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by

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ABSTRACT

This paper discusses the major mission objectives and technical characteristics of an evolutionary family of advanced robotic space systems that would permit the detailed exploration of the outer Solar System and support precursor interstellar missions in the mid- to late 21st Century. Included in these advanced robotic space systems are: a demonstration autonomous robot mission to Titan, the TAU Probe Mission, the TAU Observatory Mission, a reference star probe mission, and the interstellar exploration implications and capabilities of a self-replicating robot system (SRS). The cosmic ramifications of the use of advanced robotic space systems by starfaring civilizations is also discussed.

INTRODUCTION

The fundamental question a modern day skeptic might ask is: "Why an interstellar mission?" Just over two decades ago, other skeptics were making similar remarks, namely, "Why go to the Moon?" Although our Solar System contains many worlds with numerous interesting and strange phenomena, these yet undiscovered scientific treasures are modest, perhaps even minuscule, when compared to the discoveries that await our exploring machines throughout the Galaxy. Since the dawn of the Space Age in 1957, interplanetary travel has transitioned from a dream to a reality. The new *dream* for mankind is now *interstellar travel* ! Most contemporary technical visionaries suggest that we cannot thrive (or even ultimately survive) as a species, if we choose to stay forever in our cosmic cradle - the Earth. In fact, the human species remains essentially at risk until we permanently expand beyond the ancestral biosphere of our home planet into the Solar System. Interstellar travel provides us with the hope of truly long-term survival of human life. Before our Earth becomes uninhabitable due to cosmic catastrophe (e.g., asteroid impact) or human folly (e.g., all out nuclear war) and, certainly, before our Sun dies (some 5 billion years or so from now), we must establish the technical, political, and economic infrastructure from which to "reach for the stars". This paper explores the important role that a sophisticated family of robotic spacecraft will play as our partners and machine precursors on this voyage of destiny through the Galaxy. [1-4]

As suggested in **Figure 1**, smart robotic machines will become our partners as we explore, in detail, the outer regions of the Solar System and, then, begin to steward the energy and material resources of the entire Solar System in the development of a **TYPE II** extraterrestrial civilization [1, 2]. For example, tomorrow's advanced robotic space systems will take over much of the data processing and information sorting activities that are now performed by human mission controllers here on Earth. Smart robot exploring machines, with onboard computers capable of deciding what information gathered is worth relaying back to Earth and what information should be stored or discarded, would greatly relieve the current situation in which huge quantities of data are transmitted back to Earth - the majority of which is often stored unprocessed and unanalyzed. (For example, the Viking missions to Mars returned image data of the Red Planet that were transferred onto approximately 75,000 reels ofmagnetic tape).

Robots with advanced artificial intelligence (AI), at levels capable of simplified "cognitive" decision-making, would have a large number of pattern classification templates or "world models" stored in their computer memories. These templates would represent the characteristics of objects or phenomena of interest in a particular mission. The robot exploring machine would then compare the patterns or objects they encounter with those stored in their memories and discard any unnecessary or unusable data. As soon as something unusual appeared, however, the smart machine explorer would examine the event or object more closely, establishing data collection priorities for a suite of onboard instruments. Upon completion of this special data collection sequence, the smart robot explorer would then dutifully alert its human controllers on Earth (many light-minutes or even light-hours distant) and report the findings.

The advanced artificial intelligence requirements for general purpose robotic space exploration systems can be summarized in terms of two fundamental tasks: (1) the smart robot explorer must be capable of learning about new environments; and (2) the smart robot explorer must be able to formulate hypotheses about these new environments. Hypothesis formation and learning represent the key problems in the successful development of artificial intelligence [1,5]. Deep interplanetary and interstellar robotic space systems will need a machine intelligence system capable of autonomously conducting intense studies of alien objects, events and phenomena. The artificial intelligence levels supporting these missions must be capable of producing scientific knowledge concerning previously unknown objects or phenomena. For a really autonomous deep-space robot exploring system to undertake knowing and learning tasks, it must have the ability to formulate hypotheses, using all three of the logical patterns of inference: analytic, inductive and abductive.

