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Contact Author:	De Leon, Pablo

NDX-2: Development of an Advanced Planetary Space Suit Demonstrator System for the Lunar Environment

Pablo de León[1] and Gary L. Harris[2]
[1] UND Space Suit Laboratory, Department of Space Studies, University of North Dakota, Grand Forks, ND 58202

Email: deleon@space.edu

[2]Principal Designer, De Leon Technologies LLC; Consultant, UND Space Suit Laboratory, Grand Forks, ND 58202

In 2009 the Space Suit Laboratory of the University of North Dakota began the development of an advanced lunar EVA suit prototype termed the NDX-2 (North Dakota eXperimental 2) under a NASA grant. The NDX-2 has incorporated the improvements achieved during the earlier NDX-1 Mars space suit demonstrator program. After the numerous lessons learned during the development of the NDX-1 Program, new advanced systems were undertaken that, due to time and budgetary constraints, could not be applied to the NDX-1. Also, after careful examination of the methods foreseen for lunar exploration, we arrived at the conclusion that the new suit system would require a specific donning/doffing capability and method that was not contemplated by the NDX-1. Rear-entry (for don/doff), as opposed to the Shallow Dual-Planar type entry (as was used on the NDX-1), would have most likely been employed as part of the Constellation Extravehicular Activity (EVA) lunar missions, if that mission had materialized. Beyond the inclusion of a rear-entry closure, improved, new type torso structure, shoulder, arm, hip, knee, and ankle joint designs were also incorporated, along with improved joint restraint methods. Accordingly the NDX-2 was configured in such a manner that it could be eventually modified to interface with a suitport airlock, capable of allowing the rear-entry closure to dock directly to a habitat or vehicle, thus avoiding dust intrusion into the cabin. Design constraints/assumptions, construction techniques and preliminary results will be presented in this paper.

[1] UND Space Suit Laboratory, Department of Space Studies, 4149 Campus Road, University of North Dakota, Grand Forks, ND 58202

[2]Principal Designer, De Leon Technologies LLC; Consultant, UND Space Suit Laboratory, 4149 Campus Road, University of North Dakota, Grand Forks, ND 58202

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I. Introduction

The principal purpose of the NDX-2 program is as follows:

1. To allow investigators and postgraduate students to explore the parameters of a dedicated EVA space suit system for lunar applications.
2. To explore the advantages associated with a rear-entry (don/doff) upper torso for a lunar-surface walking suit.
3. To explore the advantages of using a Single Wall Laminate, Malleable-Hybrid Upper Torso (M-HUT) with self-sealing characteristics.
4. To test new synthetic materials and construction techniques for restraint layer, bladder and outer chaffing layer fabrication.
5. To investigate if an EVA surface suit system with minimal bearings could be devised with adequate mobility for lunar tasks.
6. To eventually act as a test bed to explore the design challenges associated with a suitport system.

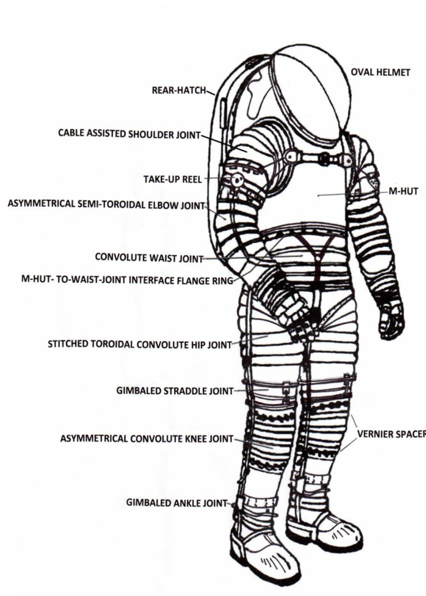

Figure 1a. NDX-2 Lunar Surface Suit Architecture

II. Parameters and Assumptions

In the spring of 2009, the University of North Dakota's Space Suit Laboratory (UND-SSL) began a program to address the requirements of a dedicated extravehicular space suit system for extended lunar applications termed the NDX-2 (see Fig. 1a and 1b). This program was carried out with financial support from a NASA grant. General parameters/assumptions associated with this program are: A lunar surface suit will need to be a "dedicated" extravehicular activity (EVA) configuration. That is, unlike the Apollo A7L and A7LB lunar Extravehicular Mobility Units (EMU), which were suit systems designed to act as an emergency intravehicular suit (IVA), with the added burden of also acting as an EVA suit, any future lunar EVA system will need to be optimized for application on the Moon's surface.

Accepting that the above assumption is a correct one, from our design parameter point of view, the overall configuration of a dedicated lunar surface suit must, of necessity, differ from past operational suit systems. Of course, space suit or aviation pressure suit system requirements must be integrated within the operational confines in which they are employed. In addition, the configuration of such a system is dictated by the environment, space vehicle design and, or, surface habitat from which it must operate.

