Professor Dava Newman in her BioSuit. Credit: Professor Dava Newman, MIT: Inventor, Science and Engineering; Guillermo Trotti, A.I.A., Trotti and Associates, Inc. (Cambridge, MA): Design; Dainese (Vincenca, Italy): Fabrication; Douglas Sonders: Photography. (Background Image of Astronaut by Henrik Lehnerer)

REVOLUTIONS IN SPACE

How USRA developed a means of supporting revolutionary advanced concepts for space exploration and applications on Earth.

Essay by W. David Cummings. Design by Erin Senoz.

NIAC

NASA Institute for Advanced Concepts

About 500,000 children in the United States have some form of cerebral palsy. These children are unable to fully coordinate their arms and legs and other body parts. Cerebral palsy is not yet a curable condition, but a group of researchers at Children's Hospital in Boston, Harvard's Wyss Institute, Boston University, Draper Laboratory, and MIT are trying to change that. Their goal is to use a "BioSuit" technology to guide the movement of infants with cerebral palsy and in the process, to reshape the motor programs in their brains.

The BioSuit technology was developed by Dr. Dava Newman of MIT to replace the bulky, gas-filled spacesuits that have been used by astronauts since before the Apollo program:

> *The BioSuit is based on the idea that there is another way to apply the necessary pressure to an astronaut's body. In theory at least, a form-fitting suit that presses directly on the skin can accomplish the job. What is needed is an elastic fabric and structure that can provide about one-third of sea-level atmospheric pressure, or 4.3 psi (approximately the pressure at the top of Mt. Everest). The skintight suit would allow for a degree of mobility impossible in a gas-filled suit.*

> *Thanks to some funding from the NASA Institute for Advanced Concepts, we were able to gather a team to begin the practical work that would test our hypothesis.* [1]

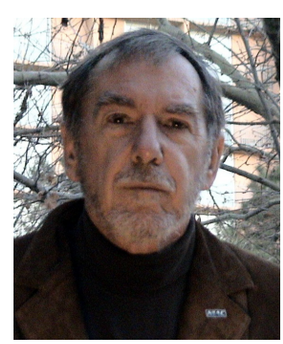
The NASA Institute for Advanced Concepts (NIAC) that helped Dava Newman start work on the BioSuit was organized and developed by USRA in 1998 in response to a NASA request for proposals.

NIAC was a virtual institute. Its members were researchers, called NIAC Fellows, who had received funding from NIAC to develop aerospace and space science concepts for systems or architectures that might be realized 10 to 40 years in the future. NIAC funded revolutionary ideas and did not require that all the enabling technologies for the advanced concepts be currently available. In many cases the NIAC concepts spurred research on the required enabling technologies.

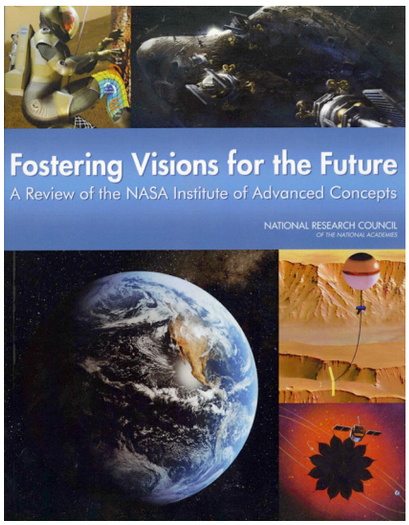
NIAC received a total of 1,309 proposals during the nine years of its existence as a USRA institute. From these proposals, NIAC made 126 Phase I grants (6 months, up to $75,000) and 42 Phase II contracts (2 years, up to $500,000) for studies based in a wide range of universities and businesses. NIAC was funded by NASA at a level of about $4 million per year, and more than 75% of the funding went to the projects of the NIAC Fellows.

NIAC provided a pathway for revolutionary discoveries by innovators with the ability for non-linear creativity to explore new possibilities for near and far term aerospace endeavors.

The Director of NIAC was Dr. Robert Cassanova, who had been the Director of the Aerospace and Transportation Laboratory of the Georgia Tech Research Institute. Cassanova was also a member of the USRA Board of Trustees and served as its Chair from 1993 to 1997.



