Robotic Communication Systems for Flexible, Sustainable, Affordable, and Autonomous Space Operations

A white paper prepared for NASA by

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Executive Summary

Space exploration will use humans and robots in partnership and leverage the capabilities of each where most appropriate and useful. For example, habitat modules, power systems, and human return vehicles can support human occupation on the Moon, would be landed autonomously, and assembled accurately by a group of communicating robots and sensors. A complex system of robots and sensors will complete their tasks only if supported by an effective communication network, and this white paper will discuss the properties of this communication architecture. Our main recommendations are that the communication infrastructure should consider end-to-end system-wide characteristics of sensing and actuation, constraints of power and computing resources, and interoperability. Moreover, the network platform must be evaluated early and continuously to ensure system efficiency and reliability. Such a communication network would enable flexible, sustainable, and affordable human-robotic space exploration.

An Example

Human exploration of Moon’s surface can be supported by a Wireless Surface Local Area Network (WSLAN) consisting of small solar-powered communication towers with simple switched patch antennas and access point transceivers, antennas, and access points on roving and fixed habitats. Each WSLAN subsystem routes voice, video, sensor streams, and data to and from space-suited humans, robots, sensors, rovers, and habitats. A WSLAN enables robots to coordinate their activities using video, sensor streams, control signals, and the exchange of software components. A companion subsystem has a microwave landmark capability whereby robots can determine precisely their position. Landmark capabilities are critical for example in a construction zone, which requires accurate landscaping and placement of structures. The WSLAN is the outpost of a space communication infrastructure that makes it possible to supervise autonomous robots from Earth-based, in-orbit, or CEV-based locations.

Past Assessment and Current TRL

The ultimate objective of communication networks is to enable the sustainable, affordable, and flexible exploration of the solar system. However, current space communication systems are monolithic, vertically integrated, mission-specific, and were not designed to support efficient space-to-space or ground-to-space communication among sensing and actuation units, such as robots or CEV. NASA centers and Cisco have supported the development of space-ground Internet Protocol that has evolved to mid-TRLs and that is flexible, affordable, and sustainable, but not targeted toward the communication between sensors, controllers, and actuation units. Sensor networks have been recently developed and are currently at TRL’s of 3-4 for terrestrial applications. Networks of sensors and actuators are used in manufacturing automation and vehicle control systems, but do not scale to the unstructured environments that are typical of space exploration.

Summary of Recommendations

The communication architecture should be generic and flexible so as to become affordable and sustainable. The technological approach should integrate communications, power, and robotic systems for an end-to-end evaluation of the design trade-offs and to achieve interoperability. The resulting system is complex, requires a high degree of interoperability, demands advanced levels of collaboration and interactivity, and should lead to the establishments of standards and practices. The technology should be continuously validated on a test bed that demonstrates the feasibility of the approach.

Detailed Recommendations

A. Robotic Communication Networks

A flexible communication suite should link sensing, actuation, and control units but it should also be independent of specific tasks or missions. The same communication platform should be used, for example, to interconnect nearby robotic assistants equally well as sensors and actuators in a crew exploration vehicle. A common platform would be flexible, affordable, and sustainable. An instantiation of such architecture is the Internet protocol suite, which is a programmable and manageable communication substrate to which new applications and software can be seamlessly added. The Internet forms a common architecture that leads to shared interfaces and re-usable systems. However, the Internet was originally designed to support bulk data transfer and remote log-in applications. Although its applicability has since extended to new domains and applications, there is relatively less work that addresses the Internet-enabled communication among sensors and actuators. For example, a networked robot should exhibit real-time properties, such as stability and tracking, in spite of communication vagaries (see [1, 2, 3, 4, 5, 6] for examples in this direction). Exploration poses special research, integration, and development challenges, which will described throughout this white paper.

> **Recommendation 1.** Internet protocols form an integrated communication substratum that can support flexible, sustainable, and affordable human-robotic missions, but they must be integrated with the communication requirements of sensing, actuation, and control units, as described below.

