

# Neutral Buoyancy Technologies for Extended Performance Testing of Advanced Space Suits

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## ABSTRACT

Performance of new space suit designs is typically tested quantitatively in laboratory tests, at both the component and integrated systems levels. As the suit moves into neutral buoyancy testing, it is evaluated qualitatively by experienced subjects, and used to perform tasks with known times in earlier generation suits. This paper details the equipment design and test methodology for extended space suit performance metrics which might be achieved by appropriate instrumentation during operational testing. This paper presents a candidate taxonomy of testing categories applicable to EVA systems, such as reach, mobility, workload, and so forth. In each category, useful technologies are identified which will enable the necessary measurements to be made. In the subsequent section, each of these technologies are examined for feasibility, including examples of existing technologies where available. All of these measurements systems taken together can provide a much more detailed and quantitative evaluation of a pressure suit in realistic simulations of its operating environment.

## INTRODUCTION

Space suit design is a field of continual development which works to further the capabilities of astronauts working in space or on a planetary surface. The tremendous increase in extravehicular activities (EVA) associated with the International Space Station (ISS) provides a continual impetus to improve the Shuttle extravehicular mobility unit (EMU) as well as the Russian

Orlan suit. Similarly, focus on manned missions to Mars and return to the Lunar surface provide the drive to develop advanced space suit systems for these endeavors.

The development of new, or improved, suit components typically culminates in laboratory tests which quantitatively measure the performance characteristics of the new component. Tests at this level may include bench-top measurements of joint torque, range of motion, strength and/or durability. Next, improved components are integrated into the suit system and tested at the systems level; again, typically through standard joint torque, range of motion and strength/durability tests [1] [2].

At this point, further performance data is typically collected qualitatively by experienced test subjects who can compare new suit performance with that of earlier generation suits. Facilities like NASA's Neutral Buoyancy Laboratory (NBL) at the Johnson Space Center are the typical sites for this level of testing for EVA suits. Planetary suits typically find performance evaluation in simulated Martian environments like the simulated Lunar/Mars terrain area at the NASA Johnson Space Center, or in field trials such as those of recent years at Silver Lake, Meteor Crater, or the Mars Society testing grounds at Devon Island [3] [4]. These simulations can, and are, being improved by testing under the reduced gravity conditions achieved during parabolic flight aboard the KC-135.

All of these methods have contributed to substantial improvements in space suit design, and each has proven useful over the years. However, each method

of system level testing is not without its drawbacks. Terrestrial testing of planetary suits provides a wealth of data on suit design; however, the reduced gravity of both Mars and the Moon will have significant effects on suit performance which are not being captured in such testing. KC-135 flights, while they do capture reduced gravity conditions, are prohibitively expensive and short in duration. And across the board, including the neutral buoyancy tests for EVA suit evaluation, the largest problem with current performance testing is a lack of quantitative data collection.

To achieve revolutionary advances in pressure suit design, testing methodologies need to be further developed to allow quantitative testing of performance during suit operations testing, which may be development, training, or even in-flight operations. This paper proposes an integrated approach to advanced suit instrumentation and testing which applies at a number of levels, ranging from simple methodologies to obtain quantitative comparison data, to unobtrusive sensor systems which will provide information on crew sensorimotor adaptation, metabolic workload, and other significant metrics of performance for the integrated human/suit system.

In a sense, this paper really presents a vision of an integrated system for suit instrumentation, testing, and evaluation that is compatible with neutral buoyancy, field trials, and even flight evaluations of advanced suits. In many cases, examples will be drawn from past and present research projects of the University of Maryland Space Systems Laboratory. These sample systems presented range from concepts, to breadboarded systems used for proof-of-concept testing, to highly developed systems already used for advanced research. In no case will this paper go into the detailed results of any of these individual component technologies; rather, this paper will focus on developing a set of useful components for an integrated suit evaluation system, and will describe how all the components may be brought together to create a useful synthesis of performance metrics.

## **DESIRABLE EVALUATION METRICS FOR SUIT OPERATIONS**

When a current space suit reaches integrated test status, the primary focus is on getting experienced subjects into the suit, and having them perform tests which correlate to prior experience. This approach is adequate for qualitative evaluation of design changes, but does not provide a full quantitative insight into the effects of suit design modifications. What, then, are the metrics which need to be included to provide a more

complete picture of human/suit performance? Within each metric, what technologies are required to provide useful quantitative measures of performance? Some beneficial candidates can be summarized under the following categories.

## **DEXTERITY AND REACH METRICS**

The vast majority of EVA development consists of answering two questions: Can you reach it? And when you do, can you operate it? A greater degree of rigor in the quantification of reach and dexterity metrics would provide hard metrics on critical suit capabilities, as well as provide the necessary data base for advanced simulations of pressure suit operations.

In this category, the objective is to quantify the reach of the suit with respect to some fiducial point on the suit itself. Often this has been the suit upper torso; this provides a reach envelope of the arms alone. This data may be reconstructed by forward transformation of arm joint angles without external measurements. In other cases, it has been a reference point between the feet, which allows the incorporation of suit flexibility in reduced or microgravity. These tests traditionally involve the use of neutral buoyancy or parabolic flight, and are therefore indicative of microgravity. There are no known full-body reach envelopes for partial gravity, such as lunar or Mars conditions.

Traditional reach envelope testing of pressure suits has been performed in the laboratory (1 g) environment. This was traditionally performed with manual photogrammetry or goniometers, but has lately been upgraded to automatic photogrammetric analysis. Electromagnetic position sensors also function well in this controlled environment.

Technologies applicable to this category of metrics include:

- Accurate automatic position sensing
- Whole-body partial gravity simulation
- Limb pose measurement
- Standardized dexterity tests

## **MOBILITY METRICS**

While reach envelopes measure the crew's capability to span distances from a fixed point, overall work station design relies on the ability to translate from task location to location. This translation task frequently is the largest "mass handling" task of the EVA, and suits which facilitate this type of motion convey an advantage for the wearer. Looking at the problem in the other direction,

EVA timelines which reduce the requirement for the crew to manipulate their own body positions free up time to perform the required tasks. However, there has been little means of measuring body motion other than coarse inference from the work station design.

A system which can monitor the subjects body motion in all six dimensions (three translational and three rotational) could provide much finer-scale data on mobility as a component of operational tasks. This would aid in refining work site design protocols. It would also provide sufficient data for direct calculation of crew energy which is expended in body motions, which will help to obtain more accurate energy estimates of the actual task operations.

Technologies applicable to this metric include:

- Automated six-axis state measurements

## FORCE/MOMENT CAPABILITIES

Forces and moments are critical to EVA operations, and to the safe design and operation of EVA systems. Crew loads are often the driving factor in the design of advanced pressure suit components, and are of primary concern in the safe design of tools and interfaces for the EVA worksite. However, forces and moments are not generally well understood from a "first principles" point of view. Suit joint torques are generally measured by simple scales applying external forces on suit components [5]; few opportunities for direct internal force measurement exist in harmony with the space suit wearer.

However, significant types of data can be learned with well-placed six-axis force/torque sensors. For instance, applied forces to a handrail can be directly measured by force-torque sensors under the handrail, and substantial information can be further gleaned from six-axis force-torque measurements in the foot restraint mounting mechanism. To obtain this data from ground-based simulations, however, these sensors have to be packaged to be compatible with the simulation environment.

Some hope still exists that direct force or torque measurements may be obtained from occupied pressure suits. Force or pressure transducers mounted between the wearer's limbs and the pressure suit garment may give readings related to the relative force between them, and therefore capable of providing estimated forces and torques applied through the pressure suit.

Technologies applicable to this category of metrics include:

- Environmentally compatible force-torque sensors
- Suit-compatible low-profile wearable pressure or force sensors

## PHYSIOLOGICAL WORKLOAD MEASUREMENTS

Ultimately, the true measure of any pressure suit is the physiological stress it places on its wearer; that is, the extent to which the EVA crew expends energy in moving the suit rather than performing the assigned task. A common tool in physiology laboratories are measurement systems for metabolic workload, particularly oxygen uptake (VO<sub>2</sub>) systems. This capability has been incorporated into pressure suits for flight EVA measurements, but has never been routinely available for neutral buoyancy or other ground-based simulations.

This type of measurement is uniquely valuable for understanding to overall issue of pressure suit limitations on the wearer. For example, metabolic workload measurements were available for the Extravehicular Assembly of Structures in EVA (EASE) activities on STS 61-C. The measured metabolic workload, based primarily on oxygen consumption, could be corrected for basal metabolic workload to find the physiological demands on the test subject. Photogrammetric means were used to calculate the energy going into the EVA tasks. Comparison of the results indicated that only 25% of the physical activity of the EVA crew was being applied to the task elements, implying that the remaining 75% of the crew's energy was being applied to operating the pressure suit. [6] This process provided a unique and graphic example of the limitations of conventional pressure suits, and illustrates the utility of routinely available physiological workload measurements.

Technologies applicable to this category of measurement include

- Pulmonary function metabolism measurements
- Thermal balance monitors

## NEUROMUSCULAR ACTIVITY MONITORING

While proposed sensor systems to this point have focused on what the EVA crew is doing and what physiological exertion is required, there has not yet been any attempt to understand how the actual motions are produced. One of the common comments following an EVA is that specific locations of the subject are heavily fatigued by the end of the operation. Frequently, this occurs in the hand and wrist, which are heavily

tasked and working at considerable mechanical disadvantage in pressurized gloves. This fatigue limits crew performance, particularly later in an EVA, and is a potential safety hazard if fatigue is allowed to progress to the point where manual tasks required for close-out and ingress become difficult to perform.

Ideally, the degree of muscular fatigue should be monitored in a noninvasive manner. Such a system would allow direct measurement of fatigue onset rates; this would provide an ideal quantitative metric for evaluating new designs for suit gloves or other suit articulations.

Technologies applicable to this category of measurement:

- Electromyographic Monitoring System

### SENSORIMOTOR ADAPTATION

One of the purposes of repeated training is to induce sensorimotor adaptation to the required tasks. This "muscle memory" produces instinctive response to stimuli, and thereby uses natural body control loops to provide near-optimal responses.

A good example of this is the use of rotary bearings in suit components, such as the shoulders of the Shuttle Extravehicular Mobility Unit (EMU). Direct shoulder extension/flexion can frequently result in forces perpendicular to the bearing rotation direction, which requires high loads to overcome bearing friction. Bringing the arms forward therefore is best done by moving the shoulders through a rotation pattern which more nearly matches the rotation directions of the bearings. Until this "patterning" becomes instinctive to the wearer, much energy may be expended on trying to force the shoulder bearings to move in directions of poor mechanical advantage.[7]

Understanding and documenting this sort of sensorimotor adaptation has been difficult in the past, and has relied upon qualitative anecdotal information. By directly measuring body joint angles, however, a running record may be kept on body motions inside the suit. This record would document when and where patterning adaptations take place, and would serve as a quantitative metric on crew training and flight readiness.

Technologies applicable to this category of metrics include:

- Joint angle measurements

## TECHNOLOGIES FOR ADVANCED SUIT INSTRUMENTATION

Each of the measurement categories from the preceding section will be briefly examined to identify feasible approaches to the creation of suitable EVA-compatible instrumentation. Where appropriate, prior art will be identified and discussed.

### AUTOMATED POSITION SENSING/ AUTOMATED SIX-AXIS STATE MEASUREMENTS

The requirement for this sensor system is to provide unobtrusive measurements of more or more positions at regular time intervals. Based on potential motion velocities, data collection rates need to be on the order of several times per second in order to facilitate accurate estimates of velocities. This should be capable of being time-tagged and automatically logged, for correlation against activities or workload measurements.

The University of Maryland Space Systems Laboratory originally developed the Three-Dimensional Acoustic Positioning System (3DAPS) as a means to collect accurate position and attitude data for feedback control of robots in a neutral buoyancy environment. Like the Global Positioning Satellite system, 3DAPS uses the ranges from known locations to receivers on the vehicle to produce a three-dimensional position estimate. Due to the physics of the underwater environment, the approach used was the time of transmission of ultrasonic acoustic pulses from multiple emitters at known locations around the periphery of the water tank to hydrophones located on the vehicle. A single hydrophone produces a three-dimensional position estimate with demonstrate static accuracies below one centimeter. By using four hydrophones fixed in relative locations to each other, a full six-axis position and attitude estimate can be obtained. This system currently uses sequential pulses from eight emitters, allowing position updates at approximately two Hertz. An upgraded system using multiple frequencies is currently under development, which should improve the update rate to approach the theoretical maximum of 10 Hz. [8]

Early tests confirmed the usefulness of such a system for suit testing. Test subjects in EMUs were placed in foot restraints and given a "wand" containing four hydrophones in a fixed pattern. The 3DAPS system allowed the direct measurement of the position and attitude of the handle of the wand, which was inside the grip of the EVA glove. The subjects moved the wand throughout the extremes of their range of motion, for conditions including right hand, left hand, and two-handed operations. This included full body motions

from the foot restraint, which produced a much wider range of motion than would be attainable in a laboratory environment, and which much more accurately replicates microgravity reach envelopes [Figure 1].

