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Joint Technical Architecture for Robotic Systems (JTARS)—Final Report

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March 2006

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Document Description

This document represents the final report for the Joint Technical Architecture for Robotic Systems (JTARS) project, funded by the Office of Exploration as part of the Intramural Call for Proposals of 2005. The project was prematurely terminated, without review, as part of an agency-wide realignment towards the development of a Crew Exploration Vehicle (CEV) and meeting the near-term goals of lunar exploration.

Executive Summary

Recognizing the need for interoperable robots to accomplish the new exploration initiative, NASA's Office of Exploration Systems Research & Technology established the Joint Technical Architecture for Robotic Systems (JTARS). JTARS charter was to identify the interface standards necessary to achieve interoperability among space robots. A JTARS working group (JTARS-WG) was established comprising recognized leaders in the field of space robotics, including representatives from numerous NASA centers along with academia and private industry. The working group's early accomplishments included identifying key issues required for interoperability, defining which systems are within the project's scope, and framing the JTARS manuals around types of interaction and classes of robotic systems. Significant work remained on the task including identifying standards, establishing an electronic database of systems, and a establishing a program to ensure agency-wide adoption of the JTARS guidelines.

Introduction

In January of 2004, NASA was given a presidential directive to "gain a new foothold on the moon and to prepare for new journeys to the worlds beyond our own." As part of this initiative, NASA is focused on returning to the moon by 2020 to serve as the launching point for missions beyond. Robotic probes were expected to be on the lunar surface by 2008, with a human mission as early as 2015, "with the goal of living and working there for increasingly extended periods of time."

To achieve NASA's mandate for creating a sustainable campaign of space exploration, a paradigm shift will have to occur in the space robotics industry. Specifically, robotic systems-of-systems must be realized through a renewed focus towards interoperability, modularity, and reuse. The practice of developing unique mission-specific components communicating through custom user-defined interfaces will have to give way to standardization.

The focus of lunar and Martian expeditions will extend from early exploration, to site preparation, to long-duration habitation. Given the hostile environmental conditions, each of these activities will require the extensive use of robotic systems. Such ambitious objectives will introduce tremendous new challenges – requiring system planners to think far beyond simply getting to the remote location safely and taking pictures or measurements. Robots that operate independently of one another, like those seen in the past (e.g. Sojourner, Spirit/Opportunity), will be inadequate to accomplish the complex tasks associated with these challenges. Rather, complex systems-of-systems will be required in which robots work cooperatively by widely exchanging information, planning and dividing complex tasks, sharing common resources, and physically cooperating to manipulate objects. The challenges associated with cooperative robotics are many, including communications, smart mechanisms, control, autonomy, physical compatibility, sensor processing, and operator control.

The development of the Joint Technical Architecture for Robotic Systems (JTARS) is funded by NASA's Advanced Space Technology Program (ASTP) in the Office of Exploration Systems Research and Technology (ESR&T) [2]. In January of 2005, the JTARS working group was tasked with establishing the technical architecture by which interoperable space robots capable of cooperative behavior can be developed. Once established, the JTARS architecture will be used by those involved in the acquisition, development, or management of new or improved robotic systems within NASA. The JTARS working group is scheduled to complete its task in 2008, but the resulting documents will be updated periodically.

A similar theme of standardization, interoperability, and reliable intercommunication was introduced ten years ago in the Department of Defense (DOD). In an effort to achieve those goals, the Asst. Secretary of Defense issued a directive to principals to "reach a consensus of a working set of standards" and "establish a single unifying DOD technical architecture (TA)…" so that "new systems can be born joint and interoperable, and existing systems will have a baseline to move toward interoperability." From that directive, the Joint Technical Architecture (JTA) was created. Though now superseded by DOD's Information Technology Standards Registry (DISR), the JTA was established to mandate the minimum set of standards and guidelines for acquisition of all DOD systems that produce, use, or exchange information. JTARS has a similar charter but with space robotics as its focus.

JTARS is a joint technical architecture that identifies required standards, protocols, and practices to be used for NASA robotics. In this context, the term "joint" refers to the architecture being crosscutting, equally applicable to in-space, aerial, surface, and subsurface robotic systems. Following the concepts put forward in the JTA, the term "architecture" refers to the structure of components, their relationships, and the principles and guidelines governing their design. As shown in Fig. 1, JTARS is part of an interrelated set of views: operational, system, and technical.

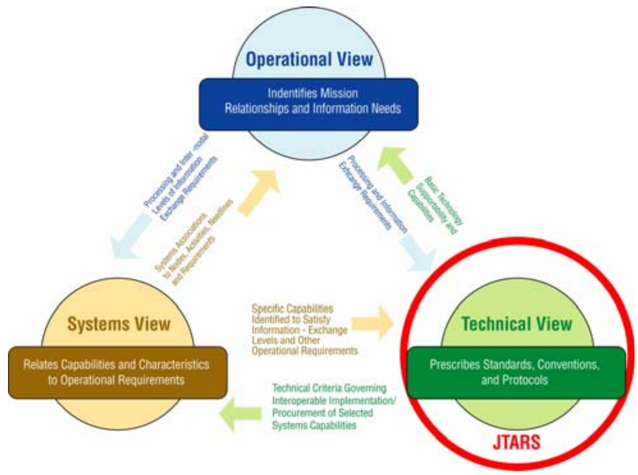

Fig. 1. Interrelated views [1]

The **operational architecture** contains descriptions of the operational elements, their assigned tasks and activities, and the information flow required between them to complete the mission. It also details the nature of information exchanged in sufficient detail to determine specific interoperability requirements.

The **systems architecture** is a description of systems and interconnections supporting mission functions. It shows how the systems interoperate, and it details the operations of particular systems within an architecture. The systems view of a single system includes descriptions of the physical connections, location of key nodes, circuits, networks, platforms, etc. It also specifies system and component performance parameters (e.g., total dose, mean time between failures, operating speed, etc.).

The **technical architecture** provides guidelines upon which engineering specifications are based, modular elements defined, and product lines developed. It includes a collection of the technical standards, conventions, and rules with criteria that indicate which are appropriate for a particular product.

Benefits

There are many benefits to standardizing space robots. The most obvious benefits would come in the form of enhanced capabilities, cost savings, and risk reduction.

Enhanced Capabilities

Standardization would prove invaluable in creating cooperative systems capable of being controlled by common operator stations. Advanced robotic systems-of-systems with individual units working cooperatively could potentially meet the upcoming technical challenges including off-planet resource extraction and processing and habitat construction and maintenance.

Cost Savings

Clear and relevant standards could serve as guidelines for acquisitions, both during development and qualification. Such standards would promote competition by effectively "leveling the playing field." This would allow for smaller companies to enter the market by reducing the high research costs associated with developing mission-unique systems. This increase in competition would ultimately lead to better product selection and cost reduction.

It is also expected that standards-driven systems would be more modular in nature, leading to the sharing and reuse of components. Finally, standards-based systems would be easier to validate and verify through the use of common reusable test sets and simulators.

Risk Reduction

The most significant risk reduction would likely come from eliminating unique "one of a kind" systems, and replacing them with robots equipped with well-understood interfaces and capabilities. Reliability is also expected to improve as the designs are verified and reused.

By increasing competition, the risks currently seen by being tied to a small set of vendors would also decrease. Finally, the JTARS manuals are expected to be "living documents," useful in distributing lessons learned, and thus helping to ensure that all vendors are aware of important design considerations.

Project Goals

The four high-level goals associated with JTARS and their relevant impact on Exploration Systems Research & Technology goals are discussed below.

Establish a comprehensive working group of senior contributors to NASA robotics

JTARS is being developed by a working group comprising representatives from seven NASA centers as well as experts from industry and academia. Dr. Bradley of NASA LaRC serves as the project's principal investigator and working group chairman. Many recognized experts working in NASA robotics are actively participating in the working group.

The working group openly invites additional participation from industry and academia, as well as from the international space community (e.g. DLR, JAXA, CSA, ESA, JSA, etc.). Working group contacts as well as the past meeting schedule can be found at www.jtars.org.

Relationship to Broader ESR&T Goals

The establishment of a comprehensive working group of senior robotics engineers assists ESR&T in advancing the current state of the art in space robots. The group will assist in the identification of standards necessary for creating robots capable of interoperating to accomplish difficult tasks. The group will also work to create an open dialogue between NASA centers, industry, and researchers as they focus on the many challenges facing exploration.

