysis and “correct-by-construction” design specifications, leading to guarantees of system behavior. Further, advances in artificial intelligences and machine learning enable on-board learning and model adaptation that allow autonomous systems to adjust to conditions over the duration of the science mission.

Benefits and Advantages: One principal advantage of autonomous systems is their ability to (re)plan their own operations and respond to their environments. On-board planning enables missions and observations that need response to hazards, extreme and unknown terrains, and transient phenomena on timescales faster than possible than by involving ground systems. Rapid response to hazards is of particular importance for increasing the productivity of long-range mobile platforms. These include subsurface missions and other missions exploring hazardous environments, like cliffs, caves, and crevices on planets, satellites, and small bodies.

Other missions that are enabled by on-board planning are those where the typical ground planning cycle incurs a prohibitive cost or science penalty. For instance, mission concepts for Venus or icy moon landers are tightly time- or energy-constrained. These missions can dramatically increase productivity by autonomously determining how and what to sample with on-board planning and data processing, instead of waiting for uplink of sampling instructions from a science team on the ground. Although not resource restricted, prospective fast flyby missions of interstellar visitors like ‘Oumuamua and Comet Borisov may need to rely on autonomous targeting for close approach navigation and science planning depending on prior knowledge of the target and the available observation window.

Transient phenomena, such as dust devils and outgassing plumes, can be detected and observed in real-time, instead of reliance on serendipity. This extends to constellation missions that may require coordinated observations of transient phenomena observed from multiple vantage points, spatially distributed sensors in the case of fields and particles in giant planet systems, or distributed transmitters and receivers on multiple platforms, such as the CONSERT bistatic radar experiment on Rosetta and Philae.

Demonstrated Progress: Experience with the Curiosity rover offers a compelling and extensible case study in leveraging autonomy to increase mission science return. Curiosity has adopted limited autonomous features that have significantly benefited the mission. For instance, the AEGIS experiment on Curiosity, which autonomously selects targets for its ChemCam instrument and has resulted in additional
science return. However, Curiosity’s ultimate reliance on traditional planning results in 48% of sols being underutilized. By adding system-level planning that integrates path planning, data processing, and health monitoring features, Curiosity would be able to utilize most of this underutilized time [1]. These productivity enhancements are not limited to surface missions and apply to orbiter and flyby missions as well. Autonomy can permit more efficient mapping campaigns by tailoring science observations to current spacecraft state instead of relying on overly conservative a priori estimates.

In the last decade, new autonomous capabilities have been demonstrated that will improve spacecraft resiliency, reducing the risk of long-duration missions and missions that cannot reliably communicate with Earth. In the current operating paradigm, entrance into a spacecraft safe mode suspends science observations and restricts spacecraft functionality for periods of a few days or even weeks, depending on the nature of the anomaly. Based on historical data, about 50% of safings can be mitigated as the system decides to permit continued science operations or restores its own functionality [2,3]. Recent work in model-based diagnosis is an example of advancements that allow an autonomous system to achieve directed goals while working around anomalies [4].

New Opportunities and Next Steps: As the barrier to space is further reduced with lower cost launch opportunities and commercial-off-the-shelf space systems, new mission architectures utilizing large numbers of assets are now feasible. For instance, these can include constellations at Venus, Moon, and Mars and missions that survey large numbers of small bodies [5]. The operational complexity in managing a large number of satellites can be cost-effectively addressed using autonomy. Rather than developing and testing detailed command sequences for each spacecraft, autonomous capabilities such as goal-based commanding can be deployed that allow spacecraft to develop context-sensitive plans based on the directed goals. This approach has the promise of reducing required infrastructure investments and operator effort, especially for networked constellations. However, the benefits of autonomy can only be realized by addressing the engineering issues associated with integration and trust of these capabilities. Investment in system verification and validation, as well as integration and analysis approaches, will enable maturation and utilization of existing technology. Mature capabilities should be deployed on technical demonstrations and extended missions to further reduce risk.

Summary: The discoveries of the past two decades have resulted in new questions and new ambitions. In 2020, Mars Helicopter will perform the first powered flight beyond Earth – soon to be followed by Dragonfly at Titan. These missions are pathfinders for new technologies and modes of exploration. The portfolio of studies for the Planetary Science Decadal Survey further conveys the ambitions of the community. It is expected that the resulting concepts will set priorities for NASA’s technology investments for the next decade, which should include drivers for expanding existing autonomous software, the supporting hardware (e.g., computer), and testbeds that provide sufficient validation and testing of autonomous capabilities.

In order to advance the frontier of robotic space explorations, NASA must pioneer resilient, self-aware, and autonomous systems able to weigh risk and make decisions locally to ensure that tomorrow’s missions are a success. Application of advances in autonomous systems technology will dramatically increase science return by extending the reach, the productivity and the robustness of NASA missions. These technologies are critical to enabling missions such as rovers on Mars that can traverse a thousand kilometers, rugged submersibles under the ocean at Europa, long-duration balloons in the atmospheres of Titan and Venus, and autonomous explorers of the Kuiper Belt. These systems will have far greater reliability, reduced mission risk and significant reductions in development and operations cost.

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References: