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Toward Human-Robot Interface Standards I: Use of Standardization and Intelligent Subsystems for Advancing Human-Robotic Competency in Space Exploration*

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ABSTRACT

NASA's plans to implement the Vision for Space Exploration include extensive human-robot cooperation across an enterprise spanning multiple missions, systems, and decades. To make this practical, strong enterprise-level interface standards (data, power, communication, interaction, autonomy, and physical) will be required early in the systems and technology development cycle. Such standards should affect both the engineer and operator roles that humans adopt in their interactions with robots. For the engineer role, standards will result in reduced development lead-times, lower cost, and greater efficiency in deploying such systems. For the operator role, standards will result in common autonomy and interaction modes that reduce operator training, minimize workload, and apply to many different robotic platforms. Reduced quantities of spare hardware could also be a benefit of standardization.

This paper discusses the need for, and benefits that derive from, human-robot interface standards from the perspective of stakeholders within NASA, in the academic community, and in industry. The discussion includes an assessment of the scope of the required standards and the extent to which existing standards are applicable and are able to meet the need. In addition, past initiatives to promote standardization and their implications for the current initiative are explored, current efforts to develop appropriate standards are described, and significant gaps and roadblocks are identified.

INTRODUCTION

THE VISION FOR SPACE EXPLORATION (VSE)

In January 2004, President George W. Bush announced "A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration," which directed NASA to implement a robust space exploration program. One month later, NASA published the "Vision for Space Exploration (VSE)," a framework that describes the guiding principles and roadmap for achieving the President's vision (NASA 2004).

The primary goal of the VSE is to "implement a sustained and affordable human and robotic program to explore the solar system and beyond," beginning with robotic missions to the Moon in 2008, followed by human return to the Moon by 2020 in preparation for human exploration of Mars. As part of the VSE, NASA intends to retire the Space Shuttle in 2010 and fly a new Crew Exploration Vehicle (CEV) no later than 2014. In addition, the VSE places significant emphasis on the development of joint human-robot systems.

A key difference from previous exploration efforts is that now exploration activities must be sustainable over the long-term. In particular, the VSE called for a significant reorganization and realignment of NASA's programs, personnel, and priorities. Most significantly, this transformation has resulted in the establishment of the Exploration Systems Mission Directorate (ESMD) and a major investment in exploration technology development (more than $2 billion per year) (NASA 2005a, 2005b).

ROBOTICS IN THE VSE

Robot systems have the potential to significantly enhance exploration capabilities, increase overall mission safety and success, and enable more robust handling of failures and anomalies. This is especially true for long-duration or deep space missions, both of which are complex and will require the crew to intermittently operate independent of ground control. Robots can perform "dull, dirty, or dangerous" tasks that are not sensible or necessary for humans to perform. Robots can also augment humans, helping to improve

Figure 1. Artist conception of humans and robots jointly building a space telescope (NASA).

performance in force, speed, precision, environmental exposure, etc. (Wilcox et al. 2005).

There are, however, two main issues concerning the use of robots in the VSE. The first is the need for a comprehensive plan for integrating, deploying, and using robotics in exploration missions (NASA 2005d). The second is that significant long-term investment in space robotics research is needed. Although industry and academic institutions and the military continue to invest heavily in terrestrial robotics, there is still a significant technology gap between what is commercially available and what is required for the VSE.

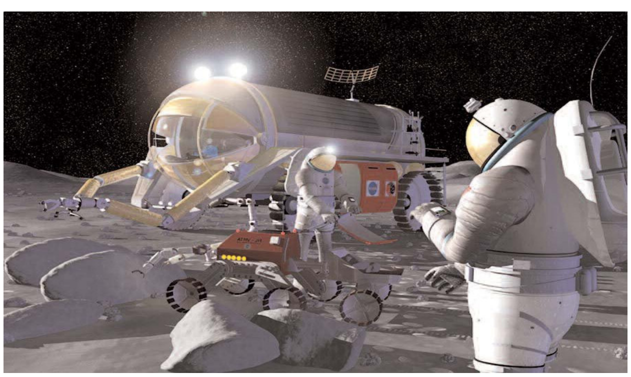

Figure 2. Artist conception of human-robot lunar exploration (NASA)

The Exploration System Architecture Study (ESAS), a study commissioned in May 2005 by NASA Administrator, Dr. Michael Griffin, recommended that robotics development focus on three areas: (1) human-system interaction (improve CEV operability, enable human-centered mission operations, facilitate human-robot teaming); (2) surface handling, transportation, and operations equipment (including surface preparation systems, material transport, and commodities distribution); and (3) surface mobility (transport and interact with EVA crew) (NASA 2005c). Two potential human-robot interactions enabled by this development are depicted in Figures 1 and 2.

The purpose of this paper, and a planned companion paper, is to promote standardization across the development spectrum for the human-robot interface. This paper will take a broader view of standardization, looking to the future while reflecting on past successes and opportunities. The second companion paper will follow with more detailed review of possible solutions in standardization that will complement future development activities.

THE NEED FOR STANDARDIZATION

Lunar and planetary surface exploration, construction, and mobility operations will be highly dependent on robots and piloted surface vehicles with varying levels of autonomy and functionality. Likewise, similar expectations are present for space-based construction, assembly, maintenance, and science missions. A key aspect of this dependency is the ability to effectively control these systems. Furthermore, the intended users of such systems will not be roboticists, and will face the need to complete extremely complex missions lasting months and years. In this environment, the need to deal with multiple complex and inconsistent robot interfaces will exact a high price in required training and in operational efficiency and crew workload. In the hazardous space exploration environment, it will also significantly increase mission and crew risks.

The types of users of these systems vary with the types of roles that the users perform (Scholtz 2003). These roles are delineated by the three *agents* that define the interaction space: humans, robots, and interfaces (Figure 3).

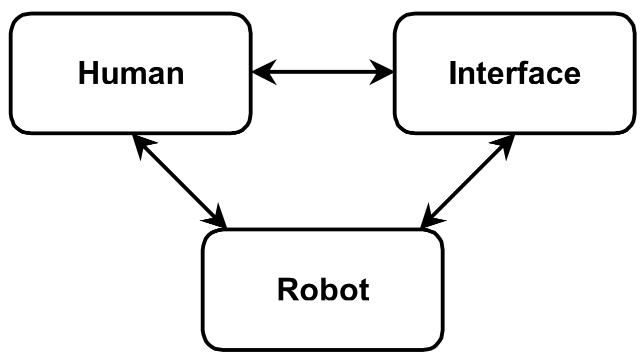

Figure 3. Human-robot interactions must be considered from multiple perspectives.

The Vision for Space Exploration implies large numbers of robots operating both remotely and in close quarters with humans. Remote interactions between the human and the robot are mediated by a workstation-based interface, but interactions in close quarters may or may not include such a mediating interface. The roles of the human in this three-way interaction include operator (either remote or proximate), engineer (of the interface and the robot), and bystander (as when a non-operator human is in close proximity to a robot). The call for standardization applies equally to the humans that will (a) interact with the robot either as operator or as bystander and (b) design, integrate, and maintain the robots. Both aspects of standardization are addressed in this paper.

SCOPE OF STANDARDIZATION FOR INTERACTION

The *fan out*, or how many robots (with similar capabilities) can be effectively controlled by a human, is currently less than or equal to one in most practical situations (Goodrich and Olsen 2003). This is largely due to a reliance on manual teleoperation for current systems. While there has been considerable work in this realm, such as McGovern (1990) and Fong and Thorpe (2001), it is clear to the robotics community that heavy reliance on this mode is not tenable as the number of robots needed increases.

As such, more robot systems will need to have some degree of autonomy in order to keep cost, inefficiency, and operational demands low. Having said this, one of the hallmarks of autonomous and mixed-initiative robots is their penchant for (a) getting themselves into trouble and (b) creating dangerous situations for those around them (Verma 2000; Steinfeld 2004). This is a major concern when operating in close quarters with humans, especially if they are not directly controlling the robot. Consistent interaction with such autonomy becomes increasingly important as a mechanism for reducing the incidence of such events and enhancing the operator's ability to recover safely and quickly.

Standardized methods of human-robot interaction (HRI) for mobile robotics do not exist at the present time. Therefore, it is necessary to develop, implement, specify, and test common methods of HRI for exploration support robots and piloted surface vehicles. These methods must be easily learned and preferably require low bandwidth and workload. Standardization will generate detailed specifications necessary for system development and serve as a cornerstone for enabling a sustained campaign of space exploration.

Furthermore, standardized HRI specifications will enhance safety by creating common methods of interaction between human and robot, thus reducing confusion, increasing speed, and enhancing predictability of robot and human behaviors. Standardized methods will also increase affordability and reusability by facilitating modular improvements and maintenance, consistent interaction with legacy robots, and reduced need for on-site robotics experts.

SCOPE OF REQUIRED STANDARDS FOR ENGINEERING: ANTICIPATED CHALLENGES

The need for establishing design and interface standards has long been recognized in space-based systems. To one degree or another, such standardization has been attempted in large programs such as the Hubble Space Telescope, Space Shuttle, and International Space Station. The degree of success has varied across NASA and industry and is directly related to the level of preplanning and the complexity of the program.

The incorporation and acceptance of design standards is a well-recognized method by which to reduce complexity and risk in designing complex systems. Furthermore, such standardization provides a basis for commonality across industry and diverse design houses. A typical goal of standards is to mitigate integration challenges when unique products, systems or users are required to come together and operate collectively.

Over the life of some past NASA programs, most recently during the long development time of the ISS, several standards have been created, used for a short period, and then changed or superceded prior to the final design of program systems. In order for standards to be adopted by program managers, they need to be clearly defined and have a basis for their requirement, without increasing the complexity or costs of the system.

An example of a successful design standard for manned space applications is JSCM-8080 (or NSTS 08080), Design and Procedural Standards Manual (NASA 1991). This standard was derived from earlier Apollo-based standards and is a collection of lessons learned and failures with guidelines and requirements to avoid these types of failures in current designs. The standard covers a diverse area encompassing general topics, electrical, fluids, materials and processes, mechanical, structural, and pyrotechnics. Each section is written for the respective topic with a section on the Statement of the Standard and a Remarks section, which gives the background on why the standard is imposed.

Two central reasons contribute to the acceptance and use of JSCM-8080. First and foremost, NASA manned applications often find this standard imposed as a program requirement. Also, due to its basis as a collection of lessons learned, it is broadly recognized as costly and increasing the risk to human life to ignore these standards on a program.

An approach to developing a working set of HRI standards would be to organize the standards with respect to the area of concern, such as general top level requirements, human interfaces, power interfaces, communication interfaces, mechanical interfaces, and thermal and fluid interfaces. As experience is gained and technology matures in a specific area, the respective standard can be modified and enhanced. Just as important is that as technology advances, out-of-date standards can be removed through sunset clauses. This will help ensure that the standards documents reflect current practices and technologies.

HISTORICAL PRECEDENTS: PROMISING PATHS AND PITFALLS

Robotics is a relatively new and emerging field with limited historical precedents. In the 1980's, mass production had occurred for industrial manipulators in factories. Around that same time, the US military also began developing unmanned reconnaissance and mine-clearing vehicles, including TTB (Technology TestBed), SARGE (Surveillance and Reconnaissance Ground Equipment), and the large-scale DEMO program. Commercial unmanned aerial vehicles (UAVs) and ground robots such as iRobot's PackBot and Foster Miller's Talon have only recently emerged as viable products.

Robots for space are still designed and produced as application specific individual units, with no two robots identical (except for possibly Spirit and Opportunity). For that matter, robots in space have a very limited history, starting with the Russian Lunokhods, the Shuttle Remote Manipulator System (RMS), Sojourner, the Viking manipulators, the Martian Lander trenching arms, the space station manipulator system, and the Mars Exploration Rovers. In NASA vernacular, the majority of all spacecraft are unmanned and also classified as robotic. We limit our scope of robots to robotic manipulators, mobile robots, and more advanced mobile manipulators. Thus, space has very few historical precedents due to the limited number of fielded systems. However, there has been a push to standardize as much as possible on the international space station, and the shuttle RMS uses the astronaut-familiar translation hand controller and a separate rotation hand controller.