Identify and document recommended standards and protocols for NASA robotic systems

The JTARS working group is tasked with identifying and documenting the standards, protocols, and practices necessary for creating interoperable space robots. It is expected that two volumes will be generated, one identifying recommended standards and practices, and a second identifying emerging technologies. The documents will identify both "core" elements common to all systems and application-specific standards organized into corresponding domains. The expectation is that future NASA robotic systems that fall within the scope of JTARS will be developed compliant with the JTARS recommended standards. Provisions will also be provided to accommodate legacy systems. Systems will ultimately be identified as "JTARS-compliant," indicating that they follow the prescribed standards, protocols, and practices.

Relationship to Broader ESR&T Goals

The development of JTARS manuals will provide NASA robot developers with a comprehensive set of guidelines prescribing standards, protocols, and practices. Such uniformity will help to ensure long term product reusability, which will result in cost reduction. Standardization will further enable more complex robotic networks by allowing better intercommunication and cooperation.

Develop an online JTARS resource

JTARS will be an evolving knowledge base, one that must keep pace with advancing technologies, technical challenges, the marketplace, and the associated standards upon which it's based. The JTARS manuals would therefore be "living documents," updated periodically by a small subset of the working group. As part of the JTARS effort, the working group would set up a NASA website where the most current JTARS documents could be downloaded, minutes from the working group meetings reviewed, and change requests processed. An online technical database will also be developed to provide developers and integrators information detailing how current robotic systems align with JTARS recommendations – helping to reduce risk, lower cost, and avoid interoperability problems.

Relationship to Broader ESR&T Goals

The online resource would allow engineers to search a technical database of robotic systems, detailing system specifications and their respective alignment with JTARS recommendations. Sharing of compliance information would help to facilitate interoperability, technical exchange, and cost reduction. The manuals and meeting minutes would also be available to disseminate the latest JTARS information. The resource will facilitate interoperability, technical exchange, and cost reduction.

Ensure End-User Product Adoption

With product adoption in mind, JTARS emphasizes participation by end users, including NASA engineers, industry developers, academic researchers, and international partners. It also leverages the expertise of technical standards programs and synergistic activities both inside and outside the agency (e.g. NASA's Technical Standards Program [3], DOD's JAUS [4], and NIST's ALFUS [5]).

The final year of the proposed 4-year effort would shift the working group from investigating standards and drafting recommendations to ensuring NASA-wide adoption. This will be accomplished though on-site presentations and training throughout NASA as well as within industry and academia. Suggestions and corrections resulting from the outreach activities will be reviewed and implemented prior to the first official release of the manuals. Once released, system developers will use JTARS to facilitate the development of systems that are capable of cooperative behavior, intersystem interoperability, and long-term reusability. System integrators will use JTARS to foster the integration of legacy and new systems.

Relationship to Broader ESR&T Goals

The widespread adoption of JTARS will ensure that the benefits of standardization are achieved across the agency. End-user briefings will serve as a valuable outreach effort and is inline with the philosophy of creating "One NASA."

Scope and Focus

NASA has many systems under development, from satellites to rovers, many of which can be considered "robotic" in nature. An important milestone of the JTARS Working Group was therefore to clearly define the scope of the effort, specifically answering the question, "What systems fall within the charter of JTARS?"

Two broad approaches were considered. One divided systems based on where and how they were used, the other divided systems based on capabilities. Ultimately, the approach based on capabilities was adopted, because it greatly simplifies the identification of what systems are within the scope of JTARS.

Fig. 2 illustrates how three metrics are used to determine which systems fall within the scope of JTARS. The metrics considered descriptive of robotic systems are processing capability, communications, and the ability to physically interact with the world.

Systems that meet a minimum level of all three metrics fall within the scope of JTARS. Within the "core" bounded region, sub-regions can be identified to indicate systems with advanced capabilities. It is expected that JTARS will levy additional recommendations on more capable systems enabling them to perform advanced cooperative activities. Therefore, there can be different levels of compliance depending on system capabilities. Note that the specific boundaries are not yet defined, and are likely to shift over time as technologies advance.

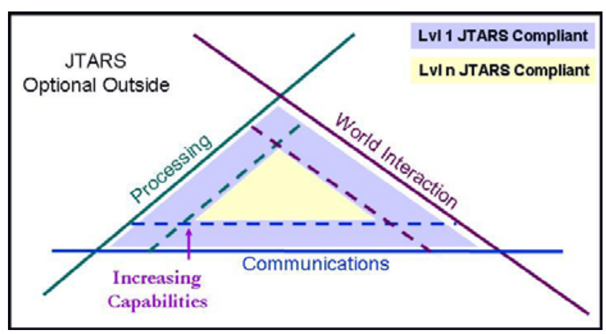

Fig. 2. Metrics to determine scope

There are several important implications that result from our definition of what systems fall within the scope of JTARS. Specifically, the definition suggests that JTARS applies to robotic systems independent of their:

Location (e.g. Mars, Earth, moon, in-space, etc.)

Function (e.g. rovers, station crawlers, air vehicles, etc.)
Level of autonomy (teleoperated to fully autonomous)

An important exception is that JTARS requirements should not supersede higher-level system-use requirements. For example, for robots used on the International Space Station (ISS), ISS requirements should supersede JTARS for similar specifications. However, this exception will be mitigated as future systems-of-systems directly leverage the standardization offered through JTARS.

Content

JTARS is robot centric in that it prescribes how a robot should interact with other systems, whether they are additional robots, sensors, payloads, satellites, etc. Fig. 3 illustrates the robot-centric view.

The specific format or technical content of the JTARS manuals has yet to be fully defined. What is known is that two manuals will be developed, one that prescribes existing technologies, and a second that identifies promising future technologies. The documents will identify both "core" elements common to all systems and application-specific standards organized into corresponding domains and subdomains.

High-Level Topics

Four high-level (Level 0) topics have currently been identified: physical interactions, information exchange, command structure, and reference frames.

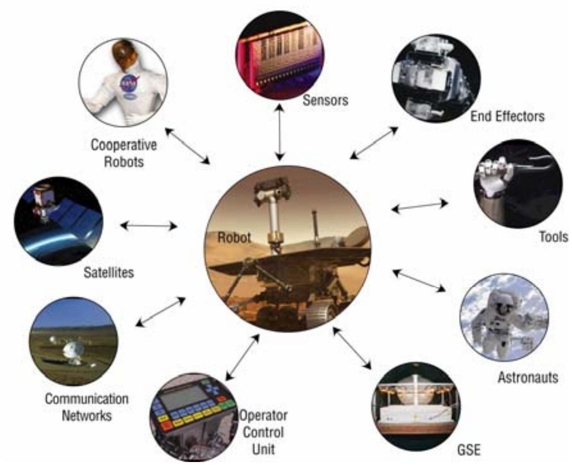

Fig. 3. JTARS robot-centric view

Physical Interactions

Standards will need to identify physical interactions associated with robots working cooperatively, including (but not limited to):

end effectors
tools
mounts and hard points
maximum loads
workspace constraints
electrical mates

Information Exchange

Defining the methods of exchanging information between robots and/or supporting systems requires the identification of an interconnection standard and a message set. The working group is currently considering the International Organization of Standards Open Systems Interconnection (OSI) 7-layer model for the interconnection standards, and the Department of Defense's Joint Architecture for Unmanned Systems (JAUS) for a message set. The important features of each are listed below.

OSI Model
As shown in Fig. 4, the OSI model defines a networking framework for implementing protocols in seven layers. Other variants (e.g.

5-layer) have also been proposed. With either model, control is passed from one layer to the next, starting at the application layer in one station, proceeding to the bottom physical layer, then over the channel to the next station and back up the hierarchy of the receiver. Additional information can be found at the International Organization of Standardization, www.iso.org.

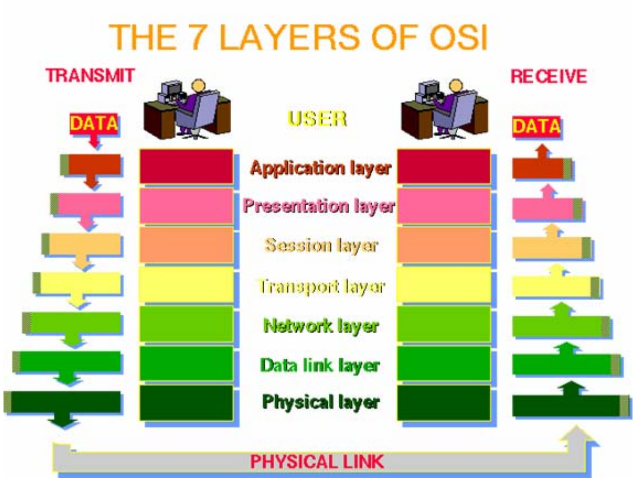

Fig. 4. OSI layers [7]

JAUS Message Set

The Joint Architecture for Robotic Systems was developed by the Department of Defense as a common message set between unmanned systems. It is currently being converted to a Society of Automotive Engineering (SAE) standard. JAUS addresses many of the important considerations of communicating between unmanned (robotic) systems, including:

Commands/Sequences
Responses
Queries
Data
Events
Periodic Communications

Command Structure

For robots to cooperative effectively, a command structure will need to be defined. The command structure will serve as a policy for processing commands, sharing data, and changing the authority structure within individual units or across the larger system. The structure would define which system(s) had authority to direct subordinate systems. Fig. 5 is a simple illustration showing how the command structure would influence the handling of incoming and outgoing information.

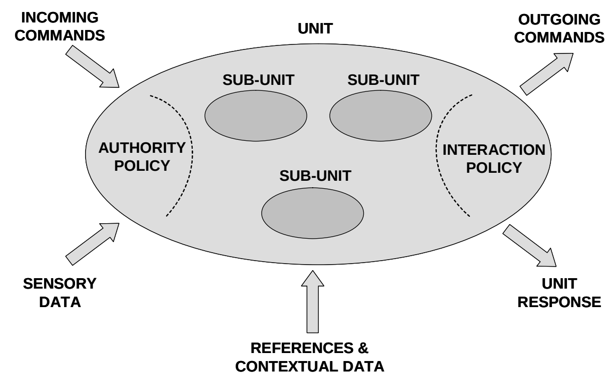

Fig. 5. Command structure concept

Reference Frames

Robotic systems working cooperatively will require common frames of reference, including time, spatial distance, units of measure, and workspace definitions.

Domains

At lower levels, JTARS manuals will likely be organized into classes of robotic systems known as “domains.” There are many ways to classify robots into domains, including:

Hierarchical (e.g. component, subsystem, system, system-of-systems)
Interfaces (e.g. communications, software, hardware)
Tasks (e.g. exploring, assembly, manufacturing, etc.)

Operating Environments (e.g. surface, transport, orbital, aerial, etc.)

To date however, the working group has not decided on the optimal domain organization.

Programmatics

The JTARS Project was initiated on February 1, 2005 with a premature termination date of January 31, 2006. The project included participation of robotic experts from NASA Centers, Langley (LaRC), Glenn (GRC), Goddard (GSFC), Marshall (MSFC), Johnson (JSC), Ames (ARC), and the Jet Propulsion Laboratory (JPL) along with experts from Case Western Reserve University (CWRU), Massachussetts Institute of Technology (MIT), and Titan Corporation. LaRC was given the responsibility of lead center on the effort with the Principal Investigator, Arthur Bradley, managing the technical effort of the team and with Project Manager, S.E. "Chip" Holloway III managing the programmatics.

NASA Headquarters directly sent each NASA Center their individual budgets to individually manage. Figure 6 illustrates the project budget with the appropriate Center break down.

Project Budget ($K)				
	PHASE I		Phase I	
Center	FY05	FY06	Total	Project Total
Total	542.4	180.8	723.2	5844.5
ARC	64.43	21.48	85.9	768.2
GRC	48.38	16.13	64.5	589.9
GSFC	50.25	16.75	67	571.6
JSC	56.18	18.73	74.9	635.5
JPL	76.73	25.58	102.3	907.6
LARC	228.75	76.25	305	2187.3
MSFC	17.7	5.9	23.6	184.4

Fig. 6. JTARS Project Budget

The JTARS team was comprised of 3 researchers from ARC, 2 researchers from GRC, 2 researchers from GSFC, 4 researchers from JPL, 3 researchers from JSC, 2 researchers from LaRC, one researcher from MSFC, one researcher from MIT, 2 researchers from CWRU, one researcher from Titan Corp and one researcher from the Department of Defense.

With the Program Office sending each Center their funding directly, the Project Manager was challenged to effectively manage the project resources. The Project Manager worked diligently to organize working group meetings that maximized working group attendance. Figure 7 illustrates the planned versus actual labor charges.

