FY02 Highlights

- Overview
- Architecture Concepts
- *Exploration Hurdles*
  - Space Transportation
  - Power
  - Crew Health and Safety
  - *Human and Robotic Operations*
  - Space Systems
- Technology Planning
- Leveraging and Partnering
- Future Direction

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Hurdles: Human & Robotic Operations

Current human and robotic collaborative capabilities are inadequate to reduce the time, distance, and safety barriers or to maximize scientific return of exploration beyond low-Earth orbit.

***FY02 Accomplishments Addressing Human & Robotic Operations Hurdle*:**

- Generated new in-space construction and assembly sequences/techniques; applied new methods to large telescope design
- Benchmarked state-of-the-art in space robotics and identified technical challenges for future technology development
- Conducted field tests and advanced the state-of-the-art in robotic surface exploration and human/machine interaction
- Developed and applied analytical tools for assessing the utility of various combinations of humans and robots to perform a given mission
  - Human & Robotic Performance Measures
  - Performance Analysis Methods

Hurdles: Human & Robotic Operations – Large Telescope Assembly Study

One likely follow-on project to the Next Generation Space Telescope would be a large telescope, intended to cover the far infrared and submillimeter spectral range, which we will take to be from 40 - 500 microns. A telescope in this wavelength regime is well suited to studying the behavior of interstellar gas and dust over a wide range of redshifts – i.e., in our Galaxy and in other galaxies, back to very early times. The compelling science that leads us to this project is that it is this interstellar matter that: feeds supermassive black holes in the nuclei of galaxies, causing active galactic nuclei to brighten; fuels starbursts in galaxies; establishes and renews stellar populations by the formation of new stars in molecular clouds; and collects and transports the heavy elements that shape stellar evolution and make life possible.

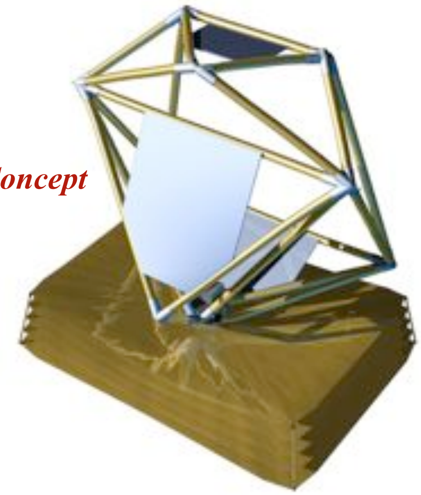
Key missions achievable within the Earth's Neighborhood, as identified by NEXT, include the assembly and maintenance of large-scale advanced scientific platforms in space. Ambitious science facilities will be extremely difficult to deploy, construct, rescue, service, and repair in space without sophisticated capabilities for manipulation and mobility. Such capabilities may be provided through the collaborative partnering of advanced robots, autonomous or remotely operated systems, and/or humans on site.

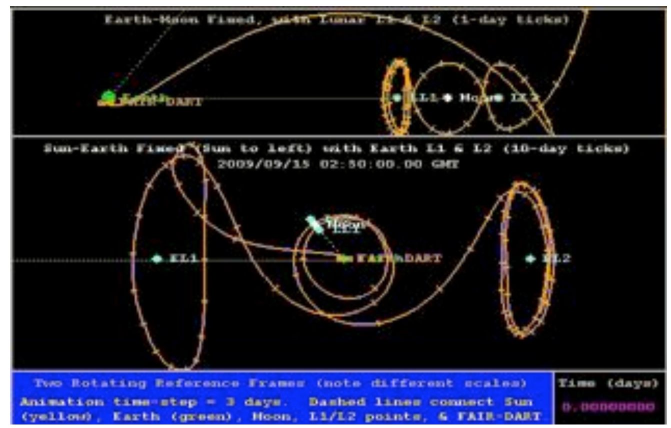
The collaborative interaction between the scientists, robotocists, extravehicular activity personal, telescope builders, and designers of supporting infrastructure identify the best methods and support infrastructure to implement such scientific investigations while identifying the technology hurdles which much be overcome.