Robert Cassanova
USRA Director of NIAC



Several of the projects funded by the original NIAC subsequently received additional funding from a variety of agencies and companies.

Several years after the conclusion of NIAC, Cassanova summarized his view of the effectiveness of the institute as follows.

> *Throughout its nine years of operation, the NIAC inspired and nurtured a number of revolutionary advanced concepts that someday may have a significant impact on future directions in aeronautics and space. NIAC provided a pathway for revolutionary discoveries by innovators with the ability for non-linear creativity to explore new possibilities for near and far term aerospace endeavors.*[2]

The accomplishments of NIAC Fellows created a near-constant demand for information from outside the institute. Press releases captured the attention of mass media outlets around the world. NIAC staff were consistently available for public comment and served as resources for a broad array of publications, radio, and television programming, allowing the media to directly interface with NIAC Fellows. Beyond the popular press, NIAC and NIAC-sponsored advanced concepts received widespread recognition in technical journals. NIAC Fellows were highly visible in technical society meetings, with numerous presentations and publication of research papers in referred journals.

NIAC held annual meetings at which the NIAC Fellows gave progress reports. Following the October 2005 meeting, the NIAC leadership team organized a program to identify and nurture innovative undergraduates who had shown exceptional creativity and promise for success in building visions of the future. The NIAC Student Fellows Prize, sponsored by USRA and managed by NIAC, was initiated in 2005 to attract these students and to facilitate their studies. The prize, in the amount of $9,000 dollars, fostered mentoring, networking, and creativity, and provided undergraduate students a first opportunity to exercise responsibility in project management.

Through his work as the Director of NIAC, Cassanova received NASA's Public Service Medal for exceptional contributions to the Mission of NASA. For her guidance throughout the operation of NIAC, Sharon Garrison, the Coordinator for NIAC at NASA-GSFC, received the NASA Exceptional Achievement Medal. The NIAC team, including NASA and USRA's partner, the ANSER Corporation, received the NASA Group Achievement Award.
Despite these and other acknowledgements of success, NASA informed USRA in 2006 that it would not be able to continue funding NIAC, owing to budget cuts imposed on the Agency. The institute ceased operations on 31 August 2007.

In the report that accompanied NASA's appropriations bill for fiscal year 2008, the NASA administrator was directed to:

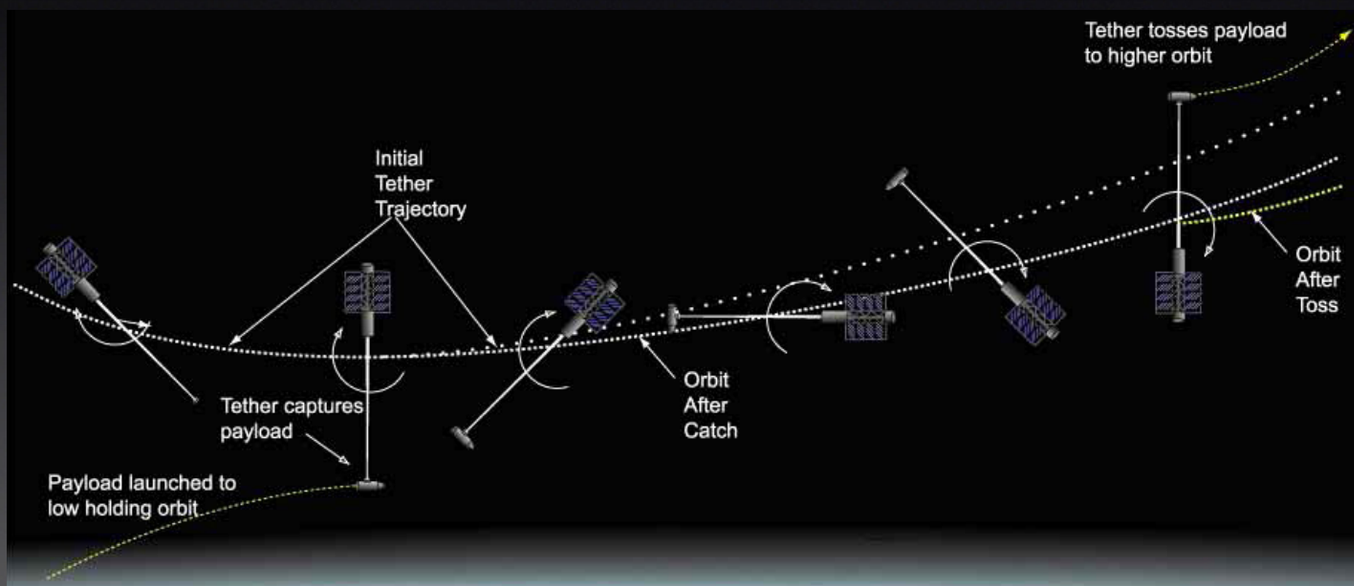
> *Enter into an arrangement with the National Research Council [NRC] to evaluate NIAC's effectiveness in meeting its mission, including a review of the grants made by the Institute, their results, and the likelihood that they will contribute to the Institute's stated goals; evaluate the method by which grantees are selected and recommend changes, if needed; and make recommendations as to whether the Institute should continue to be funded by the federal government and, if so, what changes, if any, should be made to its mission, goals, operations, or other matters.*[3]