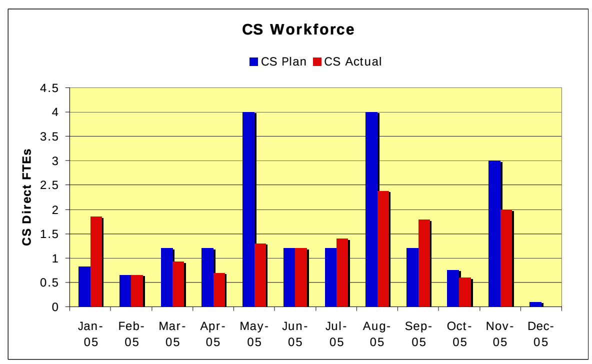

Fig. 7. Civil Service Workforce

The MIT researcher was brought on board by contract. The period of performance was from February 3, 2005 through the end of the year. The Titan Corporation researcher was brought to the team by a task level contract for 150 hours of support for the working group meetings. The two CWRU researchers were brought on board via an institutional grant with a period of performance from February 9, 2005 to February 8, 2006.

In 2005, JTARS was a low-level man-hour supported project of approximately 0.1 full time equivalent (FTE) per person except for the Principal Investigator and Project Manager. With the low-level support, most of the productivity was accomplished at the quarterly meetings with only minimal planning for the execution of the meetings done outside of the working group.

The Project Manager reported directly to NASA Headquarters via a database file system called “WindChill”. Each month the project manager would upload a Word file and PowerPoint file outlining the accomplishments, schedule, risks, and budget.

The project was directed to use Earned Value Management (EVM) reporting. For a project of this size, EVM was burdensome and beneficial. EVM was burdensome because it required extra personnel to generate the reports. EVM benefitted the project as the EVM tools clearly illustrated when one center erroneously overcharged the project $210K the first month. Figure 8 illustrates the erroneous overcharge which was corrected three months later. After the correction was made, the spending rate closely followed the plan. The project’s EVM reporting was adversely affected until this error was corrected.

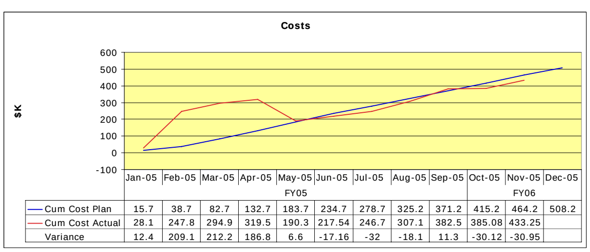

Fig. 8. JTARS Monthly Costs

The project maintained it’s schedule throughout the duration of the base period and achieved all milestones on or ahead of schedule. Figure 9 illustrates the project schedule.

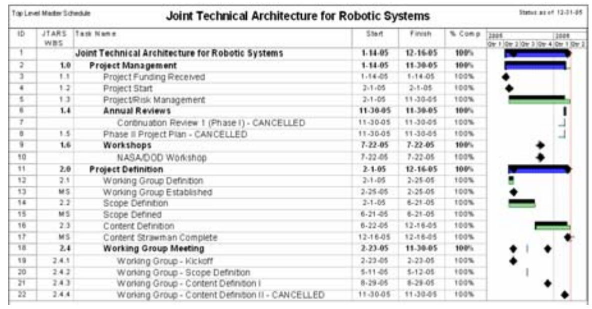

Fig. 9. JTARS Schedule

Summary

In January of 2005, JTARS was initiated by NASA’s Office of Exploration Systems Research and Technology. The primary goal of the project was to establish the technical architecture by which interoperable space robots could be developed. JTARS would prescribe standards, protocols, and practices to be used for NASA robotics, and had the long-term goal of broadening into an international standard.

When defining the scope of JTARS, an approach was adopted that divided systems based on capabilities rather than function. As a result, JTARS applies to robotic systems ranging from teleoperated to autonomous independent of “where” or “how” they are to be used as long as they meet or exceed three metrics. Those metrics are processing capability, communications, and physical interaction with the world.

The specific format or technical content of the JTARS manuals had yet to be fully defined. What is known is that two manuals would be developed, one that prescribed existing technologies, and a second that identified promising future technologies. The documents would identify both “core” elements common to all systems and application-specific standards organized into corresponding domains. Four high-level categories had been identified: physical interactions, information exchange, command structure, and reference frames.

JTARS was being developed by a working group comprising representatives from many NASA centers as well as experts from industry and academia. The working group openly invites additional participation from industry and academia, as well as from the international community (e.g. DLR, JAXA, CSA, ESA). Working group contacts as well as the past meeting schedule can be found at www.jtars.org.

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