Large Telescope Assembly Study

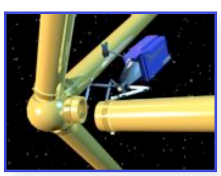
- **Mission:** Develop assembly and deployment concepts for a post-Next Generation Space Telescope, large-aperture far-infrared and sub-millimeter astronomical telescope concept. The operational location for this telescope is the Sun-Earth L_2 libration point.
- **Accomplishments:**
  - Analyzed the assembly and deployment of a large telescope at libration points and from the shuttle payload bay
  - Developed sample mission timelines and categorized assembly tasks for human/robot performance optimization analysis
  - Identified potential groups of human extravehicular activity and robotic system partners to serve on collaborative assembly teams
  - Refined infrastructure requirements for supporting in-space construction and servicing of large gossamer structures

Telescope Concept

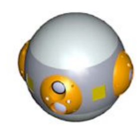




Telescope Deployment (Animation)







Potential Telescope Assembly Agents

Hurdles: Human & Robotic Operations –
Roadmap To Determine Optimum Roles for Humans and Robots Engaged in Large Space Telescope Construction and Maintenance

Studies completed to date indicate there are distinct advantages to multi-agent planning. However, limited data is available to define when a particular agent or group of agents should be used.

Construction and maintenance of a large space telescope is relevant to long-term agency goals, is realizable as a near- to mid-term goal, and involves a variety of technical challenges suited for focusing and uniting efforts to define space operations in Earth's Neighborhood.

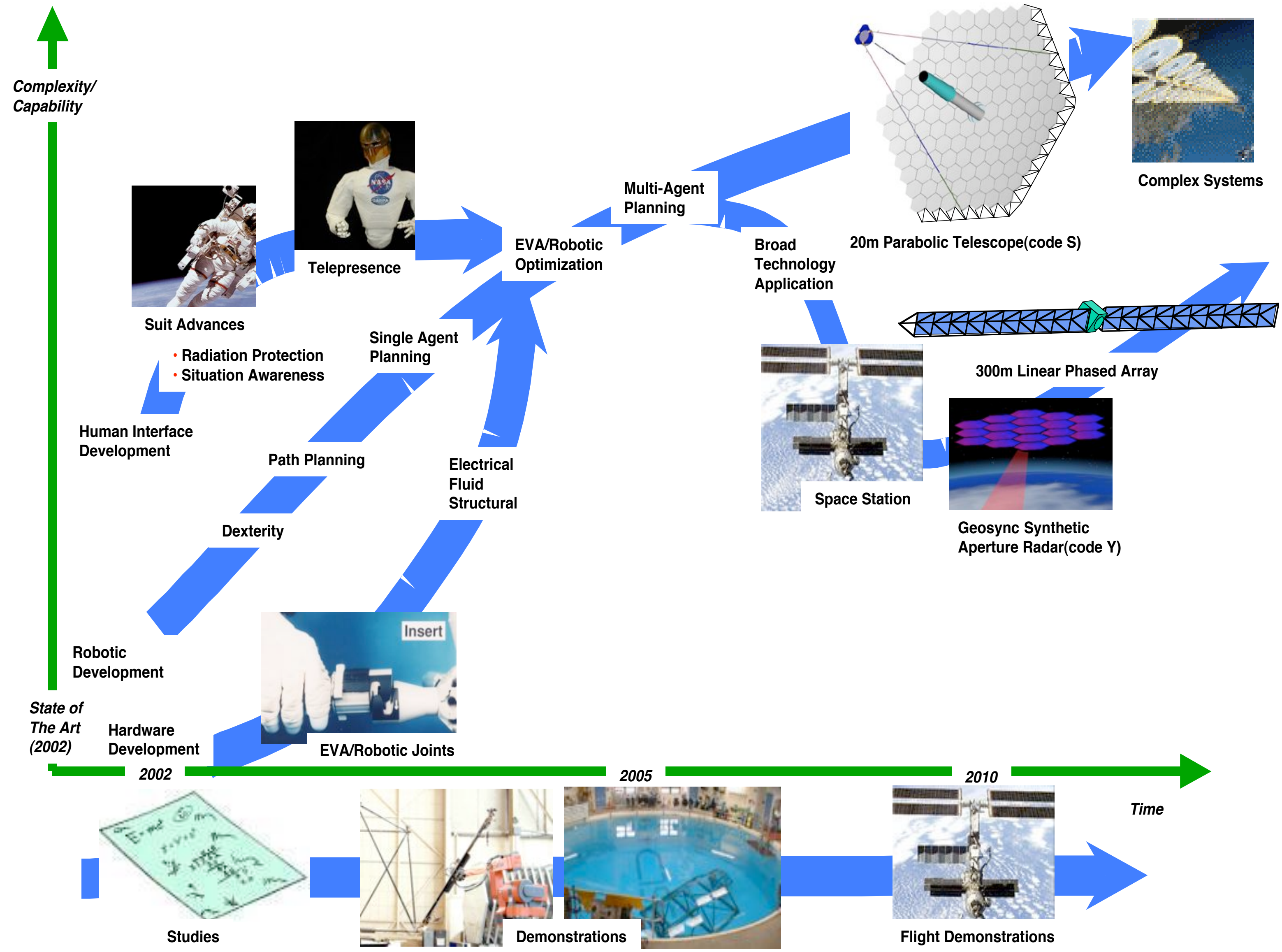
Techniques and hardware developed for effective large space telescope construction and maintenance are directly applicable to broad range of space and planetary missions directly supporting the NASA Office of Space Science, Office of Earth Science, and Office of Space Flight (Codes S, Y, and M).

Advances are required along 3 fronts to realize this vision:

- Human : Interface development, suit enhancements, and telepresence
- Robotic : Autonomous planning and coordination, mobility, dexterity
- Hardware : Lightweight components (including structural, electrical, and fluid connections) that are compatible with human/robotic operation

Advances will be validated through a logical progression of studies, laboratory experiments, and flight demonstrations.

Hurdles: Human & Robotic Operations
Roadmap To Determine Optimum Roles for Humans and Robots Engaged in Large Space Telescope Construction and Maintenance



Hurdles: Human & Robotic Operations – Robotic State-of-the-Art Summary

The purpose of this study was to provide mission designers with appropriate expectations for the roles that robots might play in the next ten to twenty years. Mission designers can then determine the optimal mix of human and robotic talent to achieve their mission and science objectives. The authors of this report believe that human-robot missions will be more effective than robot-only or human-only missions. However, there will be missions that will be robot-only because of cost or safety constraints and missions that will require significant human presence for scientific reasons.

This study looks at robot functionalities required to support two broad mission classes. In both classes this study also investigates functionalities unique to human-robot teaming:

- Planetary surface exploration – focuses on robotic mobility, science perception, instrument placement, and sample manipulation
- In-space operations – focuses on robotic assembly, inspection, and repair

To conduct the study, the functionalities were decomposed into a set of metrics that measure the current and future state-of-the-art for each functionality. These metrics were then distributed to robotic experts who were asked to rate each metric on a scale that ranged from that metric being within the current robotic state-of-the-art to that metric requiring a fundamental breakthrough in robotic technology. In the middle of the scale were metrics that could be achieved in the next ten years with either nominal or intensive work. The authors then distilled the responses to these metrics into a comprehensive set of current and predicted robotic capabilities.

http://ic.arc.nasa.gov/projects/questionnaire/

Robotic State-of-the-Art Summary

- **Objective:** Survey current/future space robotics for mission feasibility and technology gaps
- **Results:**
  - Human control has safety concerns
  - Building general purpose systems is a significant challenge
  - Human-level adaptability and response to adversity is not likely in the near future
  - Significant gap exists between flight and terrestrial systems
  - Many technical challenges
    - Perception and computer vision
    - Robot health monitoring
    - Cognition
    - Human-robot interaction
    - High degree-of-freedom systems (humanoid, snake robots)
  - Significant programmatic challenges
    - Robot experimentation in μ-gravity analog and space environments
    - Inclusion of robotics from beginning of system development

Hurdles: Human & Robotic Operations –
Integrated Analog Studies – Prerequisites for Human Exploration

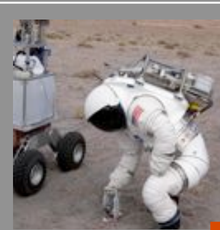
Analog sites and scenarios (i.e., Earth sites and scenarios similar or analogous to extraterrestrial sites and scenarios) are used to support development and testing of hardware and operations, as well as the training of both flight and ground crews. Field tests at analog sites are aligned with ongoing scientific fieldwork with specifically designed joint activities in which planetary tools and techniques are used to support an Earth-based scientific program. Collaborators in these efforts include field scientists, medical researchers, robotics engineers, operations and training personnel, human factors researchers, communications engineers, as well as others. Certain analog sites are more conducive to some activities than others. The results and lessons learned from all the analog site activities and scenarios are integrated and fed back into successive field tests. This chart shows the relative focus on the elements in various field tests currently being conducted.

NEXT has leveraged multiple fund sources for field tests and augmented funding on some specific analog studies to help focus on areas of specific interest to NEXT.

Integrated Analog Studies - Prerequisites for Human Exploration

Haughton-Mars 1

H. Remote Science 2

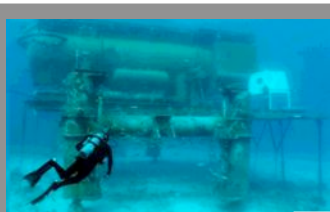


Desert RATS 3

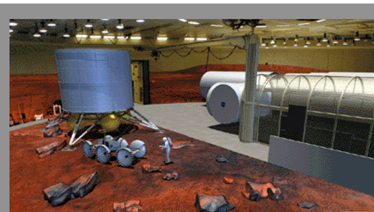
Mars Desert R. S. 4

Flashline Arctic R.S. 5

Elements (○ low, ● high)	Analog Field Studies									
	1	2	3	4	5	6	7	8	9	10
Science Value	black	gray	light gray	gray	black	gray	white	gray	gray	black
Science Operations	black	black	dark gray	dark gray	dark gray	dark gray	gray	gray	gray	light gray
Technology Development	dark gray	black	black	gray	dark gray	gray	black	gray	black	dark gray
Techology Integration	light gray	dark gray	black	gray	gray	gray	dark gray	light gray	black	gray
Mission Operations	gray	gray	dark gray	light gray	gray	black	dark gray	dark gray	light gray	light gray
Crew Training/Biology	gray	gray	black	dark gray	dark gray	black	dark gray	black	light gray	gray
Human Factors	dark gray	gray	gray	black	black	black	dark gray	black	light gray	black
Cost effectiveness	dark gray	dark gray	dark gray	black	gray	dark gray	light gray	white	dark gray	dark gray
Outreach/Education	black	black	dark gray	black	black	black	dark gray	dark gray	dark gray	black
Overall Integration	dark gray	dark gray	gray	dark gray	dark gray	gray	dark gray	gray	gray	dark gray



NEEMO 6



Integrity 7

Intl. Space Station 8

Mars Yard/Chamber 9

Antarctic/Desert 10

Hurdles: Human & Robotic Operations – Performance Testing in the Field

The purpose of these tests was to evaluate an extravehicular activity robotic assistant over a two week period in several operational scenarios and to evaluate new extravehicular activity support hardware.

The main experimental task of the field test was to deploy geophones – seismic sensors deployed in a straight line approximately 10 meters apart. In the first experiment, an extravehicular activity-suited human deployed geophones alone. In the second experiment a suited human deployed geophones while being assisted by a robot. The robot pulled a trailer with the geophones, stopping to let the human take one geophone of the string and deploy it. A final experiment where an autonomous robot deployed all the geophones was conducted. Data including deployment time and placement accuracy of the geophones in each of these experiments was compiled and is being analyzed.

Additional experiments included the first use of InfoPak, an extravehicular activity support system containing a differential Global Positioning System unit, a variety of sensors for suit telemetry, a compact Pentium processor, and a wireless 802.11b connection to an off-board control workstation. The InfoPak attaches to the experimental space suit and allows observers to track position (to within 2 centimeters), elevation, and suit telemetry.

Several experiments with the robotic assistant were also performed including following a suited subject during a lengthy traverse over hilly and rocky terrain and following the suited subject during a night traverse. The robotic assistant also autonomously deployed geophones while following a human. The robot deployed a half dozen geophones which were then "excited" by the resident geologist. Data from this experiment will be compared with a similar data set gathered during human deployment of the geophones to understand any differences between robots and humans performing this task.

Imagery:
http://zaphod1.grc.nasa.gov/~caseibe/Field_Media

Performance Testing in the Field

- Realistic simulations of planetary science and infrastructure setup scenarios have been conducted since 1998
- NEXT sponsored tests in Sept 2002 enabled more robust science (geophones, microscope, spectroradiometer, rock splitter, differential GPS) with local and satellite communications links for data collection
- Robotics and Information Technology support leveraged
- Lessons learned include :
  - Involvement of the right expertise with good equipment can yield successful meaningful results
  - Preparation and debugging prior to field deployment is as critical as creative real time troubleshooting
  - Suited test subject is able to accomplish objectives with reliability (spacebar key and voice interactive with robot)
  - Robotic systems have progressed but need more work to augment or approach human capabilities (e.g. mobility, manipulation, tracking)
  - Local science instruments are valuable assets to enhance science productivity
  - Environment heavily influences all test systems and results (rain, wind, dust)
  - Resulting data can apply to analytical performance models and designs for all destinations/environments

Hurdles: Human & Robotic Operations –
Collaborative Human/Robotic Exploration: Devon Island Field Experiments

The purpose of this pilot experiment was to compare scientific productivity between: (1) telepresence control of an advanced (circa 2020 capability) Mars surface rover from a Mars libration point, (2) in-person geologic field exploration, and (3) Earth-based robotic teleoperations.

The hypotheses under examination were:

- In combination with high resolution orbital maps, digital imaging from a surface site can, under the right circumstances, enable an experienced, remote geologist to successfully determine the *ground truth* for the site in question
- A principal difference in terms of science productivity (i.e., time required to achieve an equal level of scientific insight) among the three methods (given unlimited communication bandwidth) is *latency* (which, with current technology, is irreducible beyond two-way light distance: zero for the in-person case, ~ 8 seconds for a scientist/controller located at a Mars-Sun libration point, and tens of minutes for a scientist/controller on Earth).

Haughton Crater, a scientifically relevant Mars analog site, was chosen for exploration by each of the three methods. The team was unable to operate the simulated rover in a manner that approached telepresence, so the question of whether or not such robotic operations will be able to closely approximate in-person capability remains unresolved.

On the basis of the 2002 experiment lessons it is possible to define (preliminary) requirements for an operational robotic system that *would* allow a remotely located geologist to accurately and reliably determine the geological ground truth at a Mars analog site.

Collaborative Human/Robotic Exploration: Devon Island Field Experiments

- **Purpose:** To learn how scientifically productive telepresence (remote, minimal latency) control of an advanced (2020 capability) Mars surface rover is likely to be compared to: (1) in-person field exploration and (2) terrestrial teleoperations
- **Hypothesis:** Control from Libration Point base in telepresence mode is an effective means of carrying out Mars surface exploration, approximating what a human explorer in a space suit could achieve
  - Digital imaging from the surface can, under the right circumstances and in combination with high resolution orbital maps, enable an experienced, remote geologist to determine the ground truth for the site in question
- **Results:** Encountered navigation difficulties that prevented the science team from achieving its objectives:
  - Intermittent panoramic images do not provide confidence in identifying the geographic relationship of one location to a previous location that may be only a hundred meters away
  - Evidently, some degree of continuous navigational information relative to landmarks is required to retain situational awareness
  - Without such continuity, navigation was time consuming to the detriment of science tasks

The plausibility of telepresence operations to achieve science insights comparable to in-person exploration was not demonstrated with these field experiments.

Hurdles: Human & Robotic Operations –
Trade Space for Future Human/Robotic Technology Utilization

A complete trade space for human-robot technology utilization must encompass complementary elements of both robot technology and the corresponding human extravehicular activity technology. Typical robot technologies are robot manipulators for transporting and handling objects, mobility mechanisms to provide robot mobility, and autonomous robotic systems to reduce the need for human command intervention

Technologies in human extravehicular activity, such as life support systems and crew mobility systems, provide alternative or complementary capabilities. Optimization methods can then be used to find the best mix of robotic and human extravehicular activity technologies that maximizes value added, defined as the benefit-to-cost ratio. Payoffs may include such mission-level performance parameters as scientific return risk and mission duration, while cost may include infrastructure development, design, and mission operations.

The methods are addressing how to calculate benefit-to-cost ratios to use as a tool in mission trade space analysis. To this end, a family of parameters are defined including benefit, probability of success, cost, difficulty, and state of technology development. From these parameters, it is possible to estimate a benefit-to-cost ratio for use in mission trade studies.