In its report, "*Fostering Visions for the Future: A Review of the NASA Institute of Advanced Concepts,*" the NRC Committee was very positive about the effectiveness of NIAC. The committee recommended that:

> *NASA should reestablish a NIAC-like entity, referred to in this report as NIAC2, to seek out visionary, far-reaching, advanced concepts with the potential of significant benefit to accomplishing NASA's charter and to begin the process of maturing these advanced concepts for infusion into NASA's missions.* [4]

NASA accepted the recommendation of the NRC committee and established the NASA Innovative Advanced Concepts (NIAC) program in 2011. The new NIAC program is very similar to the original NIAC but is operated within NASA. Robert Cassanova was chosen to be the first chair of the NIAC External Committee.

Several of the projects funded by the original NIAC subsequently received additional funding from a variety of agencies and companies. Three of these projects are briefly described on the following pages.



Concept of operation of a momentum-exchange tether facility.[5]

Tether Transport Systems

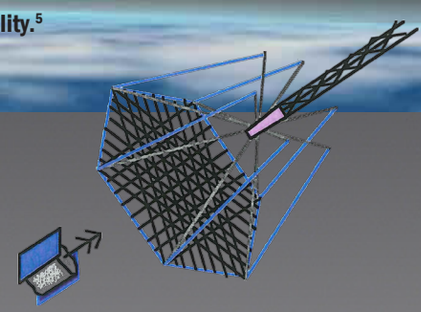
Robert Hoyt of Tethers Unlimited, Inc., won a NIAC Phase I award in November 1998 for a study on *Tether Transport Systems for LEO-MEO-GEO-Lunar Traffic*. Based on the successful completion of that study, Hoyt was awarded a Phase II contract in August 1999 for the study of a *Moon & Mars Orbiting Spinning Tether Transport* system.

The basis for the space technology studied by Hoyt and his colleagues is a system of momentum exchange that makes use of a satellite with a tether that has the capability to catch payloads in one orbit and toss them into another.

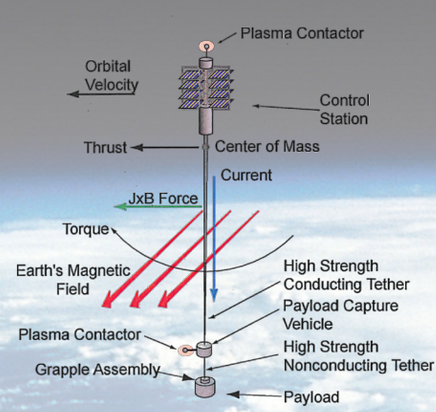
> *In a momentum-exchange tether system, a long, thin, high-strength cable is deployed in orbit and set into rotation around a central body. If the tether facility is placed in an elliptical orbit and its rotation is timed so that the tether is oriented vertically below the central body and swinging backwards when the facility reaches perigee, then a grapple assembly located at the tether tip can rendezvous with and capture a payload moving in a lower orbit, as illustrated in Figure 1. Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit. This concept is termed a momentum-exchange tether because when the tether picks up and tosses the payload, it transfers some of its orbital energy and momentum to the payload, resulting in a drop in the tether facility's apogee.*[5]

In his study, Hoyt examined the technological challenges of developing his Tether Transport System. These challenges included (1) a means to restore the tether facility to its original orbit after a transfer, (2) a reliable way to capture the payload, and (3) the design of a high-strength cable that could withstand the space environment.