The military ground robot community may set precedents for standards for all unmanned vehicles. In 1998, the Office of the Secretary of the Defense chartered the Joint Architecture for Unmanned Ground Systems (JAUGS) to be a working group, and mandated for use by all of the programs within the Joint Robotics Program (JRP) portfolio. Their first task was to develop architecture for the mobile robot domain, especially the upper level design interfaces. It should be noted that this project is a work in progress and was subsequently renamed the Joint Architecture for Unmanned Systems (JAUS) as it was broadened in scope to include all unmanned systems. JAUS has a goal of reducing the life cycle costs of all mobile robots, reducing the development and integration time for components (hardware and software), providing a framework for technology insertion, and accommodating expansion by adding new capabilities to existing systems. Essentially, the working group would like to create a plug-and-play capability such that all contributors (large companies, small companies, academia, and consortiums) could have their respective technologies fielded in larger operational systems. The interfaces specify data formats and methods of communication among its computing nodes. JAUS is changing to become an SAE standard (JAUS 2004).

The JAUS effort may be promising from a standards point of view. However, the focus has been on internal communication protocols (a.k.a. message sets), and is limited in its effort to describe the interface between the robot and the human. This effort has not gained traction with the entire community, and the majority of the key players have not yet committed to this standard. If it becomes accepted as an industry standard, then the key players will probably join in. One of the major obstacles with JAUS is its lack of details and definition (especially for implementation), and its vagueness such that many solutions fit within its confines.

EXISTING STANDARDS

At present, there are no formal standards (defacto or otherwise) for human-robot interaction (HRI). This is due primarily to: (1) the field of HRI is still in its infancy and common interaction design methods, operational models, and metrics have yet to be established; (2) many interaction techniques are highly application or task specific; (3) there is an incredibly diverse range of human-robot applications, even in "constrained" domains such as space exploration.

There are, however, standards that are highly relevant to the design of human-robot systems for space exploration. In particular, guidelines and procedures for operating industrial robots, for ergonomics and human engineering, for graphical user interface design, and for operating space hardware systems can all be applied to the development and use of such systems.

INDUSTRIAL ROBOTS

In 1987, the Occupational Safety and Health Administration (OSHA) published guidelines for the safe operation and use of industrial robots (OSHA 1987). These guidelines describe safety practices for selecting and installing robots as well as necessary employee training. The 1987 OSHA guidelines are based upon safety standards defined by the American National Standards Institute (ANSI 1986) and the National Institute for Occupational Safety and Health (NIOSH 1984). The ANSI standard defines consensus provisions for robot construction, modification, installation, safeguarding, maintenance, and testing. The NIOSH Alert contains safety recommendations (including robotic design, training, and worker supervision), based on a field evaluation of the first identified robot-related fatality in the United States.

ANSI, in partnership with the Robotic Industries Association, has published numerous standards for industrial robots including robotic definitions, engineering guidelines, evaluation criteria, testing requirements, and safety requirements:

- ANSI/RIA R15.06-1999. Provides guidelines for industrial robot manufacture, installation, and safeguarding to enhance the safety of personnel (ANSI 1999a)

- ANSI/RIA R15.02-1-1990. Presents human engineering guidelines for the design of operator control pendants for industrial robots and robot systems (ANSI 1990)
- ANSI/RIA R15.05-1-1990 (R1999). Defines the most important performance criteria and a method for evaluating robot point-to-point and static performance, including performance classes, standard test paths and standard test loads (ANSI 1999b)
- ANSI/RIA R15.05-2-1992 (R1999). Defines the fundamental dynamic path-related performance characteristics and provides a method to quantify dynamic performance (ANSI 1999c)
- ANSI/RIA R15.05-3-1992 (R1999). Provides the minimum testing requirements that will qualify a newly manufactured of a newly rebuilt industrial robot to be placed into use without additional testing (ANSI 1999d)

HUMAN ENGINEERING (ERGONOMICS)

Two well-known standards for ergonomics are NASA's "Man-Systems Integration Standards (MSIS)" (NASA 1995) and MIL-STD-1472F (Department of Defense 1999). NASA created MSIS (also referred to as NASA-STD-3000) to provide a single, comprehensive document defining all generic requirements for space facilities and related equipment that directly interface with crewmembers. The standard includes human-systems integration design considerations (including anthropometry and biomechanics), design requirements, and example design solutions for the development of manned space systems. The MSIS is based on numerous human engineering standards and terrestrial data from many other NASA, military, and commercial human engineering standards applicable to space environments.