Analytic inference is needed by the robot explorer to process raw data and to identify, describe, predict and explain extraterrestrial events and phenomena in terms of existing knowledge structures. Inductive inference is needed so that the smart robot explorer can formulate quantitative generalizations and abstract the common features of events and processes occurring on alien worlds. Such logic activities amount to the creation of new knowledge structures. Finally, abductive inference is needed by the smart robot exploring machine to formulate hypotheses about new scientific laws, theories, concepts, models, etc. The formulation of this type hypothesis is really the key to the ability to create a full range of new knowledge structures. Creation of these new knowledge structures by smart exploring machines is essential, if we are to successfully explore and investigate unknown worlds at the edges of our Solar System and alien worlds around distant suns [1,5].

Although the three patterns of inference discussed above are distinct and independent, they can be ranked by order of difficulty or complexity. Analytic inference is at the low end of the new knowledge creation scale. An automated system that performs only this type of logic will probably successfully undertake only extraterrestrial reconnaissance missions. An exploring machine capable of performing both analytic and inductive inference would most likely be capable of successfully performing space missions combining reconnaissance and exploration. This assumes, however, that the celestial object being visited is represented well enough by the world models with which the smart robot has been programmed. However, if the target alien world is not well represented by such fundamental world models, then automated exploration missions will also require an ability to perform abductive inference. This logic pattern is the most difficult to perform and lies at the heart of knowledge creation. An advanced robot system capable of abductive reasoning could successfully undertake missions combining reconnaissance, exploration and intensive study. **Figure 2** summarizes the adaptive machine intelligence required for advanced robotic space exploration missions in the 21st Century [1-6].

DEEP SPACE ROBOTIC SYSTEMS

Figure 3 presents a synoptic view of possible advanced robotic space systems that could be developed in the next century to support automated investigations of the outer regions of the Solar System and then to support our first focused attempts at interstellar exploration. The technology scale chosen reflects three levels of technical maturity: extrapolatable technology, horizon technology, and over-the-horizon technology. On the near term side of the technology scale, extrapolatable technology represents technologies that exist or can be developed from planned space technology activities in the 2000-2020 time period [6]. Horizon technology levels represent space missions that have performance requirements that cannot be met, even if we extrapolate known space technologies. These horizon technology levels and their companion horizon missions generally lie in 2030-2100 time period. At the far side of this technology scale, the over-the-horizon technology level represents technologies so vast and radically different, that serious discussions of specific details is extremely difficult in today's technology culture. A time period beyond 2100 is generally given to the over-the-horizon technology level and its companion over-the-horizon space missions, which include interstellar self-replicating robot system (SRS) missions and sophisticated inhabited interstellar arks [1,3,5,6].

Automated Pluto Fly-By

Building upon the successful *Voyager*, *Galileo*, and *Cassini* missions, and advanced nuclear-powered and nuclear-propelled robot mission of both reconnaissance and exploration (including probes to the surfaces of Pluto and Charon) could be performed in the 2005-2015 time period. This automated mission would complete the cataloging of the basic science information of the planets by extensively imaging and investigating the (then) outermost planet in our Solar System. (* Note until approximately 1999, Neptune will actually be farther from the Sun than Pluto.) The parent spacecraft on this mission might either orbit the Pluto-Charon system or else be sent on an interstellar trajectory, as a spacecraft engineering precursor to other deep space missions.

Thousand Astronomical Unit (TAU) Probe

This mission involves an advanced technology robot spacecraft that would be sent on a 50-year journey into very deep space about 1,000 astronomical units (some 160 billion kilometers) away from Earth. The TAU spacecraft would feature an advanced multimegawatt nuclear reactor, ion propulsion, and a laser (optical) communication system. If desired, the TAU spacecraft could be initially directed for an encounter with the Pluto-Charon system, followed by passage through the heliopause. This advanced robot spacecraft would investigate low-energy cosmic rays, low-frequency radio waves, interstellar gases and other deep space phenomena. It would also serve as an engineering demonstration of advanced spacecraft automation technologies, including: self-repair, sensor reprogramming, resource allocation, and data evaluation.

Titan Automated Mission

This advanced robotic mission would visit the largest moon of Saturn and deploy a sophisticated robot lander and buoyant atmospheric probes. This mission would conduct detailed scientific exploration of a Solar System body that is believed to have life precursor conditions. From the *Voyager* missions, we now know that Titan is a fascinating celestial object - in some ways more like the Earth than any other object in the Solar System. Its unique atmospheric conditions cause the production of large quantities of organic materials and their accumulation on the surface. Titan's methane, through photochemistry, is converted to ethane, acetylene, ethylene and (when combined with nitrogen) hydrogen cyanide. The last is an especially important molecule, because it is a building block of amino acids. However, Titan's low temperature most likely inhibits the development of more complex organic compounds.

The Titan Automated Mission will serve as an important demonstration of both the technologies and scientific exploration strategies needed to perform a successful robot star probe mission. Titan lies far enough away from Earth (between approximately 70 and 87 light-minutes - one way) to prevent effective Earth-based investigation or even simple teleoperator control of robot explorer systems. Yet, it still lies close enough for effective system montoring and even human intervention during the overall operation of this advanced robot system. This mission could also make extensive use of virtual reality technology to give Earth-based scientists a pioneering (simulated) "real-time" exploratory and research presence. The advanced mission will also help resolve the technical challenges associated with automated investigation of an alien world, including: life search, sampling, and analysis at multiple locations; the simultaneous operation of surface landers and buoyant atmospheric platforms; and stationkeeping of the "mothership".

Oort Cloud Probe

The Oort Cloud Probe represents a "horizon technology" level mission to investigate the Oort Cloud - a region of deep space some 40,000 to 50,000 AU from the Sun containing up to 10^{12} long-period comets which are gravitational captives of our parent star. This probe would help verify the existence of an inner Oort Zone (believed to begin around 10,000 AU), characterize the population of the Oort Cloud, and study the depletion mechanisms for loss of comets out of this cloud. This advanced robotic system would also investigate the structure of the heliosphere and help determine the location of the heliopause, study the composition of the interstellar medium and measure the spectrum of low energy cosmic rays outside the heliosphere. This horizon technology-level mission would build on the technical heritage of the TAU Probe and Titan Automated Mission, improving on the AI levels necessary to support very long-lived spacecraft functioning, self-repair, and investigative sensor management and reprogramming. The Oort Cloud Probe represents a direct technical precursor to the first Robot Star Probe.

Tau Observatory

The TAU Observatory is an advanced, automated observatory that would be sent to a distance of 1,000 AU from Earth, normal to the galactic plane. Despite the similiarity of names, this mission is far more demanding in both technical and scientific scope than the TAU Probe mission previously discussed. The TAU Observatory would support parallax measurements to the edge of the Galaxy by increasing the triangular baseline from the Earth orbit (around the Sun) diameter of 2 AU to 1,000 AU. This observatory would study other star systems using "gravitational lens" focusing by the Sun - effects which begin at approximately 550 AU. This advanced automated observatory would require autonomous, self-assembly of a very large structure (perhaps 1-kilometer in diameter). Its deployment and successful operation would help resolve technology challenges involving long-term autonomous maintenance and calibration of a large, flexible space structure. Use of a Jupiter-Gravity-Assist or solar-gravity-assist maneuver might permit arrival at the 1,000 AU location (normal to the galactic plane) in about 50 years.

Robot Star Probe

The paramount "horizon-technoloy" level mission would be the Robot Star Probe. This mission would be targeted for a nearby star system, such as the triple star system Alpha Centauri (some 4.3 light-years away) or Barnard's star, a red dwarf star some 6 light-years away. This very sophisticated robot probe would conduct pioneering interstellar medium research - first in the outer boundaries of our own star's heliosphere, then in the pure "interstellar" space of our Galaxy, and finally into the heliosphere of another star system. It's primary mission would be to encounter a second star system in our Galaxy with the possibility of finding planetary systems and even life. This "horizon-technology" level mission would help resolve challenging technical obstacles involving propulsion, long-term spacecraft life, autonomous operation, and scientific investigation of alien worlds with useful data return for time periods in excess of 100 years at distances of several light-years.

Self-Replicating Robot System (SRS) Interstellar Probe

In transitioning from a **TYPE II** to a **TYPE III** extraterrestrial civilization with the launching of the first Robot Star Probe, our starfaring descendants will eventually seek more efficient ways of exploring the millions of star systems that populate the Galaxy. For exploration beyond 100 light-years from the Sun, the self-replicating robot system (SRS) could become the system of choice. With missions similar to that of the Robot Star Probe described above, the SRS Probe - representing technology levels that can best be described today as "over-the-horizon" - would not only be capable of conducting detailed investigations of the star system visited, it would also be capable of refurbishing itself and making one to several copies of itself (each sent forward to another star system). One successful "seed" SRS Interstellar Probe, might therefore, triggering a literal chain-reaction of exploration that would diffuse through the Galaxy at propagation rates determined by the transit speed (some fraction of the velocity of light) of the probes and the time required for an SRS probe to replicate itself (perhaps several years to a century) using the resources found in each new star system. The processes of exploration, refurbishment and repair, replication, and selection of new star systems as exploration targets would all be performed by magnificent levels of machine intelligence. Researchers back in the Solar System would inherit a more-or-less continuous stream of exploration data from the "seed" SRS probe and its machine progeny as each went forward into the Galactic void exploring, evaluating and propagating [1,2,5].

THEORY AND OPERATION OF SELF-REPLICATING SYSTEMS

The Hungarian-American mathematician, John von Neumann, was the first person to seriously consider the problem of self-replicating systems. From von Neumann's pioneering work and more recent investigations, we can arrive at five broad classes of SRS behavior:

(1) *production* - the generation of useful output from useful input. In the

production process, the machine unit remains unchanged. Production is a simple behavior demonstrated by all working machines, including SRS devices.
(2) ***replication*** - the complete manufacture of a physical copy of the original machine unit by the machine unit itself.
(3) ***growth*** - an increase in the mass of the original machine unit by its own actions, while still retaining the integrity of its original design.
(4) ***repair*** - any operation performed by a unit machine on itself that helps reconstruct, reconfigure or replace existing subsystems, but does not change the SRS unit population, the original unit mass or its functional complexity.
(5) ***evolution*** - an increase in the complexity of the unit machine's function or structure. This is accomplished by additions or deletions to existing subsystems, or by changing the characteristics of these subsystems.

Figure 4 provides a graphic summary of these SRS characteristics. The issue of closure (total self-sufficiency) is one of the fundamental problems in designing self-replicating systems. In an arbitrary SRS unit there are three basic requirements necessary to achieve closure: (1) matter closure; (2) energy closure; and (3) information closure. For example, if an SRS unit does not successfully command and control all the processes necessary for complete replication, it has not achieved information closure [1,5].

Within our Solar System SRS technology would allow our extraterrestrial civilization to manipulate large quantities of matter, making possible serious attempts at planetary engineering (terraforming) and the construction of truly large space habitats that represent miniature, multigravity level worlds [1,4]. It also appears most likely that before humans move out across the interstellar void, smart robot probes will be sent ahead as scouts. Interstellar distances are so large and search volumes so vast, that self-replicating probes represent a highly desirable, if not totally essential, approach to surveying other star systems - especially as these explorations exceed 100 light-years in distance. In fact, reproductive probes might permit direct reconnaissance of the nearest one million stars in about 10,000 years and the entire Galaxy in less than one million years - starting with a total investment by the human race of just one self-replicating interstellar robot spacecraft [1,5].