To restore the tether facility to its original orbit after it has been used to toss a payload into a higher orbit, Hoyt proposed using thrust from a current that would run down the tether and interact with the Earth's magnetic field. Depending on the direction of the current in the tether, the force on the tether would either produce a drag on the system or give it thrust and raise it to a higher orbit. For this "electrodynamic reboost," no rocket propellant would be required to restore the tether facility to its original orbit.



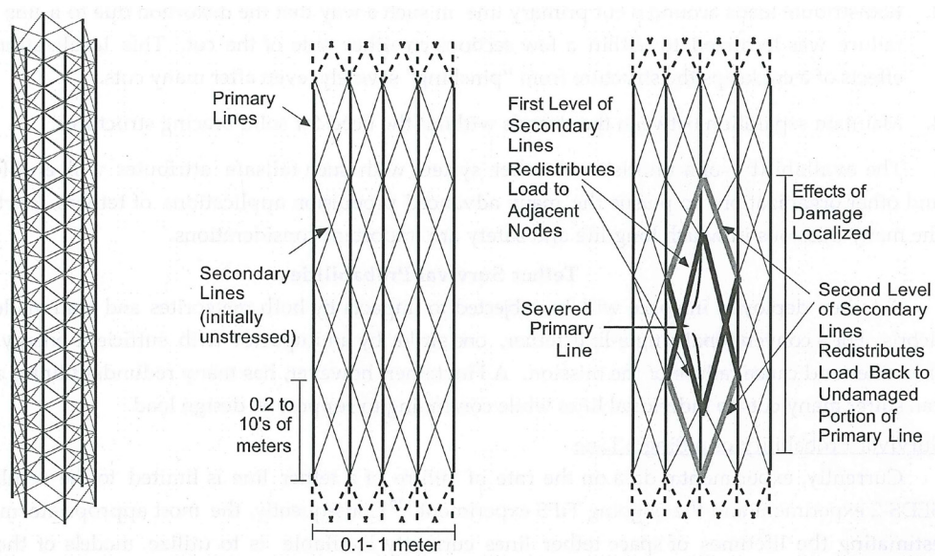
Concept for a payload capture method.[6]



The tether facility concept, showing the effect of the interaction of the tether current with the Earth's magnetic field (JxB Force).[23]

Hoyt thought that the design of the capture process was the most difficult challenge for his Tether Transport System. He envisioned that the length of the tether would be of the order of 100 km and that the tip of the tether would be travelling at about 1 km/s as it passed close to the payload to be captured. By letting the payload capture mechanism at the tip of the tether release a tethered grapple,

The Hoytether™ [7]



Hoyt envisaged his tether transport system as being used to transport payloads not only to higher orbits around Earth but also to the Moon and Mars.

the encounter time for the capture could be extended to several tens of seconds.

A possible grapple mechanism is a "net and harpoon" design. The payload maneuvers to the proximity of the net and then shoots a tethered harpoon into the net. One half a rotation later, the payload is released by retracting the barbs on the harpoon.[6]

The third major challenge for Hoyt's tether transport facility was the design of the tether. It had to have high strength and low weight, and it had to be durable in the environment of near-Earth space. Hoyt's solution was a

