**AUTONOMOUS SPACE VEHICLES OF THE FUTURE.** L. M. Fesq, R. R. Some, N. E. Lay, R. Castano, I. A. Nesnas, J. C. Castillo-Rogez, R. J. Doyle, and P. M. Beauchamp Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Ave, Pasadena, CA 91109 (Lorraine.M.Fesq@jpl.nasa.gov)

**Introduction:** Based on recent discoveries, some of the most intriguing science will demand more physically- and cognitively-capable robotic space explorers to push the boundaries of exploration. Examples of such exploration include searching for life by navigating the rugged surfaces of Ocean Worlds [1] (Europa, Enceladus, Titan, to name a few), sampling their plumes, and accessing and exploring their oceans. They may also span spelunking into the caves of Mars and the Moon, browsing the atmospheres of Titan and Venus, assessing the resource potential for exploitation of near Earth objects [2], and cruising to the Oort cloud or even a neighboring planetary system. Such ambitious missions will face similar challenges: (a) they will seek destinations and new worlds where little is known *a priori*, (b) they will need to conduct more sophisticated and complex operations for extended periods of time or under the stress of short durations to achieve their goals, and (c) they will need to react to unpredictable events and outcomes.

Advances in sensing, computing, communication, reasoning, design and materials will usher a new generation of explorers that will increasingly rely on their cognition to react and adapt to unknown environments and situations. *Smart sensors* will be capable of data processing with large paralellelism. Their abundance on a spacecraft will be enabled not only by their smaller footprint and decreasing power requirements but also by a wireless-communication backbone that will eliminate the complexity and weight of large connectors and harnesses. These highly capable robots will be able to see, touch, taste, and even smell their environment. This increased sensory and cognitive load will be handled through *advanced computing* and reasoning that will enable these robots to have situational and self-awareness. They will be able to detect, isolate, and diagnose faults and failures from their redundant sensing suite and be able to take appropriate action. They will be able to react immediately to events, rapidly optimizing their science return and replanning their missions consistent with overarching science goals and changing situations. Interplanetary robots to nearby bodies will communicate back to Earth via a deep space relay system at extremely high optical data rates compared to what can be done today while scientists, in a Virtual Reality room observe, interact, plan, analyze, command and suggest activities.

By 2050 many of the technologies identified in NASA's Technology Roadmaps [3] will be tested and available for routine use. The vehicles of the future will be highly capable and will be able to autonomously perform science goals and collect scientific data as defined by those goals. These vehicles will have computing capablilities that are orders of magnitude better than we have now. Three key technology areas will provide vehicles with these autonomous capabilities, and will be discussed in this paper.

**High Performance Spaceflight Computing:** Autonomy relies on capable avionics to host advanced algorithms. Recent investments in high performance computing by NASA's Space Technology Mission Directorate [4] are showing promising progress in developing low-power board-level flight computing products that will a) decrease downlink requirements for extended exploration to the Kuiper Belt, the Oort cloud and beyond, by orders of magnitude through onboard data processing, b) enable real-time processing needed for terrain relative navigation and hazard detection/avoidance during entry, descent and landing onto planetary objects, and c) increase detection of dynamic, transient events from 10% to 75%, thereby increasing science return.

Beyond 2050 we will likely have transitioned from standard Silicon, Gallium Arsenide based electronics to graphene, nanowires, spintronics and beyond. Neuromorphic computing will be established, and computer vision, machine learning (including deep learning) and scalable data analytics will be routinely hosted onboard and handled by custom hardware that is built into every computer. We will have extremely high density, high performance memories, processor-in-memory architectures and all that goes with a highly capable flight computing ecosystem: adaptable, composable and extensible.

**Wireless Communication:** Ubiquitous, wireless network connectivity will be a core element of future spacecraft autonomy. In much the same way that the "Internet of Things (IoT)" is permeating our daily lives with sensors and control for work and home, a highly connected, wireless ecosystem will become routinely available for use in spacecraft systems. Wireless interconnect will largely eliminate the need for custom wiring and harnessing, and opens the door for adding sensors without the mass and volume costs due to additional cabling. The extent of these additional sensors will enable fine-grained and continuous inspection of spacecraft health, resources and remote sensing observations. Dynamic access to this information will be driven by autonomy algorithms that control spacecraft operation and science planning. Beyond computing horsepower, extremely high density sensors and sensor processing – imagine a robotic skin - kinesthetic sensing, in general, will be significantly more capable than today's sensors – think vision into the deep UV and IR, audio into the deep ultrasound and, on the other end, extreme long wavelength. Power distribution will still require wiring but this is minimal and can be used for data distribution as well – primarily for intelligent power systems but also as a backup/back door for wireless, and perhaps for fault tolerance. This will eliminate much of the cost and difficulty of assembly, integration and test of new sensors and subsystems, (re)configuration of spacecraft electronics, and enable software defined spacecraft and similar concepts. It will also enable greater modularity, in particular, for self-assembling and self-organizing assets, such as large telescopes [5] or deployable solar arrays. The building blocks for realizing wireless network connectivity on spacecraft is now under development [6],[7].

**Self-aware and Self-directed Reasoning:** Autonomous space explorers will be able to perceive their environment and their internal state through the additional sensors that the wireless communications allow, to see, hear, touch and even smell in real-time. These explorers will be guided by higher level goals that can be flexibly executed instead of low-level, single-path commands. They will amass large volumes of data at high rates, and possess onboard abilities to organize and model the world around them. For example autonomous navigation must rely on the visual and gravitational knowledge gained while approaching a target, and build the reference shape and gravity model on approach in order to achieve orbit and map the target. They will have huge databases of knowledge at their disposal, and the intelligence to use these data both individually and as a team for learning, analysis, and decision making. These vehicles will have the ability to continuously monitor the system state, resources and health of its hardware including fault/failure detection, isolation, diagnosis, prognosis and repair/response through regrowth via 3D printing. Recent progress in health state estimation [8], planning and scheduling [9], and risk-aware execution systems [10] are now being integrated through internal research efforts at JPL to achieve system-level autonomy capabilities that will provide self-awareness and self-directed reasoning.

**Summary:** In the next 35 years, we envision current technological advancements trends to accelerate, especially in the areas of a) high performance computing – a natural technology multiplier for space missions that will provide orders of magnitude performance improvement over current spacecraft processors, b) wireless on-board communication that will eliminate the need for onboard data harnesses and thereby excellerate the proliferation of sensors, and c) self-directed and self-aware reasoning software that will assess vehicle state and its environment, determine what goals are achieveable, and plan activities to optimize science operations. These key technology areas will be instrumental in realizing NASA's vision to send robotic space vehicles to autonomously travel to the far reaches of and possibly beyond our solar system, in the quest to seek out life in the shadows of caves, under the water on icy moons, and in the atmospheres of alien planetary bodies.

**References:**

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