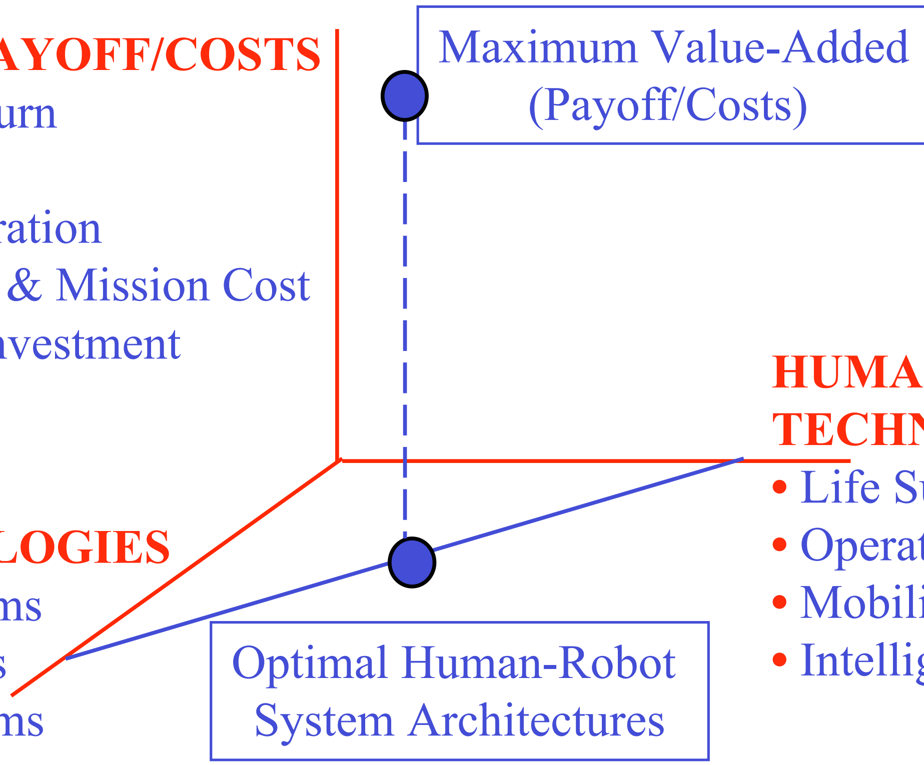
Various ways to do such benefit-to-cost computations for complex human-robot systems have been developed and are under further investigation. Key questions being addressed include:

- What is the mission level impact of human-robot technology investment?
- What is the optimal investment strategy for selected high-payoff technologies?
- Which human-robot technology mix leads to highest return on investment?

Trade Space for Future Human/Robotic Technology Utilization

Key Questions:
- What is mission-level impact of fundamental human-robot technologies?
- What is best mix of human-robot technologies to maximize mission-level goals?

MISSION PAYOFF/COSTS
- Science Return
- Risk
- Mission Duration
- Technology & Mission Cost
- Return on Investment



HUMAN EVA TECHNOLOGIES
- Life Support Systems
- Operator Interfaces
- Mobility Systems
- Intelligent Tools

ROBOT TECHNOLOGIES
- Autonomous Systems
- Robot Manipulators
- Mobility Mechanisms
- Perception Systems