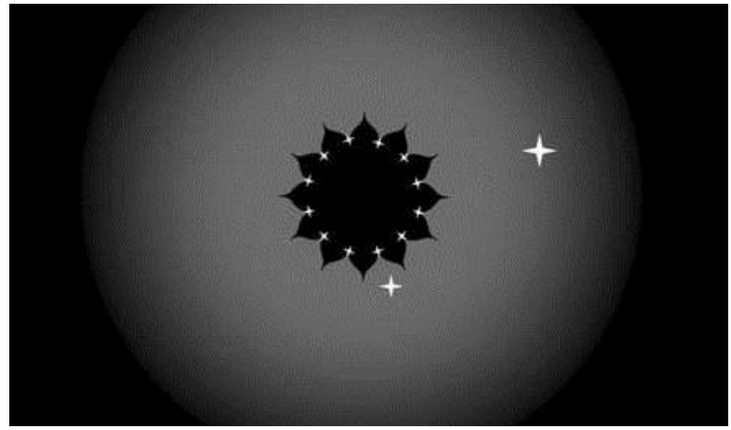
Robert P. Hoyt
NIAC Fellow

trademarked product, the Hoytether, which is an open net structure that provided redundant linkages to allow for the possibility that the tether might be damaged by micrometeoroids or space debris.

Such a possibility was demonstrated in 1994 during an actual tether experiment in space (the Small Expendable-tether Deployment System–2) that used a cylindrical braided line with a diameter of 0.8 mm and a length of 20 km. This tether (not a Hoytether) was cut by a meteoroid or debris impactor about 4 days after deployment.[7]

Hoyt envisaged his tether transport system as being used to transport payloads not only to higher orbits around Earth but also to the Moon and Mars, and he thought about it in terms of a commercial venture.

If a tether-based transportation architecture is to be developed in part or in whole by a commercial venture, the deployment of the system must follow a path that is commensurate with a viable business plan. An Earth-Moon-Mars Tether Transportation System will require at least three tether facilities, one in Earth orbit, a second in lunar orbit, and a third in Martian orbit. Each of these will require a significant investment in technology development, system fabrication, and facility launch. To keep the capital investments small enough for a business plan to close, the system architecture must be designed in a manner in which the first components can immediately serve useful functions to generate revenue to fund the development of the rest of the system. This would be quite analogous to the development of the cross-continental railroads, where each extension of the rail line was used to generate revenue to help build the rest of the line.[8]



Schematic showing how a flower-petal starshade in position against a nearby star might appear. At the base of each petal a small amount of light from the parent star diffracts around the shade. Planets simply appear as faint stars in the field of view. [11]

The New Worlds Imager

In 1962, Lyman Spitzer, Jr., (1914-1997) delivered a lecture at the Third International Space Science Symposium (COSPAR) in Washington, D.C. with the title of *The Beginnings and Future of Space Astronomy*.[9] In the lecture, Spitzer discussed the opportunity and challenge of detecting planets around other stars, which he viewed as:

> *(A) matter of very great philosophical and cultural as well as scientific interest. Our view of man and his place in the universe naturally depends very much on whether planetary systems like ours are exceptional or whether they occur very frequently throughout the Galaxy. In fact, in many ways, the question of how frequently stars are accompanied by planets capable of supporting life is fully as important as the over-all structure of the universe, i.e., whether space is flat or curved.*
>
> *The detection of other planets, however, is an extraordinary difficult problem. Not only are planets intrinsically very faint, they are necessarily very close to a star if they can be detected at all, and light from the central star, scattered or diffracted in the telescope system, inevitably tends to mask the very faint planetary light.*[10]

Webster C. Cash
NIAC Fellow

Spitzer discussed a possible approach to the problem of detecting planets around stars, namely the use of a large occulting disc far in front of a space telescope. He attributed this idea to his Princeton colleague, Robert Danielson (1931-1976). This was the idea behind the NIAC proposal submitted by Webster Cash of the University of Colorado in 2004, titled *New Worlds Imager*. In his Phase I and Phase II studies, Cash examined the many challenges related to the use of an occulter to observe planets around other stars.

To understand how an occulter works, imagine if our solar system were viewed from a distance of 30 light years. The distance from the Sun to the Earth would subtend an arc of about 0.1 seconds (1/36,000th of a degree), and the Sun would be ten billion times brighter than the Earth. Cash viewed the primary challenge as that of finding a way to almost totally eliminate the light from the star in the shadow of the occulter, which he called a starshade.

