THE SSI RESEARCH OVERVIEW

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From a management of technology perspective, it is appropriate to briefly reflect on our objectives, the changing environment and previous research thrusts before we launch into a discussion of present and future research projects.

REAFFIRMATION OF THE HIGH FRONTIER

At the Thursday evening roundtable (May 8), Professor O'Neill's original SSI vision was overwhelmingly reaffirmed. Technology should be applied in support of the high frontier vision for the advancement of the human spirit and material security. Despite the fascination with Mars, the most effective colonization path is to build space habitats — which can provide comfortable acceleration without gravity — rather than develop the surfaces of moons or planets. After initial developments, all required matter and energy will be derived from space resources, not lifted from Earth. The criteria applied to select our research programs continue to be: the uniqueness of the project, its significance in support of the high frontier, its affordability, its achievability and its potential catalytic impact on other research in the space field.

THE CHANGING ENVIRONMENT

Our environment continues to be strongly affected by the transients due to the end of the cold war and space race. We observe many conflicts between old priorities and the struggle to define new missions. Despite the glorious predictions over the past three decades regarding lowering the cost of lifting mass from Earth to orbit, there has been virtually no progress, just a continuing series of new hopes and promises. Balancing this major disappointment is the miracle of the electronic, computer and communication technologies which have advanced several orders of magnitude over this same time span. We must be cognizant of these diverse technology trajectories and balance them appropriately as we conceive of new system concepts and research thrusts.

Another major change in our environment is the discovery of literally millions of asteroids and comets whose orbits cross the orbit of the Earth. These so-called near-Earth objects (NEOs) comprise at least 60 trillion tons of diverse material with only trivial gravity wells — potentially an enormous resource from which to build space habitats.

With the end of the space race, the need to force humans into space where telerobots can do the job is diminished. Similarly, beaming power is more effective than transporting chemical energy. Most effective of all is communication, where it satisfies the operational purpose. This "ladder of ease" — communication easiest, then beamed power, then robots, and finally human space operations —may appear trivial and obvious, but the space race priorities have dictated less effective architectures and research sequences. It is emphasized that we are not losing sight of our primary goal of human space colonization, we are merely constructing a more robust strategy to achieve the goal.

ONGOING RESEARCH PROGRAMS

SSI's several research thrusts since its establishment have followed the criteria summarized above and to various degrees have been catalytic and ongoing. The mass driver, originally conceived to transport matter from the surface of the Moon into orbit, would need less Delta V for asteroidal applications but more vectorial accuracy. The solar power satellite concept catalyzed enormous study efforts within NASA and DoE and is still undergoing analysis at NASA, which unfortunately still labors under the assumption that the SPS material must be lifted from Earth's surface to orbit. Geostar's space-based navigation and communication satellite made excellent progress in its initial development but ran into the Global Positioning System as a government competitor. Many studies continue to validate the eventual practicality of space-based manufacturing, especially as our knowledge of the vast resources available in near-Earth space increases. Low cost to-orbit studies and proposals are quite active presently and the US government is not only supporting hardware developments but is paving the way for a graceful transfer of management from government to industry in a manner which will follow the previous path of government to industry transfer regarding commercial air travel.

FOUR NEW RESEARCH PROGRAMS

With the foregoing as background, the SSI board of directors approved in November 1995 the following four new research thrusts (described in the Feb 1996 SSI Update): SKIT (sub-kilogram intelligent telerobots), MNTS (molecular nanotechnology for space), ADNEO (acceleration of the detection of near-earth objects) and QSRS (Quest for self-replicating systems). These four projects met the research criteria described above and only the first required SSI financial support.

SUB-KILOGRAM INTELLIGENT TELEROBOTS

The goal of the SKIT project is to develop a new generation of robots with the ability to lower the cost of exploration, prospecting and exploitation of near-Earth resources as a precursor to space colonization by human beings. The first operational design environment is that of the asteroids — rather than the lunar or planetary surface environments of the vast majority of space robots today — and its mass goal is to be well under a kilogram for each operating unit — rather than the 1000 kilograms of most of its predecessors. Its architecture stresses distributed functions among several diverse, cooperating telerobots. Alberto Behar was the principal investigator and his work thus far was presented and demonstrated in Princeton on May 10, 1997. Alberto is scheduled to complete his work on SKIT for a PhD in Engineering in the Computer Science Department at the University of California in 1997.

Even prior to Behar's PhD, the catalytic effect of SKIT on space robotics research has been excellent. Dr. George Bekey, the director of USC's robotics laboratory and the chairman of Behar's PhD committee stated that most future PhD candidates working is his laboratory will work on continuing research issues arising from Behar's SKIT work. The existence of the SKIT project as related experience was a substantial factor in USC's acquisition of a $1.5 million contract from DARPA, in the transfer from MIT to USC of a key researcher in small robots, and in the continued interest and support of the Jet Propulsion Laboratory which is responsible for the robotic design of an asteroid prospector —a major new international relationship between NASA and the Japanese government.

MOLECULAR NANOTECHNOLOGY FOR SPACE

The goal of the MNTS project is to extend industrial engineering's "location science" models from terrestrial to space application and to determine the potential advantages of MNT to space transportation and manufacturing. Tom McKendree was the principal investigator and his work thus far was presented in Princeton on May 9. Tom is scheduled to complete his work on MNT for space for a PhD in Engineering in the Industrial and Systems Engineering Department of the University of Southern California in 1997.

The catalytic effects of MNTS have also preceded Tom's PhD. Tom's work has helped define a new Computational Nanotechnology effort at NASA Ames Research Center and created a baseline for developing novel MNT missions and infrastructure concepts with the Foresight Institute.

ACCELERATION OF THE DETECTION OF NEAR-EARTH OBJECTS

The ADNEO project was supported by John Lewis, Lee Valentine and George Friedman in concert with their other ongoing activities. Since this project will not be described elsewhere in these proceedings, some additional detail is provided here.

Over the past two decades, evidence that the end of the age of the great dinosaurs at the Cretaceous/Tertiary boundary 65 million years ago was caused by the impact of a large (greater than 1 km diameter) asteroid or comet has become overwhelming. Presently, the astronomical community has catalogued less than 10% of the NEOs over 1 km and a far smaller percentage of those over 100 m in diameter. Although the annual likelihood of such an impact is extremely low, its consequence is without comparison in human experience: 100 m high tidal waves, hundreds of millions of casualties, the extinction of millions of species, the end of civilization and even the end of mankind. Merely extrapolating present programs designed to detect NEOs would take over a century to attain the 90% level (longer for comets); therefore it is vital to sharply accelerate NEO detection for planetary defense. Obviously, such an acceleration would also be extremely beneficial to the goals of the high frontier since the NEOs contain over 60 trillion tons of material both easier to obtain and more diverse than the material to be found on the lunar or Martian surface.

In his support of the Space Frontier Foundation and ProSpace, Lee Valentine has been actively supporting citizen groups advocating space development and NEO detection programs. Both John Lewis and George Friedman have also been actively supporting asteroid exploration through their associations with SFF and their participation with the Planetary Defense Workshop held at the Lawrence Livermore National Laboratories in 1995. Lewis recently published two highly acclaimed books: Rain of Fire and Ice, and Mining the Sky. Friedman has served as the AIAA's chairman of planetary defense for the past three years and published several papers on applying risk management to planetary defense with the AIAA and IEEE as well as establishing planetary defense as a graduate project at USC's school of engineering. Friedman's position paper, written for the AIAA has been submitted to Congress to help establish a special committee which will consider including planetary defense as a formal mission area within DoD this year.

QUEST FOR SELF-REPLICATING SYSTEMS

Of the four new projects, the Quest for Self Replicating Systems has been the most difficult, which is perhaps commensurate with its high goals. In 1980, NASA conducted an intensive summer study which addressed the potential for advanced electronics, robotics and self-replicating factories to advance space manufacturing. This study, documented in NASA publication CP 2255, captured the attention of the SSI Board of Directors — especially the potential for non-biological self-replicating systems to advance space manufacturing and exploitation at an exponential rate. Unfortunately, no new funding resulted from this exciting study; not even for the less aggressive programs which did not involve self-replication. George Friedman agreed to investigate the maturity of non-biological self-replication technology prior to any SSI investment of research funds.