Such a system could be used for a variety of other testing purposes. 3DAPS hydrophones mounted to the backpack of the EVA subject could be used to provide accurate continual measurement of body position throughout an EVA, which would allow direct measurement of all body translations and attitude reconfigurations required for any given task. Use in conjunction with the ballasted partial-gravity simulation technique described below would provide similar reach and mobility measurements for planetary surface EVA simulations.



**Figure 1**

### **EMU Reach Envelope Measurement using 3DAPS WHOLE-BODY PARTIAL GRAVITY SIMULATION**

Traditionally, partial gravity EVA simulation has involved either parabolic flights at reduced  $g$ , or counterbalance harnesses to offset body weight. While the parabolic flight approach produces excellent simulations of partial

gravity, test times are limited to approximately 30 seconds at a time, and test subjects are frequently debilitated by the cyclical  $g$  loading of parabolas and pull-outs. In addition, this test mode is prohibitively expensive, in excess of \$5000 per hour.

Counterbalance harnesses work adequately for whole-body activities such as walking, but do not attempt to provide partial gravity simulation for body components such as limbs. The complexity of overhead harnesses creates the need for considerable infrastructure, which generally limits testing to specific small areas inside a laboratory. For these reasons, the vast majority of surface EVA training for Apollo was performed in 1  $g$  without attempting to offset gravity conditions, other than the use of lightweight backpacks and mockups. [9]

The underwater environment, so familiar from neutral buoyancy simulations, offers a opportunity for partial gravity simulations as well. By ballasting individual body components proportionally to their relative masses, practical underwater simulations of lunar and Mars gravity can be achieved. This has been used in the past at NASA Ames for studies of partial gravity walking gaits, using a treadmill to reduce water drag effects on the test subject. [10] While this approach is limited because of the dynamic effects of water, it is more than adequate for a wide range of static or quasistatic activities, such as reach envelopes. In fact, tests recently conducted in the KC-135 aircraft on planetary rover ingress and seating, and on effects of backpack center of gravity on posture and stance stability [11], could be beneficially conducted underwater using this technique.

### **LIMB POSE/JOINT ANGLE MEASUREMENTS**

To truly understand what the EVA crew is doing, the ideal situation would be to fully document all of the motions of the body. One approach would be to build this capability into the pressure suit itself; this would keep the instrumentation transparent to the wearer, and would provide direct measurements of suit motion. However, to really understand the human element, it would be more beneficial to mount the joint angle sensors directly onto the suit wearer. This could be accomplished for most of the major body joints by embedding bend sensors (such as fiber optic or variable resistance strips) into the liquid cooling garment, which ideally fits conformally to the skin of the suit wearer. This would provide the transparency to the EVA crew (i.e., no additional overhead in donning or operations), which providing useful data to the researchers.

Perhaps the most important portion of the body to instrument are the hands. The hands are the critical reason for performing an EVA, and therefore are the most likely to fatigue and reach states of degraded

performance. The University of Maryland has developed several generations of instrumented comfort gloves [Figure 2],[Figure 3] to continually measure finger joint positions, compatible with use inside of standard and experimental pressure gloves [12], [13] These instrumented gloves were used with a self-contained data collection system inside NASA EMUs for data collection on hand motions and wrist fatigue[ref]. They were also used to document hand motions in the performance of standardized dexterity tests; data from the gloves was used to determine finger motions in pressure suit gloves, which was then used to select the standard dexterity tests most appropriate for use as a standard fiducial test in comparative testing of advanced glove concepts. [14]