A starshade in the form of a disc would not work, because light waves diffracted all along the circular edge of such a disc would arrive at the center of the shadowed area with the same phase and thus constructively interfere. A bit off center in the shadowed area, diffracted light waves from one half of the disc rim would destructively interfere with the diffracted light waves from the other half, producing a dark ring. Still further out from the extension of the line defined by the star and the occulter, constructive interference would occur. The result would be a pattern of bright and dark circles, as demonstrated in an undergraduate student lab experiment using laser light, seen here in the background image.

Cash found a way to shape the starshade so that it would create a circular zone with the diffraction brightness in this zone reduced by a factor of ten billion across a broad range of frequencies in the visible range. The zone would be produced tens of kilometers behind the starshade, and it would be at least two meters wide. His starshade is flower-shaped, with an opaque circular central part and petals extending from this core.

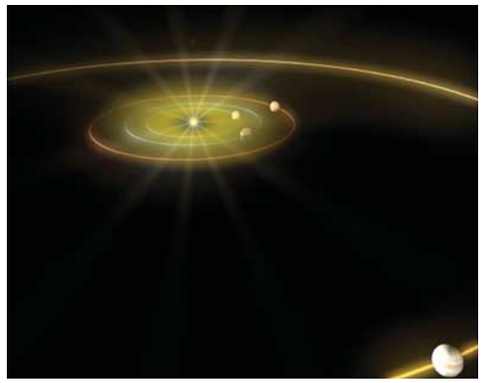
> *The New Worlds Observer [is comprised of] two spacecraft, a flower-shaped starshade about 50m from tip to tip, and a conventional-quality telescope. The telescope optic must be diffraction-limited in the visible band and at least 1m in diameter. The mission operates by flying the starshade into the line of sight of a nearby star, a move that can take several days.*[11]

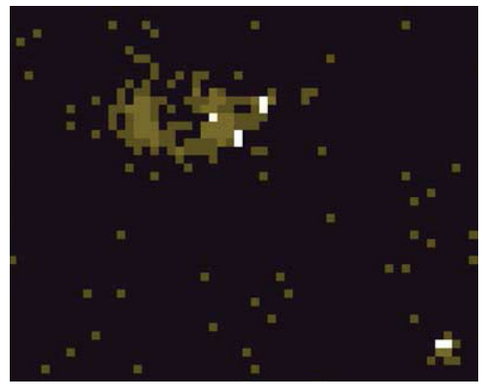
Background Image: Diffraction pattern using an occulting disc and laser light. (From a University of Michigan student lab experiment)

Cash concluded that his New Worlds Observer could be used to directly photograph major features of planetary systems to a distance of about 30 light years and beyond.

Cash examined other challenges for his New Worlds Observer, including ways to deploy the large starshade and keep it stationary, relative to the celestial sphere, through automated station-keeping with small thrusters.

Cash also performed computer simulations to show what might be possible with his system. He demonstrated that If the New Worlds Observer were turned onto our own solar system from a distance of about 20 light years, using an occulter and the James Webb Space Telescope, then Earth, Mars and Jupiter would be visible as bright white spots.[12]





Seeing Earth-like planets – a simulation. Artwork is courtesy of Ball Aerospace. [11]

Cash concluded that his New Worlds Observer could be used to directly photograph major features of planetary systems to a distance of about 30 light years and beyond.

> *It can detect all the major planets (from the habitable zone outward), the zodiacal light, debris disks and possibly even comets. Photometric variations might show the presence of surface features like oceans and continents.*

Follow-up spectroscopy of the detected planets would enable classification by type, and the presence of water would be clearly visible in atmospheric absorption lines. Atmospheric markers (like free oxygen absorption lines) could potentially provide the first evidence of life outside our Solar System.[13]

Background image: BioSuit illustration.
Credit Trotti and Associates, Inc.

Astronaut BioSuit System for Exploration-Class Missions

The spacesuit worn by Apollo astronauts was gas-filled and able to keep a uniform pressure of 3.7 psi on the bodies of the astronauts. Advancing spacesuit technology was not among the critical issues identified by the National Commission on Space in 1986 in their report titled *Pioneering the Space Frontier*.[14] Judging by Robert McCall's artwork for the report cover, the spacesuits worn by astronauts on Mars ca. 2030 would not be much different from the Apollo suits.