Over the past year, the authors of the self-replicating systems (SRS) chapter 5 of CP 2255, Robert Freitas and Richard Laing were interviewed, as well as Robert Frosch, the NASA Administrator in 1980. Additional in-depth conversations were held with professors in computer science at USC and UCLA who pointed to Chris Langton at the Santa Fe Institute as the recognized leader in the emerging field of artificial life (AL) who was subsequently interviewed as well. All these inputs were discussed and reviewed with Freeman Dyson. Our findings can be summarized as follows:

In the 1940's, John von Neumann's digital computer architecture logic was originally viewed with alarm by many computer scientists because allowing the arithmetic unit to manipulate programs as if they were data appeared dangerously self-referential and could be the cause of computational instability. However, this architecture has been the world standard for many decades and millions of programmers have not only mastered this logic but yearn for the greater complexity of asynchronous, parallel processing. Shortly afterwards, just before his untimely death, von Neumann started work on his theory of self-replicating automata. On the surface, this logic, which also is self-referential in that it requires a "genetic code" which can duplicate itself as well as control the construction of real artifacts, does not seem to be substantially more difficult than his computer logic. However, even half a century later there does not appear to be a single researcher willing to undertake the design and construction of a self-replicating automaton in the real world (von Neumann's "kinematic model"). Building even the simplest kinematic model is, in the opinion of computer science researchers, far more difficult than originally imagined. Instead, the relatively new computer science field of artificial life (AL) concentrates all its energy regarding self-replication on von Neumann's cellular automaton (CA) model, where complex games are played out on highly simplified and idealized automata entirely within the computer itself In fact, many researchers propose the "strong A-Life" hypothesis that the CA's do not merely simulate life, they are life! As fascinating as these semantic and philosophical views are, they do not appear to be helpful in achieving the goals of the High Frontier.

There are encouraging signs on the horizon. As mentioned several times earlier, the field of computer science continues to advance at astounding rates. The A-Life community claims we are on the verge of creating "virtual robots" which can simulate in increasing detail any automaton that can be designed. While these virtual robots will still exist only within computers, they can characterize potential self-replicating designs with far more detail than the simple CA constructs. When the performance appears satisfactory, they can be built and tested in the real world. Thus, we can conceive of a logical bridge between the CA models and the full kinematic model. Chris Langton is very interested in this line of research and promised to point us to additional research with the eventual goal of fully autotrophic, mechanizable, autonomous self-replicating systems, employing "broadcasted" genetic control, all in the real world outside the computer.

THE FUTURE

Although detailed research plans must be approved by the SSI Board of Directors, we are in general agreement that our previous and ongoing research programs should be continued at some level appropriate to each. We still believe every one was a good choice which was unique at the time, of significant value to the high frontier, affordable, achievable and has proved to be catalytic — in some cases amplified thousands of times by government continuations. Despite this, more diligence is clearly required since our ideas have not yet achieved operational application.

At the May 11, 1997 Board of Directors meeting, we generally agreed that the mass driver concept has not been worked thoroughly for years and is now ripe for new study and analysis from a broad systems perspective which include NEO applications, momentum transfer and receiving, as well as transmitting systems.

CONCLUSION

SSI has made and continues to make a difference. As the cold war and space race fades further into the past, we look forward to a greater clarity of policies, priorities and missions. As with many other organizations, we will consider mutually beneficial "symbiotic" relationships with other groups having similar objectives.

Technologically, we hope that the recent thrusts by advocates, government and industry will decrease the cost to orbit by at least an order of magnitude. We hope that the effectiveness of space exploitation will increase another order of magnitude by the transfer of management from governments to commercial control. Finally, the selective introduction of computers, communications, beamed power, telerobots and other rapidly developing electronics technologies we hope will improve space development effectiveness by three orders of magnitude.

The High Frontier, which appeared to be receding for a time can be brought closer. It is apparent we must work harder and more intelligently. But that is the requirement of all great dreams.