B. Systems Complexity

Robotic control software is complex and constantly evolving. A networked control system is the intricate composition of complex subsystems that collectively address the needs of sensing, actuation, communication, computing, and power supply. Complex control and robotic communication requires:

- Flexibility and interoperability to support different applications, protocols, and communication needs,
- The ability to coordinate multiple units and to aggregate robot teams into controllable units,
- Control evolvability, in terms of

    - Rapid re-programmability (addition of new functionality after hardware deployment),
    - Dynamic reconfiguration (creation of new collections of sensors, actuators, computers, robots, vehicles, and instruments into coordinated, task-oriented teams), and
    - Extensibility (growth through modular incorporation of additional assets),
- Adaptive power management,
- Adaptation to computing needs and resources,
- Survivability and fault-tolerance (automatic reallocation of communications software in response to component failures).

The requirements of complex applications can be supported by advanced middleware (e.g., for resource discovery that enables modular growth [2]) and overlay networks (e.g., to ensure an evolvable network). Furthermore, mobile software can support survivability and rapid re-programmability by allowing software component to stop their execution on one host and resume seamlessly on a different host [2]. A correct architecture will also ease the maturation of innovative technical contributions.

Recommendation 2. Control and robotic communication is complex and can only be supported by the extensive use of middleware, overlay networks, and software mobility.

C. Communication Network: Middleware for Adaptable Control

Networked control poses the unique challenge that the communication is closed through an end-to-end feedback loop, whose real-time characteristics affect the performance and stability of the connected physical systems. As a result, the communication infrastructure must adapt to long and unpredictable time delays inherent in space-communication. Communication adaptability must account for the physical dynamics of the embedded units and in particular it must exploit continuous or hybrid descriptions of the target physics. At the same time, communication adaptability must be flexible and sustainable, and in particular it must be applicable across a range of robotics or actuation units, and across missions [5]. Flexible adaptability can be incorporated in middleware or in generic software mobility behaviors.

Recommendation 3. Control and robotic communication must be adaptable to long and unpredictable delays. Adaptability necessitates an understanding of the underlying physics and affordable solutions can be implemented through middleware support.

D. Communication Network: Rate Control

A fundamental issue in networked systems is the rate at which networked units inject data into the network. Rate control is a broad issue that affects the traffic, performance, quality of service, and reliability of a network. Rate control has been extensively investigated in terrestrial networks, recently under the name of congestion control, for example. However, the state-of-the-art has focused mostly on bulk data transfers and streaming media, but little work has been done on networked control, where injection rates should be a function of the underlying physics and should strive for appropriate task or control-theoretical objectives. At the same time, rate control must be as flexible and generic as those implemented in current transport layers, and interoperable with them.

Recommendation 4. Control and robotic communication will need novel rate or congestion control algorithms to determine the rate and timing of data injection into a network. Rate control must depend on the target physical dynamics but must also be generic and flexible.

E. Communication Network: Space Internet Protocol

The Internet relies on IP (Internet Protocol) as a global network layer. Terrestrial IP embodies years of research, development, and deployment that have made it into a stable and robust architecture for terrestrial networks. As a result, IP is associated with a rich set of data link drivers that abstract the specifics of individual communication channels, transport solutions for reliable communications, and powerful middleware libraries that make it easy to write flexible and complete application within short time frames. Current work is extending terrestrial IP to space communication by taking appropriate measures to front the long delays and unreliability of long-haul space links (e.g., [7, 9, 10]). The migration to IP includes many facets such as, for example, the construction of appropriate data link drivers that will allow for interoperability with existing link types, a delay-tolerant architecture [7], and corruption- and delay-tolerant TCP [8, 9]. The transition of IP to space communication will have broad implications and, in particular, it is instrumental to supporting the evolution of applications, middleware, and overlays (as discussed under Recommendation 2). Space IP should mature and advance to higher TRL, especially in the context of networked control and of power management.

Recommendation 5. Terrestrial IP has proven to be flexible, affordable, and sustainable, and efforts should continue to port it to space communication and to evaluate it in the context of networked control and power management.

F. Test Bed

The communication architecture should be generic and flexible so as to become affordable and sustainable. However, it should also be grounded in a representative test bed. The evaluation process should be introduced as early as possible in the design of the communication infrastructure and pursued continuously throughout a project.

Recommendation 6. Network protocols and algorithms should be tested as early as possible on representative test beds of networked sensing and actuation units.

Conclusions

The recommendations above will enable the development of a sustainable, flexible, high performance communication network, which is a critical mission element for human-robotic space exploration.

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