NASA SBIR 2022 Phase I Solicitation

H6.23  Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration

Lead Center: ARC

Participating Center(s): JSC

Scope Title
Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration

Scope Description
Future deep space human missions will place crews at long distances from Earth causing significant communication lag due to the light distance along with occasional complete loss of communication with Earth. In deep space, crews will be required to manage, plan, and execute the mission more autonomously than currently required on the International Space Station (ISS) due to time delays and communication blackouts. NASA must migrate current operations functionality from Mission Control to the spacecraft to be performed by the crew and autonomous agents supervised by the crew so that the crew is not overburdened.

Novel capabilities for crews and ground staff will be required to manage spacecraft operations, including spacecraft and systems health, crew health, maintenance, consumable management, payload management, and activities such as food production and recycling. Autonomous agents with cognitive architectures could interface directly with the crew and with the onboard systems, reducing the cognitive loads on the crew, as well as perform many of the tasks that would otherwise require scheduling crew time. Cognitive agents can provide assistance, operate systems, provide training, perform inspections, and provide crew consulting, among other tasks. In addition, cognitive agents are necessary in many circumstances to respond to off-nominal events that may overload the crew, particularly when the event limits crew activity such as high-radiation events or loss of atmospheric pressure events requiring crew safety or sequestration.

Today, typical computer agents can easily perform super-human memory recall and computation feats, but at the same time are severely cognitively impaired in that they fail to recognize the values, implications, severity, reasonableness, and likelihood of the assertions they hold, and how inferences can be applied. The consequence is that computer agents often fail to recognize what is obvious and important to humans, appear to be easily deceived, and fail to recognize and learn from mistakes. Thus, crew interfaces to such typical computer agents for the current state of the art can be burdensome.

Due to the complexity of such systems and the need for them to be continually updated, the architecture must be modular, such that modules can dynamically be added, removed, and enhanced. Such a cognitive architecture is consistent with that proposed by Prof. Marvin Minsky in "The Society of Mind", 1988. The cognitive architecture is required to be capable of supporting multiple processes executing on multiple processors to be able to meet the expected computational loads as well as be robust to processor failure.

This subtopic solicits intelligent autonomous agent cognitive architectures that are open, modular, make decisions under uncertainty, and learn in a manner that the performance of the system is assured and improves over time. Cognitive agents for space applications need to adapt and learn from observation, instruction, and interaction as
missions proceed. The value of preprogrammed agents that do not adapt over time will diminish in extended missions. This subtopic will enable small businesses to develop both the learning technology and the necessary assurance technology within the scope of cognitive agents that forward base mission control to spacecraft and habitats and multiply the cognitive assets available to the crew. It should be feasible for cognitive agents based on these architectures to be certified or licensed for use on deep space missions to act as liaisons that interact with the mission control operators, the crew, and most, if not all, of the spacecraft subsystems. With such a cognitive agent that has access to all onboard data and communications, the agent could continually integrate this dynamic information and advise the crew and mission control accordingly by multiple modes of interaction including text, speech, and animated images. This agent could respond to queries and recommend to the crew courses of action and direct activities that consider all known constraints, the state of the subsystems, available resources, risk analyses, and goal priorities. Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable for providing crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true, necessitating this NASA investment.

An effective cognitive architecture would be capable of integrating a wide variety of artificial intelligence modules or managers depending on mission requirements. The following (nonexhaustive) list of managers provides capabilities useful for a wide variety of spacecraft cognitive agents:

State estimation manager: This manager’s capabilities include extracting information from sensors, including images, for use by other managers and by crew. State estimation includes separating signal from noise in sensor data, extracting and compressing useful information, along with fault management and prognostics. The state estimation manager must categorize information on both vehicle-wide and subsystem-by-subsystem bases, including crew health and performance, security, and scientific objectives.

Skill/behavior manager: This manager orchestrates execution of individual tasks on short timescales. This involves incorporating specialized knowledge needed for different tasks, e.g., orbit/trajectory planning, robotics operations, and spacecraft subsystem control. The skill/behavior manager includes a “smart executive” that robustly executes high-level plans produced by the planner/scheduler manager, on schedule, by coordinated commanding of multiple subsystems.

Planner/scheduler manager: This manager creates and updates plans and schedules that accomplish goals. This functionality involves maintaining lists of goals, priorities for achieving those goals, and spacecraft and mission-wide constraints.