Of course, the problems in keeping track of, controlling and assimilating all the data sent back to the home star system by an exponentially growing number of robot probes is simply staggering. Our descendants might avoid some of these problems by sending only very smart machines capable of greatly distilling the information gathered and transmitting only the most significant quantities of data back to Earth. A command and control hierarchy might also be set up, in which each robot probe only communicates with its "parent". Thus a chain of "ancestral repeater stations" could be used to control the flow of messages and exploration reports.

The use of SRS probes to explore the Galaxy raises some fundamental ethical questions. Is it morally correct for a self-replicating machine to enter an alien star system and convert a portion of the star system's material and energy resources to satisfy its own mission objectives. Does an intelligent race legally "own" its parent star, home planet and any materials residing on other celestial objects within its star system? Does it make a difference whether the star system is inhabited by intelligent beings, or is there some lower threshold of galactic intelligence (e.g. **pre-TYPE I civilization**) below which the machines of advanced civilizations may ethically (on their own value scale at least) enter a new star system and approprate the resources needed to continue the wave of galactic exploration?

CONCLUSIONS

Advanced robotic technology will permit detailed study of the outer Solar System and will enable our descendants to initiate focused attempts at interstellar exploration. The development and use of SRS probe technology will, in time, enable humanity to set in motion a chain reaction that helps spread life precursors, organization, and even consciousness across the Galaxy in an expansion wave that may be limited by only the speed of light itself. With these truly smart machines as our close partners in interstellar exploration, we could literally green the Galaxy in about one million years!

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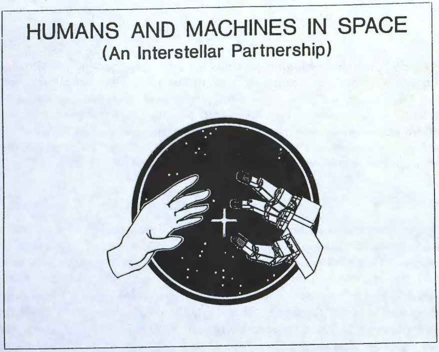

Figure 1

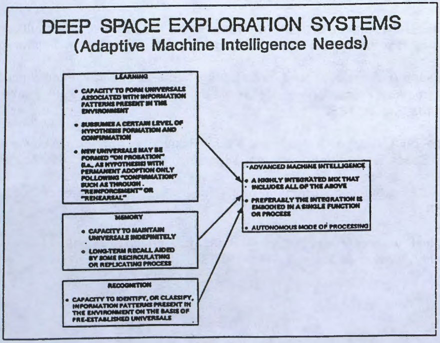

Figure 2

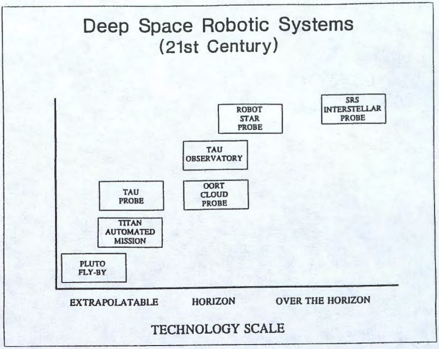

Figure 3

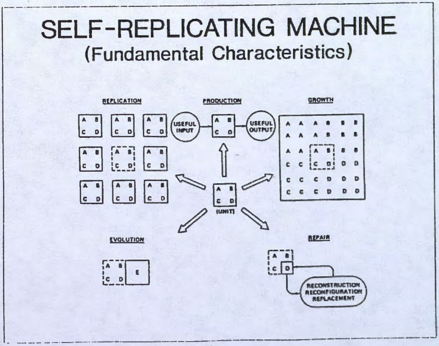

Figure 4