Figure 1b. NDX-2 Lunar Suit in Early Fit Checks

III. Upper Torso Assembly

Considering the EVA space suit enclosure holistically, the torso structure is the foundation of the entire suit enclosure fabrication i.e., the starting point of the design and suit build. All other elements, such as shoulder joint design options, wrist joint type selection, etc., radiate out away from, and are affected by the torso geometry and structure/shell/closure configuration selected. A good example to illustrate this interrelationship would be a dual-planar closure, such as was employed in the Litton RX-2A of the 1960s (see Fig. 2). This closure type allowed torso room for a sophisticated, fore and aft waist joint. But it also allowed the vertical length to install a side-to-side waist joint between the upper torso and brief. The benefit to the astronaut's reach envelope and enhancement to natural torso motion is without question with such an additional joint. In contrast a torso that employs a rear-entry closure generally precludes the side-to-side function of an RX-2A style waist joint as the length of the rear-entry opening and hatch height take up too much vertical room. This type of torso waist configuration only allows room for fore and aft flexion/extension. [1, 2]

Figure 2. Litton RX-2A

For a comparison, in its lunar surface studies, NASA has chosen to employ a rotational waist bearing in its ZPS Mk-III (also variously termed the “H” suit or the Mark-III – see Fig. 3) mated to a rolling convolute waist joint to render side-to-side motion, and fore and aft flexion. However, the engineering trade-off of a waist bearing means that suit weight is increased as the bearing is comparatively heavy. In addition, waist bearings are expensive, complex and create additional gas leak paths and torsion loads. They are also areas of potential seal failure, have dust intrusion failure modes and are arguably unnecessary as they do not mimic true anthropomorphic motion, i.e., the human body does not actually have a rotation joint at the waist, rather it relies upon the highly limited twisting range of the whole spinal column to rotate from as little as 7 to 15 degrees, depending on the individual. True upper body rotation does not take place at the waist but rather it takes place at the hips and ankles. [3, 4, 5]

Based upon the above examples, and trade-off experience emerging from the earlier NDX-1 program we settled upon an upper torso configuration that used a rear-entry closure in combination with a Single Wall Laminate (SWL) upper torso shell for the NDX-2 Lunar Surface Suit. After consultations with retired former space suit engineers from the firms of Litton Industries and former AirResearch/Aerotherm designers (who have the most experience with SWL structures) we arrived at the conclusion that a SWL structure would have advantages worth exploring over a rigid upper torso (of aluminum or composite fiber), or an upper torso of conventional layering; that is, having a bladder and separate restraint layer such as ILC employed in its “I” suit (see Fig. 4).

Figure 3. ZPS Mk-III, or “H” Suit

During consultations there were arguments against a soft upper torso (conventional design), or even a hybrid upper torso of SWL design (as was used in the NDX-2) on the grounds that a rigid (metal or composite) upper torso structure: (1) would be used to store extra EVA gloves, EVA suit maintenance tools and various other items associated with the suit system anyway, so a malleable (stowable) torso would have few advantages (2) a rigid aluminum upper torso could be made very light weight (3) a rigid upper torso was also well understood technology with mature fabrication techniques (4) a rigid upper torso is a stable platform on which to mount a rear-entry hatch/ring, waist ring, scye bearings, life support, etc. (5) it is also a rigid structure of unchanging geometry, thus imparting a constant pressure/volume relationship.

It stands to reason these are excellent points supporting a rigid upper torso for a dedicated lunar suit. The argument might also be made that NASA’s projected Lunar Surface Access Module (LSAM) may have had the necessary internal volume to store four EVA suits with Hard Torso Structures (HTS) for each proposed crewmember. Moreover, in similar historical studies, in the 1960s, NASA and Litton Industries undertook investigations into methods to integrate Litton’s hard suits into the volume restricted Apollo Lunar Module (LM). Litton’s hard lunar suit prototypes were composed of an inner core of thin, 0.030 of an inch thick, aluminum with a composite of Hexel Honeycomb glass fiber bonded to the outside, covered by a tough, white emissive gel-coat. Litton’s studies demonstrated that the RX-3 through RX-5A hard suits could be used in the Lunar Module (see Fig. 5). The astronauts would have to stand in the RX suit’s lower torsos (which were strapped down to the LM’s deck) during lunar landing. The hard upper torsos of the Litton suits would be stored in the LM during launch and the trans-lunar and trans-earth phases of the flight. As might be expected, another difficulty with this arrangement was that on the Lunar surface the volume penalty from the rigid hard suits left restricted room for the astronauts to sleep, work, etc., inside the LM. [6]

In contrast with an aluminum or composite upper torso, the NDX-2 utilizes a Malleable Hybrid Upper Torso structure (termed an M-HUT) built from an SWL hand lay-up (see Fig. 6 and Fig. 8). The M-HUT build has certain advantages: (1) a Single Wall Laminate fabric structure when unpressurized is foldable, giving it the similar potential stowability of a soft suit. When pressurized, however, the SWL suit shell will mimic the attributes of a hard suit shell. That is, it will take on the beneficial rigid, constant volume geometry of a hard suit, i.e., its shell modulus of elasticity is such that it exhibits no stretch in any direction of fabric bias. This enhances suit mobility thru volume monostability. [7]

Figure 4. ILC "I" Suit

Though the Single Wall Laminate pressure suit construction method was first invented by the Arrowhead Rubber Company in the 1950s, it was in the late 1960s and early 1970s, that AiResearch engineers fabricated SWL space suit elements of the EX-1A and AiResearch Advanced Extravehicular Suit (AES) for the later Apollo Program (Litton also used an SWL system for its Constant Volume Suit and Advanced Extravehicular Suit programs). These Apollo era SWL elements, such as torso, elbow joints, knee joints, etc., were formed on hollow Plaster of Paris mandrels (the mandrels themselves were cast inside rigid molds). The fabric was hand-laid around the mandrels, with three layers: an outer layer, an inner bladder and an inner comfort layer. Each layer was biased at 22.5 degrees from the previous laid-up layer (see Fig. 7). All were bonded together forming a single monolithic wall that "locked in" the shape of the elements and prevented bias stretch omni-directionally. After drying, the completed fabric shell, or mobility component, was removed from the mandrel by breaking the Plaster of Paris. This process, while allowing repeatable production of shell components, nevertheless, made for a lot of steps to production [7].

Figure 5. Litton RX-3 Lunar Hard Suit in LM Integration Tests

Like earlier SWL elements (such as the torso) made by AiResearch and Litton, the M-HUT of the NDX-2 is also constructed with similar SWL layers, all set at 22.5 degrees of bias. The outer layer utilizes a white, extruded plastic, tightly woven fabric cut in a one piece pattern. This synthetic acrylic fabric weighs eight ounces per square yard (271 grams per square meter) and was selected due to its resistance to mold, human sweat and body oils and it was a pliable, soft but robust fabric with a plain-weave that demonstrated acceptable adhesion with Isoprene (a type of liquid Latex), while at the same time not allowing membrane bleed-through. It was also flame resistant in air. This fabric also exhibited good rip propagation qualities; that is, individual "pics" or fibers would not rip after a 0.25 inch (6 mm) linear incision was made at suit over-pressure levels of 1.5 times nominal operating pressure (nominal operating pressure is 4 psi or 27.6 kPa). The fabric was coated, on the inside, with three layers of thin, white Isoprene and three layers of yellow Isoprene. The contrasting colors were selected to insure complete coverage and to prevent permeability. At this point we differed from the earlier SWL construction practice and instead of using a fabric bladder layer we laid a fiberglass mesh layer, biased at 22.5 degrees from the inner, to the outer layer and coated it with white Isoprene (see layer 2, in Fig. 8) making sure all of the cells in the mesh were filled in. A soft fiberglass mesh was chosen as it displayed no stretch in the direction of Warp and had approximately one percent limited stretch in the Weft (fill picks). In other words, it displayed similar linear characteristics as the extruded plastic fabric to which it would be bonded. Equally important, the mesh would render considerable self-sealing ability to the shell. This last feature requires some explanation: The Shuttle EMU (also termed Enhanced EMU) uses a Hard Torso Structure of fiberglass in a resin matrix. However the soft mobility elements and lower torso are fabricated with a Dacron Polyester restraint layer overlaying a Nylon bladder layer on which is bonded a polyurethane membrane. This bladder is more robust and resistant to tears than an equal type conventional Nylon supported Latex bladder (such as is used in the Russian Orlan EVA suits), but once penetrated displays no self sealing qualities, i.e., the Nylon supported polyurethane bladder will continue to leak at a constant rate.

In contrast the NDX-2 M-HUT was designed to allow penetration of the torso shell wall by a 1 to 1.5 millimeter needle and still reduce its leakage by 70 percent, or greater, over that of a polyurethane bladder. The M-HUT achieves this through each of the fiberglass mesh cells being filled with Isoprene. When an object penetrates the M-HUT, the mesh fiberglass strands are forced outward by the penetration. But since they are imbedded in a flexible Isoprene matrix, the fiberglass strands attempt to reassume their original shape around the penetrating object. If the object is withdrawn, the fiberglass strands, working in concert with the Isoprene, and the tightly-woven plastic fabric supporting layers, reseal the penetration. In practice such a structure can never fully reseal itself and is more accurately termed leak-limiting (much like military aircraft fuel tanks).

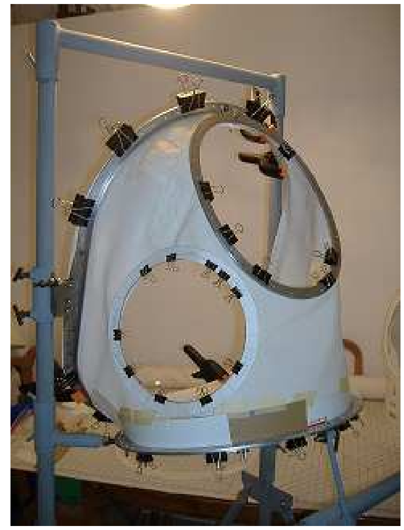

Figure 6. NDX-2 M-HUT SWL Construction

Over the middle fiberglass mesh layer an innermost layer of the white extruded plastic fabric, coated with six layers of Isoprene (like the inner contrasting color layers), and biased at 22.5 degrees from the lay of the fiberglass mesh was bonded on (again see Fig. 8). Darts cut from the inner layer to let it conform to the two previous layers were overlaid with coated patches and glued with a bonding agent specifically formulated for the extruded plastic fabric.

The M-HUT was fabricated by interfacing with a series of aluminum metal rings. The rings, as were most metal components of the NDX-2 suit system, were fabricated through the process of Computer Aided Design/Computer Aided manufacturing (CAD/CAM) water jet cutting and Tungsten Inert Gas (TIG) welding. The CAD/CAM method was chosen as unlike plasma-arc, CAD/CAM cutting would not thermally warp some of the thin metals used in the suit. Fabric elements of the suit were clamped to the metal rings by matching flange rings and sealed using a 0.5 mil polyester, non-permanent tape, coated on both sides with 3 mils of ultra high peel acrylic adhesive. This sealing tape method was chosen as it will adhere well to aluminum, polyurethane or acrylic, and has been used in our glove box penetration sealing at differential pressures of 10 pounds per square inch (69 kPa) and in the DL/H-1 suit bladder-to-wrist and helmet ring interfaces.

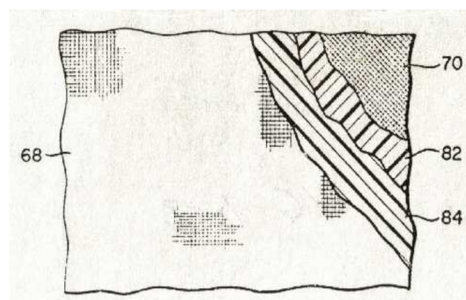

Figure 7. AiResearch SWL Construction

The helmet rings, rear-entry and waist rings were pre-mounted to an adjustable metal form that later also served as the don/doff stand. The stand is Shielded Metallic Arc Welded (SMAW) from mild steel pipe, bolted at oblique nodes and is equipped with castors. It is also equipped with steps and a seat to allow the suit occupant to slide into the rear-entry hatch. An overhead handrail tops the stand to allow the suit occupant to lift themselves into the suit (see Fig. 9).

IV. Helmet

The helmet is an oval shape, with internal dimensions of 10.56 inches (268 mm) wide by 12.93 inches (328mm) fore and aft, and 7 inches (178 mm) tall, set at an angle 50 degrees to the horizontal (see Fig. 10). The helmet shape is dictated by the upper torso's rear-entry concept (where only a true hemisphere, or hemispherical-oval would interface), and by the need to minimize the interstitial distance between the shoulder openings in the M-HUT, i.e., the oval helmet bubble allows the left and right shoulder joints to have less distance between them, thus creating a closer anthropomorphic fit to the suit occupant's shoulders. This allows greater flexion-extension and lateral-medial motion range for the shoulders. If a true hemispherical helmet had been used on the NDX-2 (as NASA employed on its rear-entry ZPS Mk-III, or "H" Suit) it would have had to be mounted on a rigid, mushroom shaped helmet mount, to get it up above the shoulders so as not to interfere with shoulder motion/width. The addition of a mushroom shaped helmet mount would have added extra weight, cost more and made the M-HUT less stowable.

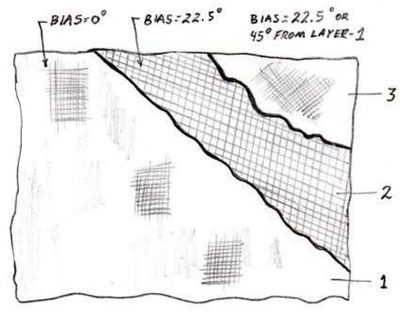

Figure 8. NDX-2 M-HUT SWL Construction (1 Outer layer, 2 Fiberglass Mesh, 3 Inner Layer

V. Rear-Entry Closure

The NDX-2 utilizes a rear-entry suit don/doff hatch, which also serves as a hermetically sealed don/doff closure and as a mounting surface/interface for the backpack portable life support system. The rear-entry don/doff hatch is entered while the suit is mounted in its mobile suit stand that supports the suit and retains it in an upright position advantageous to donning/doffing. The rear-entry closure configuration dictates the architecture/dimensions of the NDX-2's upper torso and helmet design, and also influences the design of the shoulder joints, and the design of the waist joint. As was noted earlier the selection of a rear-entry closure was chosen as it allowed the suit to interface with a suitport and was the easiest design to don/doff. [8]

Advantages

A. Easier to don/doff. It can be made truly self donning.
B. Has a long history of successful operational employment within the Russian Orlan family of EVA space suits.
C. Less complex and less expensive to manufacture. Does not have to be machined from a large metal billet on multiple planes. It can be cut affordably using mature, well understood CAD/CAM water jet processes or CAD/CAM machining.
D. The rear-entry hatch can also serve as the back pack, placing the Life Support System (LSS) components within the pressurized volume of the suit; or the rear-entry hatch can serve as the mounting structure to bolt the LSS pack to, if the suit components are to be exposed to the space vacuum.
E. Has the added LSS benefit of allowing back pack maintenance by simply opening the hatch, thus exposing all of the LSS pack components to easy reach.
F. Can use a simplified knife edge seal and compression gasket to hold in suit pressure (on the NDX-2).
G. In the future, it can be manufactured from composite materials to save weight.

Figure 9. NDX-2 Helmet, Waist, and Rear-Entry rings

Disadvantages

A. Requires a suit stand to hold up the suit for don/doff. This creates an inconvenience of moving the suit stand where the suit is needed in the lab or field. In weightlessness the suit can be mounted to a bulkhead, so this is not a problem, but the majority of time any suit is employed is mostly in training.[9] The Shuttle EMU (using a single-planar body seal ring closure at the waist), or a suit that uses a dual planar closure, can be donned by sitting down on the floor and pulling on the Lower Torso.
B. A rear-entry hatch limits the vertical room available for a multi-axis waist joint; but, this problem may render itself to an engineering effort. Generally a highly mobile walking suit would need not just a fore and aft motion waist joint like the NDX-2; it might also need a waist joint with side-to-side motion range. In the past, experimental NASA EVA space suits such as the AiResearch's EX-1A and Litton and AiResearch Advanced Extravehicular Suits (AES) have used

a side-to-side joint in the waist. This allowed the suit user to have acceptable reach in the side range while also bending over. In the Shuttle EMU to have side reach, NASA employed an Ames Research Center innovation of a waist rotational bearing.

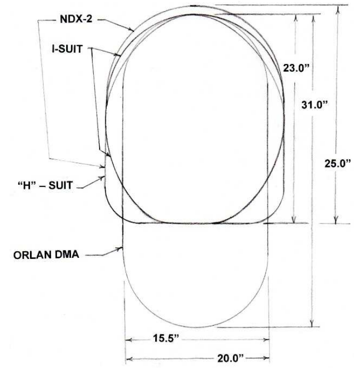

Figure 10. Rear-Entry Dimensions of the Orlan, I-Suit and Mk-III Hatch

The rear-entry hatch opening of the NDX-2 is 20 inches (508 mm) wide by 25 inches (635 mm) tall. After a low fidelity test and a search of papers published on the subject these dimensions seemed the most appropriate engineering trade-off based on the rear-entry opening sizes of three other rear-entry configured EVA suits. The early Russian Orlan EVA suits used a rear-entry opening of 15.5 inches wide (394 mm) by 31 inches (787 mm) tall. Cosmonauts are, collectively, the shortest in anthropomorphic dimensions in comparison to American and European astronauts of European descent and Americans are the tallest astronauts with Europeans falling between the two extremes. We note that the newest versions of the Orlan family of suits, the suit that evolved from the Russian-European Space agency (ESA) Space Suit-2000 Program, and experimental suit the Russian's title the "Z" suit has a rear-entry opening of 17.87 inches (454 mm) wide by 28.5 inches (724 mm) tall. This disparity in comparison to the older Orlan suits came about so that European and American astronauts could fit Russian EVA systems.[10, 11]

The NASA/ILC/Hamilton Sunstrand built ZPS Mk-III (or Hybrid suit or "H" suit: no name seems to be arrived at permanently for the suit) rear opening is 20 inches (508 mm) wide by 23 inches (584 mm) tall and the ILC "I" suit rear opening is also 20 inches wide by 23 inches tall (see Fig.-10). The NDX-2 rear-entry opening is tilted 15 degrees forward of the vertical. This angle was arrived at after donning tests with a low fidelity mock-up ring mounted in the suit donning stand. This angle allows the suit user to more easily slide "down" into the suit rather than work into the suit only on a horizontal plane