Knowledge manager: This manager ensures that the system’s declarative knowledge is consistent and updated, including the incorporation of learned knowledge. Learning and modeling techniques capture system and operational knowledge from different types of knowledge sources; these must be incorporated into existing knowledge bases.

Human-machine interactions manager - Natural Language Processing (NLP), Extended Reality (XR): This manager enables multimodal interface/communications with the crew about the current and future state of the systems. This manager must communicate information from all other managers.

Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA software, with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable for providing crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true, necessitating this NASA investment.

Proposals should emphasize analysis and demonstration of the feasibility of various configurations, capabilities, and limitations of a cognitive architecture suitable for crew support on deep space missions and should address learning and adaptation during mission scenarios. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

Expected TRL or TRL Range at completion of the Project
2 to 5
Desired Deliverables of Phase I and Phase II
Research Analysis Prototype Software
Desired Deliverables Description
The emphasis of the proposed efforts is on analyzing and demonstrating the feasibility of various configurations, capabilities, and limitations of a cognitive architecture suitable for crew support on deep space missions. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

For Phase I, a preliminary cognitive architecture, preliminary feasibility study, and a detailed plan to develop a comprehensive cognitive architecture feasibility study are expected. A preliminary demonstration prototype of the proposed cognitive architecture is highly encouraged.

For Phase II, the Phase I proposed detailed feasibility study plan is executed, generating a comprehensive cognitive architecture, a comprehensive feasibility study report including design artifacts such as Systems Modeling Language/Unified Modeling Language (SysML/UML) diagrams, a demonstration of an extended prototype of an agent that instantiates the architecture interacting with a spacecraft simulator and humans executing a plausible Human Exploration and Operations Mission Directorate (HEOMD) design reference mission beyond cis-lunar orbit (e.g., Human Exploration of Mars Design Reference Mission: https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf), associated source code, and a detailed plan to develop a comprehensive cognitive architecture feasibility study suitable for proposing to organizations interested in funding this flight capability. Open-sourcing prototype agent and simulation software on https://github.com/nasa or a similar open-source platform is encouraged. A Phase II prototype suitable for a compelling flight experiment on the ISS is encouraged.

State of the Art and Critical Gaps
Long-term crewed spacecraft, such as the ISS, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in low Earth orbit and still require significant real-time support from Earth. Autonomous agents performing cognitive computing can provide crew support for future missions beyond cis-lunar by providing them robust, accurate, and timely information, and perform tasks enabling the crew more time to perform the mission science. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to onboard agents that team with flight crews to autonomously manage a spaceflight mission.

The majority of Apollo missions required the timely guidance of mission control for success, typically within seconds of an off-nominal situation. Outside of cis-lunar space, the time delays will become untenable for Earth to manage time-critical decisions as was done for Apollo. The emerging field of cognitive computing is a vast improvement on previous information retrieval and integration technology and is likely capable of providing this essential capability. This subtopic is directly relevant to the HEOMD Advanced Exploration Systems (AES) domain: Foundational Systems - Autonomous Systems and Operations.

Relevance / Science Traceability
There is growing interest in NASA to support long-term human exploration missions to the Moon and eventually to Mars. Human exploration up to this point has relied on continuous communication with short delays. To enable missions with intermittent communication with long delays while keeping crew sizes small, new artificially intelligent technologies must be developed. Technologies developed under this subtopic are expected to be suitable for testing on Earth analogues of deep space spacecraft, as well as the Deep Space Gateway envisioned by NASA.

References
IBM (Watson), Apple (Siri®), Microsoft (Cortana), Amazon (Alexa), Google (Dialogflow) are just a few of the companies developing intelligent autonomous agents. However, as they generally are proprietary, they do not meet the need of this subtopic. Importantly, these types of systems only contain limited knowledge about specific tasks such as making reservations or ordering takeout from a restaurant, but do not have the depth of knowledge to
represent and reason about the spacecraft systems and operations.

A survey of cognitive architectures can be found at: https://arxiv.org/pdf/1610.08602.pdf

Conferences that include cognitive architecture papers include International Joint Conferences on Artificial Intelligence (IJCAI), Association for the Advancement of Artificial Intelligence (AAAI), Advanced Computer Systems (ACS), Autonomous Agents and Multiagent Systems (AMAAS), as well as the ongoing Cognitive Architectures (CogArch) series of workshops.