Dr. Dava Newman of MIT had a different perspective. In her Phase I and Phase II studies for NIAC, titled *Astronaut Bio-Suit for Exploration Class Missions*, Newman examined a different kind of spacesuit that would allow astronauts to move freely and quickly on the Martian surface.

> *The suits that kept NASA astronauts alive on the moon and those worn by Space Shuttle and International Space Station crewmembers for extravehicular activities (EVAs), including the Hubble repair missions, are technological marvels; in effect, they are miniature spacecraft that provide the pressure, oxygen, and thermal control that humans need to survive in the vacuum of space. The greatest problem with these suits is their rigidity. The air that supplies the necessary pressure to the bodies of wearers turns them into stiff balloons that make movement difficult and tiring. These suits are officially known as EMUs—extravehicular mobility units—but they allow only limited mobility. Astronauts who perform repair work in space find the stiffness of spacesuit gloves especially challenging: imagine manipulating tools and small parts for hours wearing gas-filled gloves that fight against the flexing of your fingers.*[15]

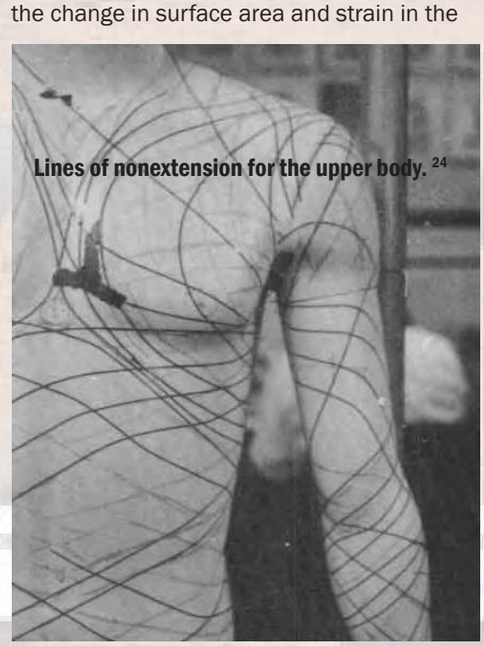
Newman also pointed out that in addition to providing better mobility, her BioSuit would be safer than the traditional spacesuit.

> *While an abrasion or micrometeor puncture in a traditional suit would threaten sudden decompression—puncturing the balloon and causing a major emergency and immediate termination of the EVA—a small breach in the BioSuit could be readily repaired with a kind of high-tech Ace bandage to cover a small tear.*[16]

Newman and her team took advantage of earlier work on the design of spacesuits that used elastic fabric garments to supply the pressure needed by the wearer in the near vacuum of space. As early as 1968, Paul Webb (1923-2014) and others worked on the design of a Space Activity Suit that Webb called an "elastic leotard."[17] Newman also made use of the research by Arthur Iberall (1918-2002) on what Iberall called "lines of nonextension" of the human body. Iberall had found that while the human skin generally stretches during body motion, there are certain lines on the body where there is virtually no stretch. About Iberall's work, Newman wrote:

> *We have expanded his great idea of a pattern of three-dimensional lines on the body that do not extend by deriving the mathematical representation and visualization of what I call a soft exoskeleton and structure of the BioSuit. ... Laminating our mathematically derived web of less-flexible lines, or the soft exoskeleton pattern, to our elastic compression suit has gotten us closer to the necessary pressure production goals, and we've exceeded our mobility and flexibility performance goals.*[18]

Newman and her team used 3D laser scanning of human subjects to measure the change in surface area and strain in the



Lines of nonextension for the upper body. [24]

Dava J. Newman
NIAC Fellow
NASA Deputy Administrator,
2015-present

human skin for various leg motions. These measurements, together with Iberall's work on lines of nonextension, suggested the orientation, or "weave" direction, of the tensile fibers for the BioSuit design.