VI. Shoulder Assembly

Figure 11. NDX-2 Shoulder, Elbow Joints and Gloves

Because we were attempting to make a stowable upper torso, we have retained a rigid helmet mount, rigid rear-entry rings and rigid waist pressure/load ring but foregone shoulder scye bearings. The placement of scye bearings would be in the direct path of where the M-HUT shell needed to fold. Drawing on experience in fabricating an earlier pressure suit system, the DL/H-1, that used a cable assisted shoulder joint (similar to that used in Apollo – see Fig. 12), we are now using an improved dual cable assisted shoulder riding on silicon bronze micro-blocks/sheaves contained in stainless steel/Teflon carrier assemblies, and mounted to a carrier assembly, in place of a scye bearing (see Fig. 11). The NDX-2 shoulder cable arrangement allows for flexion/extension of the shoulder from 0 degrees (zero being with the arm down resting against the side) up to about 140 degrees. Of course these numbers are somewhat subjective as they depend on the sizing/fit of the suit occupant. The cable assisted shoulder also allows adduction/abduction from about 114 degrees (the arm out away from the upper torso) to approximately 40 degrees (arm horizontally crossing the upper torso). The stainless steel cable is rove in a cloths-line pattern with the cable bitter ends anchored at the upper arm interface assembly. No torque values were available for the shoulder joint at the time of writing this paper.

VII. Arm Assembly

The shoulder joint material was of the same synthetic fabric used in the M-HUT; however, the shoulder is not SWL construction but rather of a more conventional restraint layer/mixed-media bladder. The shoulder convolutions are of flat-panel convolution design but using preshortened tapes to form the circumferential minor diameters of the convolute segments. The shoulder joint and upper elbow joint are joined at an aluminum ring with no upper arm bearing.

The elbow joints are termed Asymmetrical Semi-Toroid (AST) joints. They are, in function, a mix between a flat panel convolution and a true toroidal joint, using the best features of both to form a highly mobile, low-moment joint. A true toroidal joint is formed on a mandrel and is SWL construction. In contrast, a flat panel joint (not to be confused with a flat pattern joint as used in the Shuttle EMU), is a convolute arrangement that is formed by cutting a series of darts from a flat sheet of rectangular fabric (restraint layer fabric). The areas between the darts then form a series of gores. The dart edges are then bonded and stitched. This section forms the tensile side of the joint, or back of the elbow. To form the compressive side, or front of the elbow, a flat piece of rectangular fabric is sutured to the tensile side to form a tunnel; a tunnel with adequate fabric relief on the tensile side of the elbow. Then webbing tapes are bonded and sewn on circumferentially around the apex of the convolutions and in the minor diameter between each convolution. The longitudinal webbing restrain member is then attached to the neutral areas at each convolute apex. This tape/restraint arrangement forces the joint, when it is flexed, to maintain co-incidence between the center of pressure and the center of restraint for much of its flexure range.

Figure 12. DL/H-1

The bladder for the elbow joints, and all of the waist and lower torso assembly, is a Nylon supported polyurethane membrane, essentially the same as the Shuttle EMU bladder. The laboratory has gained considerable experience with complex patterning and welding polyurethane/Nylon bladder material from two earlier suit programs. Each finished bladder element of the NDX-2 was subjected to a "stand-alone" test load of 8 psi (55 kPa); that is, each was tested to twice its nominal operating pressure of 4 psi (27 kPa). This test was performed to insure seam weld integrity. In past tests, however, we have created polyurethane/Nylon welded seams that achieved 30 pounds per square inch (207 kPa) burst strain. All tests were undertaken without the restraint layer for support.

The elbow joint bladder patterns are designed to "nest" the bladder convolutions inside the bladder restraint layer patterns. The apex of each joint convolution is nested and attached to the corresponding layer of restraint material to prevent bladder "wandering" and alleviate bladder bunching.

The restraint system of each elbow joint is a Teflon impregnated stainless steel cable. The cable is anchored by a ratchet mechanism at the shoulder joint/elbow joint interface ring then rove through a series of Silicone Bronze spool shaped guides attached at the apex of each convolution (on the neutral seam). The cable is then passed through a Fluoroplastic guide tube at the wrist and travels back up the elbow joint, being anchored once again at the interface ring in the Scye area. This cable arrangement allows the joint vernier length to be quickly resized, imparts low joint moment to the elbow and renders limited arm medial/radial motion. The Russians utilized this concept in their early Orlan EVA suits.