MIL-STD-1472F establishes general human engineering criteria for the design and development of military systems, equipment, and facilities. The standard contains extensive, detailed requirements for control/display integration, audio and visual displays, controls, labeling, workspace design, etc. It also describes general requirements for standardization, function allocation, human engineering design, fail-safe design, interaction, safety, and ruggedness. MIL-STD-1472F was developed for use by the U.S. Department of Defense to contractually specify human engineering design criteria for detailed design phases such as engineering and manufacturing development.

USER INTERFACE

When humans and robots communicate, the dialogue is mediated by an interface. Some interfaces, such as text-based command languages, offer great power and flexibility but have an associated high learning cost. Other interfaces, such as option menu or direct manipulation (point-and-click) displays, are easier for novices, because they make few assumptions about what the user knows. Regardless of type, however, an interface is effective only if it is well designed.

User interface design, particularly for computer displays, often follows a sequential approach. Task analysis is performed to identify design objectives, which lead to detailed requirements. These specifications then guide implementation and serve as a basis for evaluation. Among the more widely used design methods are heuristic design, guidelines (e.g., style-guides), and iterative design (rapid prototyping).

For example, two frequently used computer interface guidelines are the "Apple Human Interface Guidelines" (Apple 2005) and the "Microsoft Windows User Experience" (Microsoft 1999). Both guidelines are designed to assist developers in creating graphical user interfaces (GUI) that are efficient, effective, and consistent across applications. These guidelines are widely recognized as de-facto standards, serving as part style guide and part design reference (incorporating numerous user-centered design principles).

STANDARD OPERATING PROCEDURES FOR SPACE ROBOTICS

Excluding teleoperated spacecraft (satellite or otherwise), few robotic systems have been used in space. Those that have been used successfully are widely recognized (e.g. RMS and the Mars Exploration rovers). Because of the extremely high development cost of these systems (e.g., the Space Station Remote Manipulator System was built at cost of $896 million), and the risks associated with launch and deployment, significant emphasis is placed on establishing detailed usage specifications and standardized operating procedures (i.e., checklists). For example, the "Mobile Servicing System (MSS) to User (Generic) Interface Control Document" defines the physical and functional interfaces that are provided by the International Space Station's (ISS) Mobile Servicing System to payloads, pallets, and Orbit-Replaceable Units (ORU's).

Given that the assembly and maintenance of the ISS relies heavily on robotic systems (primarily extra-vehicular), the design of controls and displays is essential for enhancing operator performance and for reducing the possibility of errors. Consequently, Currie and Peacock (2002) have proposed a set of design guidelines based on human factors considerations. These include: workstation topography and design; graphical user interface commonality within and between systems; adequacy of alignment cues for maintenance of safe approach and mating corridors during berthing tasks; spatial awareness challenges; integration of supplemental computer graphic displays to enhance operator global situational awareness; and methodologies to preserve critical skills during long-duration missions.

A PATH TO STANDARDS

As the preceding discussion has shown, there is an immediate and critical need for HRI standards for the space exploration enterprise if the vision of a robust and sustainable space exploration effort enabled by effective cooperation between robots and human explorers is to be realized. However, the barriers to their creation and effective implementation are significant and the history of many previous efforts in the space flight community is less than encouraging. Success will require a determined and coordinated effort that begins now in the formative stages of the enterprise and persists throughout its lifetime.

The most significant barriers to the success of the standardization effort we envision include:

- Lack of precedents for effective standards of this type within the space flight community
- Resistance in the design community to adopt standards that can restrict system development choices and design optimization
- Program structures that tend to isolate individual vehicle or mission programs administratively and technically
- Limited dialog and a lack of common perspectives and understanding between the human support and robotics technical communities
- Technical uncertainty associated with the early developmental stage of the robotic and mission systems that will comprise the exploration enterprise
- Requirements uncertainty associated with current levels of exploration mission definition
- Methodology for verifying that systems meet all required standards, even across international boundaries

To overcome these obstacles, we propose an effort that will:

- Make the case for and gain the commitment of Constellation program management to the creation and implementation of effective human-robot integration standards at the enterprise level
- Engage the key stakeholders in a dialog to establish a shared vision of and commitment to the standards process in this key area
- Draw heavily on the practices and, where appropriate, the content of existing successful standards and standards development efforts (such as IEEE and ANSI standards development groups and procedures)
- Identify key areas where industry standards can not be leveraged, and new standards must be developed specific to the space industry
- Develop open standards that reflect and accommodate current knowledge gaps through provisions for extensibility and evolution
- Maintain and evolve those standards through the life of the enterprise

The support and commitment of Constellation program management is essential for success. Human-robot interface standards will be truly valuable only if they cut across missions and vehicles to provide a consistent set of interface design standards for robotic and human support systems and consistent interfaces to the astronauts who will use them. Management commitment is essential to sustain the effort required to develop the standards and provides the muscle that will be required to ensure that they are followed in the face of contrary pressures in specific systems and missions. To gain that commitment and support, the discussion that has been begun in this paper must be extended to involve more of the stakeholders in the exploration enterprise. The benefits of the envisioned standards and costs that will result from their absence must be more clearly defined and communicated together with the process by which they will be created and applied.

The participation of key stakeholders representing robotics technology interests, human support systems, vehicle systems, exploration science, and mission operations is necessary to define a framework for the standards that can accommodate the range of human-robot interactions that will ultimately be required in the context of realistic technologies and capabilities on both sides of the interface. This dialog is the best way of combining today's best vision of what needs to be done, how it will be accomplished, and under what conditions with an assessment of the uncertainties in that vision that will define the essential provisions for extensibility. The participation of a broad cross section of stakeholders in the process will establish the necessary foundation for a community commitment to the standards that emerge by establishing broad ownership and making the standards truly workable and useful.

Standards development practices that have proven effective in successful efforts in the past are expected to benefit the development of human-robot interface standards. The formation of a standards development team with voluntary participation that includes a broad cross section of stakeholder perspectives is envisioned. One process that may be particularly useful is the approach used by the IEEE Standards Association (IEEE SA), as shown in Figure 4. This approach is based on a well-defined structure for standards sponsorship, community review and comment, and continued, on-going evaluation of the standards. This ensures that issues addressed in the standards are not restricted to the knowledge and experience of the (necessarily small) standards development team.

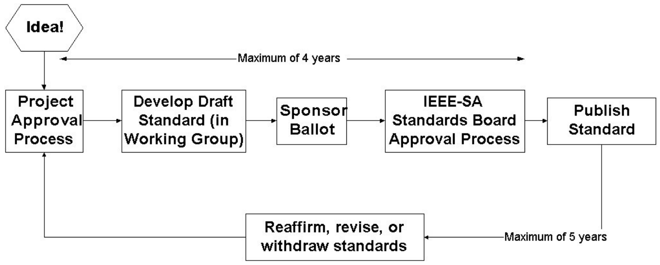

Figure 4. The IEEE Standards Association (IEEE-SA) uses a well-defined process to develop standards.

OPPORTUNITIES TO INFLUENCE EMERGING REQUIREMENTS

In support of the VSE, near-term programs that can influence and benefit from standardization initiatives include CEV/CLV, the NASA Robotic Lunar Exploration Program (RLEP), and continued support of the ISS. CEV's targeting 2012 to 2014 for its first launch and RLEP2 is expected to launch in early 2011. The ISS is expected to be operational thru 2016 and will likely continue thru 2020. System Requirements Reviews (SRRs) and subsequent preliminary and critical design reviews (PDRs and CDRs) for some of these programs will be taking place as early as 2008. The ISS provides a unique opportunity as an existing platform to accelerate thru DTOs or system upgrades the validation of potential design solutions that relate back to standardization initiatives. The lead-time to develop new standards (perhaps up to 4 years) as depicted in Figure 4 and the onset of these new programs shows the immediacy of taking steps if the benefits of standardization are to be realized.

CONCLUSION

There is a need for HRI standardization as NASA transitions to the Constellation program as outlined in President Bush's Vision for Space Exploration. Effective standards will benefit the engineer by reducing development lead times; the standards will benefit the operator by converging on autonomy and interaction modes as well as reducing training and operational workload. Best practices currently used in existing standards development groups will be leveraged to help in creating an HRI standard for space applications. A follow-on paper will be written to (1) identify specific areas for standardization and (2) provide an initial roadmap for standardizing the human-robot interface for space exploration.

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