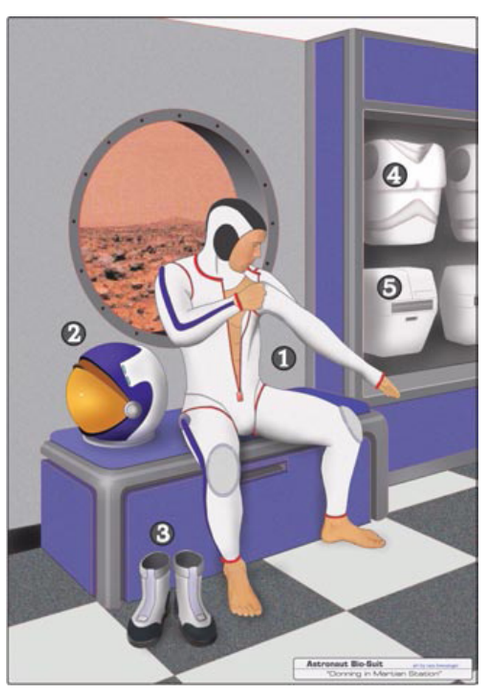
One of the challenges of the BioSuit is to find a way to quickly put it on and take it off. This challenge led Newman to investigate the use of "smart" materials, such as shape memory polymers that are pliable below a transition temperature but return to a more rigid "memory" state above the transition temperature. The team also investigated electroactive materials, as an alternative to shape memory polymers, to solve the "don/doff" problem. This led Newman's team to study the possibility that electroactive materials in the BioSuit might be used as a countermeasure for astronaut deconditioning.

> *If such materials were incorporated into the boots or legs of the BioSuit, an electrical forcing function could drive them to vibrate the legs and mechanically stimulate bone growth.*[19]

Newman's research on electroactive materials in her BioSuit led to an important collaboration on an effort that is not related to space exploration.

> *We have been working with colleagues at Children's Hospital in Boston, Harvard's Wyss Institute, Boston University, and Draper Laboratory to see if we can use our technology and engineering designs to help infants with brain damage that affects motor skills, children with cerebral palsy, and stroke victims, who typically lose motor skills on one side of their bodies. The idea is first to use BioSuit "sleeves" with built-in sensors on the legs to measure movements—to understand, for instance, how much motion and kicking by infants is typical and compare that with the limited kicking and motions of children with cerebral palsy. The next step—a big one—is to add actuators that can enhance and direct movement. In the case of cerebral palsy and stroke victims, that would be a way of giving back some of the lost motion. People with cerebral palsy expend a lot of energy moving and have stiffened muscles; our BioSuit technology and know-how could guide movement and enhance mobility to make it more efficient. And because the brains of newborns are still so plastic, enhancing the natural kicking of infants with potential motor problems from brain damage might actually reshape the motor programs and partly "heal" their brains.*[20]

"we'll probably send a dozen or so people to Mars in my lifetime. I hope I see it. But imagine if we could help kids with cerebral palsy just move around a little bit better."



BioSuit illustration. (Trotti and Associates, Inc.)

In an interview with Mihai Andrei in 2013, Newman put a finer point on the broader application of BioSuit technology, *"we'll probably send a dozen or so people to Mars in my lifetime. I hope I see it. But imagine if we could help kids with cerebral palsy just move around a little bit better."* [21]

As the NRC review committee concluded

> *At the onset of soliciting advanced concept proposals, NIAC's criteria for selecting concepts for funding included the statement that the concept should have the potential for revolutionizing aerospace endeavors and that enabling technologies may not be available. Many of the funded concepts were notably successful in providing an expanded vision for the development of technologies that would have applications far beyond the original advanced concept.*[22]

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[9] Spitzer, L. (1962). The beginnings and future of space astronomy. American Scientist, 50(3), 473–484. Retrieved from http://www.jstor.org/stable/27838468.
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[19] Newman, D. J. (2005), Astronaut bio-suit for exploration class missions: NIAC phase II final report, *the NASA Institute for Advanced Concepts, Universities Space Research Association*. Columbia, MD: Universities Space Research Association.
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[21] Anfrei, M. (2013). The sleek, sexy suit that could take astronauts to Mars. Retrieved from http://www.zmescience.com/space/astronaut-suit-dava-newman-11122013/.
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[23] Hoyt, R. P. (2000a). Tether rendezvous methods. *Interim Report on NIAC Phase II Contract*, 07600-034. Columbia, MD: Universities Space Research Association.
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