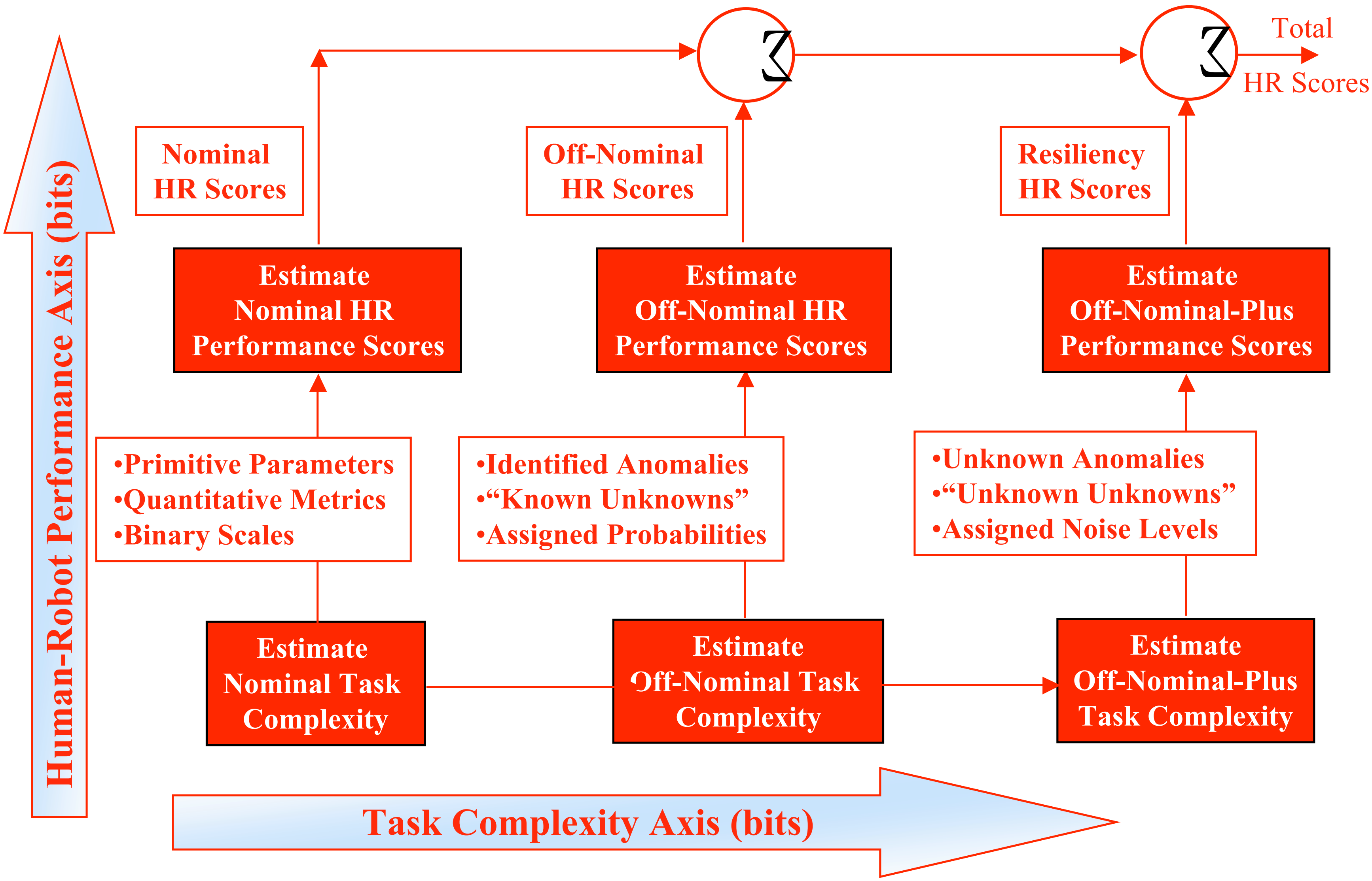
Hurdles: Human & Robotic Operations –
Performance Measures and Analysis Method

One of the major hurdles to be overcome in human-robot system operations is that of responding to unexpected events, either in the context of recovering from anomalies during operational sequences, or in responding to the opportunistic discovery of unexpected scientific findings. While it is generally known conceptually that humans are better able than current robots at responding to unexpected events, it is important to measure, analyze, and evaluate human and robot performance in the presence of unexpected events.

The block diagram illustrates the major steps in such an evaluation process intended to estimate human and robot performance in three distinct regimes of system operations: (1) the extreme left of the diagram summarizes the major features of an evaluation process to measure and analyze performance for nominal operations, which are pre-planned in advance; (2) the middle of the diagram focuses on off-nominal operations that can be anticipated in advance, that have a predictable probability of occurrence, and for which contingency plans may be developed; and (3) the extreme right of the diagram represents a process to evaluate performance in the presence of totally unexpected lightning-bolt-like events, about which no information is available before they occur.

This means that human-robot performance evaluation is conducted for nominal performance, for "known unknowns" where specific types of anomalies can be anticipated, and for "unknown-unknowns" where there is no information about what the unexpected events may be. As task complexity increases, the potential for unknown-unknowns increases and the system performance becomes less predictable. Humans tend to do better in these situations because of their reasoning and perception skills. Typical questions that the method in the block diagram addresses for a given task (e.g., structural assembly) are: What is the relative risk of not achieving success for any given human or robot agent? What is the probability of success? How does the probability of success vary with increasing task complexity? What types of anomalies are the most challenging for robots or humans? What are the human or robot skills that enable scientific discovery?

Performance Measures and Analysis Method



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