The wrist joint is not equipped with a bearing. Funding and time was simply too limited to allow design of such an assembly. The NDX-2 gloves are copies of an earlier glove designed for the DL/H-1 emergency pressure suit under De Leon Technologies LLC funding (see Fig. 11 and Fig. 12). They are a Nylon fabric construct; with rolling convolute joints providing flexion-extension and adduction-abduction range of motion in the wrist. The thumb and finger joints are of a tucked-fabric configuration providing motion in a single plane. The palm is equipped with a malleable (adjustable) palm bar to restrain palm cross sectional shape. De Leon Technologies has developed a series of high mobility EVA gloves, but did not apply them to the NDX-2 suit due to funding reasons.

VII. Waist and Lower Torso Assembly

The waist joint of the NDX-2 is presently of a conventional flat panel convolution design; however, the waist joint will be replaced with a lower torque Asymmetrical Semi-Toroid joint during the summer of 2011. The waist joint is equipped with redundant restraint straps (in the neutrals of the joint) and back-up straps on the anterior and posterior. The hip, elbow and knee joints, while of conventional materials (bladder/ restraint combination) are also an advanced design AST joint system. The AST joints can closely mimic the volume stability effect of a true toroidal convolute joint but are less labor intensive and less expensive to fabricate, with few of the tiny piece-parts of a conventional toroidal joint. The AST joints also borrow some concepts from the flat pattern joint. The AST joints are built using a proprietary pre-stressed method developed independently by one of the authors of this paper while employed with a previous employer. However, it can be noted that the AST joints are fabricated using conventional sewing techniques. The upper hip joint elements are also AST joints, but lower hip (straddle) elements are convolutes supported by gimbal rings.

In part what assists the AST joint to maintain a constant volume through much of its flexion range is an extra fabric strip sutured onto the apex of the convolute section of the tensile and compressive side of the joint, and the stable "nesting" of the bladder into the joint convolutions.

Figure 13. NDX-2 Soft restraint Layer Components

The high mobility knee AST joints differ from the hip joints in that they use a convolution on the tensile side (front of the knee) with a partial flat pattern fabric on the compressive side (small of the knee), though they do use the toroidal tape across the apex of the tensile convolution (see Fig. 13 and Fig. 14).

However, unlike a conventional flat pattern joint, the tensile convolutions do not end at the neutral vertical line on the sides of the joint. Instead they extend several inches (horizontally) into the compressive side of the joint. This patterning innovation was done to (1) eliminate the bending resistance endemic to the flat fabric section in the neutral area of the standard flat pattern joint (2) create a series of more predictable joint break lines on the compressive side of the joint (3) allow for a larger fabric relief and radius on the tensile side of the joint, thus creating a more stable geometry when the joint is flexed to its extreme angle (4) have the benefit of some "spring return" (neutraling tendency) to help the suit user to swing (extend) the leg back to neutral in the lower 1/6th lunar gravity, and lastly (5) eliminate the "bunching" discomfort that would be experienced in the small of the knee, from so many circumferential tape lines (minor diameter and apex of the convolutions). In bench tests at 4 psi (27 kPa) pressure the knee joint can maintain a relative constant joint moment through most of its bending radius (standing full erect, for example) to complete flexure of approximately 130 degrees.

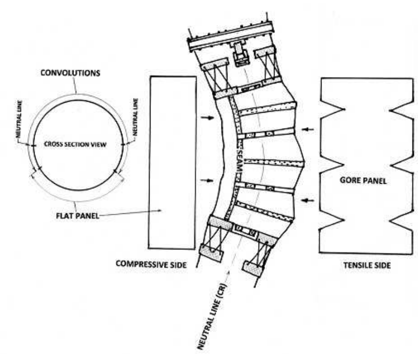

Figure 14. AST Knee Joint

The AST knee joints also receive part of their low torque performance from a restraint member (strap) innovation developed at the UND suit lab that uses a one inch wide (25.4 mm) heavy Nylon restraint strap. Generally speaking, longitudinal restraint members (straps, cables, linkages) for single axis mobility joints must of necessity be narrow (side-to-side width), but pliable/flexible with limited longitudinal stretch. Generally speaking, when a wide restraint strap comes under longitudinal loading, as a mobility joint, to which it is attached, is pressured up, a wide strap is more difficult to flex, i.e., as the restraint strap is flexed the wider strap will have a radius on the tensile side of the strap that is much greater than the radius on the compressive side of the restraint strap. When the joint is flexed (bent) these resultant incongruous radius values place the strap under a stretching load on the tensile side of the strap and a compressive load on the compressive side of the strap. On the compressive side of the restraint strap, this Delta load is of limited consequence as the strap, once it gets relief (by the onset of the smaller radius during bending) will simply fold up to come into co-incidence with the radius imposed upon it. In contrast, the restraint strap force that contributes to high torque in the mobility joint emanates from the tensile side of a wide strap. The tensile side, due to its inelasticity under load, simply can not elongate enough to come into co-incidence with the radius, or joint motion range, to which a mobility joint is capable.

That said, a narrow restraint strap is not going to be as strong as a wider strap (of equal material), and it goes without saying that a designer wants the strongest restraint member possible, within the boundaries of other conflicting requirements such as pliability, etc. As a safety feature, and to avoid the possible catastrophic consequences of a restraint strap failure, NASA requires two restraint straps on each side of its single axis mobility joints. The result of this redundancy is that multiple restraint straps (and, or, stronger straps) often result in higher joint torque. To avoid this redundancy and contribute to low torque values, the NDX-2 knee joints use a single, one inch wide, heavy Nylon restraint strap on each side of the knee joint neutral line (see element A in Fig. 15). The one inch wide (25.4 mm) restraint strap is pre-folded on the horizontal plane coincidence with the minor diameters of the AST knee joints (see element B, Fig. 15). The folds are then bonded and lock stitched. This folding has the effect of turning the restraint strap sideways in the local area of the fold. The unfolded section of the restraint strap is lapped-over by a short section of webbing strap (again see element B, Fig. 15) and both are bonded and sewn to the webbing tape that runs circumferentially around the apex (major diameter) of the joint convolutions. During joint flexure the restraint member now "bends" at its narrowest diameter, i.e., horizontally coincident with the minor diameter of the joint and the majority of restraint member induced joint moment torque is eliminated (see element C Fig. 15).

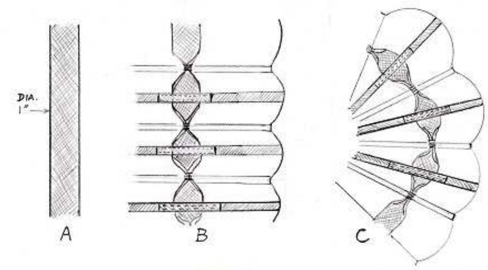

Figure 15. AST Knee Joint

As part of the knee joint assembly, above and below the knee joints are lacing supported vernier sizing spacers. These spacers are capable of adding length to the leg assembly of approximately 4 inches (about 101 mm). Stainless steel friction buckles, as part of the knee longitudinal restraint system also contribute to rapid vernier sizing. Once the friction buckles are adjusted, the restraint strap is locked-in to the buckle by a redundant safety keeper/fastener.

A straddle joint is provided between the knee joint and hip joint. The straddle joint is anchored to the hip joint restraint straps and upper leg interface ring and rotates on a stainless steel gimbal ring. The joint is equipped with redundant longitudinal restraint members.

Figure 16. NDX-2 Boot Assembly

VIII. Ankle and Boot

The ankle joint also uses a single stainless steel gimbal ring. This ankle joint design is a direct influence of Russian engineering and was first used in an experimental Russian walking EVA suit prototype in the early 2000s. We used this design in the earlier NDX-1 walking suit and were impressed with its mobility range, and stability. The gimbal ring imparts excellent flexion/extension combined with adduction/abduction. Since using this joint in the earlier NDX-1 suit, we have also improved its support in the adduction/abduction motion. This was done due to the ankle joint being too flexible in the adduction/abduction motion range. This large range of motion, while mimicking the nude range of which the ankle is capable, nevertheless created fears of allowing the ankle joint to "twist" too far during lunar locomotion in the adduction/abduction plane, and thus injuring the suit occupant's ankle. This motion range in the adduction/abduction plane was reduced by removing one convolution from the ankle joint (in comparison to the earlier NDX-1 walking suit ankle joint). Additionally we also enhanced safety by developing redundant longitudinal restraint straps in the ankle area.

The space suit boot (lower half) is a synthetic, cold weather boot lower element. To further strengthen the boot, we combined the lower assembly with an upper transitioning, composite, rip-stop fabric, bonded and sewn to a Zylon para-aramid composite backing that is stronger than leather (in trapezoidal tear strength). Field testing in the undulating North Dakota Badlands test site during the fall of 2011 will demonstrate if the boot and minimal bearing system was a wise choice.

IV. Conclusion

As funding becomes available a more sophisticated system, now under development will allow the rear-entry system to hopefully interface with a simulated suitport airlock. As of the time of this writing, the Constellation lunar return program has been cancelled; however, limited funding is still available and early bench tests continue on the NDX-2. Full pressure testing is in intermittent progress and field tests are scheduled to begin in the late summer or autumn of 2011. The M-HUT SWL and advanced mobility concepts utilized in the NDX-2 suit system, along with the minimal bearing approach is proving to be a workable concept but final results rely on further testing and interface tests with a suit port/habitat/vehicle system now under development at UND.

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