**Figure 2**  
**Prototype Fiber Optic Sensor for Finger Flexion**



**Figure 3**  
**Instrumented EVA Comfort Glove**

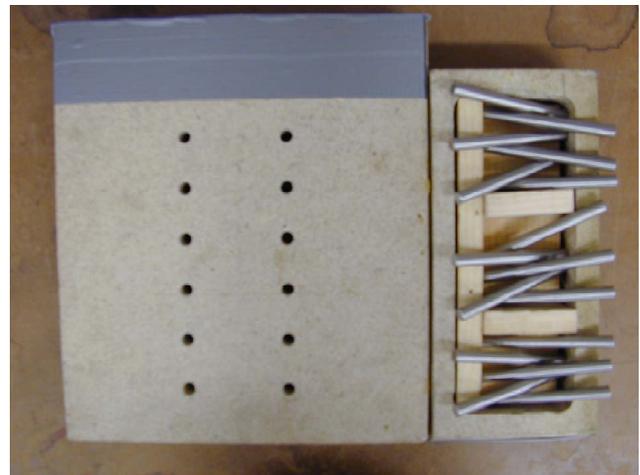
#### STANDARDIZED DEXTERITY TESTS

The tendency to adopt operational tasks for qualitative evaluation of suit performance reduces the ability to transfer results between different studies at different locations. Performance of an International Space Station servicing task, while informative, does not produce

results which carry over if the task changes, or if the next study is performed at a location without the same high-fidelity training mockups.

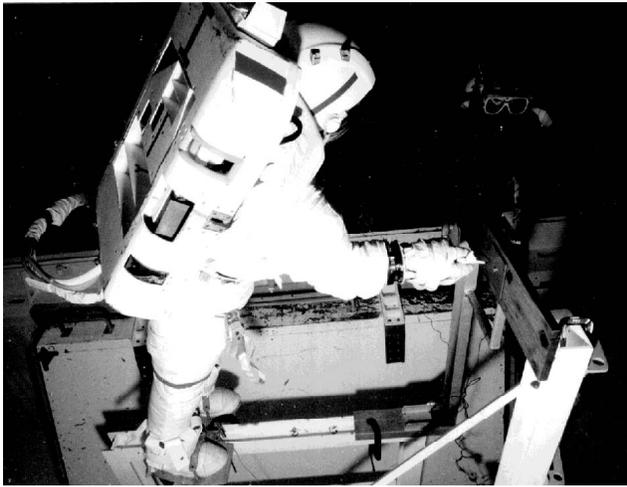
An alternative approach is to investigate standard dexterity or body kinematics performance tests from the kinesiology and rehabilitation communities for applicability to space suit operations. This approach leverages a large body of data on standard performance metrics, and provides standardized test protocols available at any participating research center.

In looking for a small number of dexterity tests which would exercise pressure suit glove mobility and allow quantitative comparisons between competing glove designs, the SSL examined a large number of manual dexterity tasks commonly used in rehabilitation assessment and therapy. The four tests most likely to be applicable to EVA glove dexterity testing were evaluated, and a single modified Purdue pegboard test [Figure 4] was selected as a simple test apparatus and protocol which provided ideal data on EVA glove performance. [13],[14]



**Figure 4**  
**Modified Purdue Pegboard Test for EVA Dexterity**

Similarly, it would be desirable to find a test which would exercise and measure suit performance over larger body components, such as arm and waist mobility. One protocol adapted to many such tests is the Fitts' Tapping Protocol. Fitts' Law states that the index of difficulty of a precision pointing task is a function of the ratio between the required precision (size of the target) and the necessary motion distance (distance between targets). Using this approach, the SSL developed an underwater Fitts' Law task board with variable sized targets and selectable intertarget distances. The subject (suited and unsuited) used a pointer to cyclically touch pairs of targets, with times and accuracies recorded automatically by computer. This setup [Figure 5] has been used to assess the effect of various design



**Figure 5**  
**EVA Subject Performing Fitts' Law Test**

decisions, such as position of foot restraints, on suit mobility.

#### ENVIRONMENTALLY COMPATIBLE FORCE-TORQUE SENSORS

Six-axis force-torque sensors may be bought off-the-shelf from several reputable companies for research purposes. At least two of these (JR3 and ATI) sell waterproofed force-torque sensors applicable to neutral buoyancy research. The SSL has used sensors from both these companies to instrument various EVA test setups, including foot restraints, hand rails, and force measurement plates.

However, many of the tests which might be done do not necessarily map well into a test sensor fixed in one location. For example, it would be highly desirable to produce a three-dimensional map of how the EVA force and torque limits change throughout the suit's reach envelope. Past testing in support of this mapping at the SSL [Figure 6] required a support diver to physically move the foot restraints and force plates between data points, a difficult and demanding task that limited the amount of data which could be collected to a sparsely populated set of widely distributed points. [15]

Tests using SSL robotic manipulators have demonstrated the potential for a robotic EVA test cell to provide much more useful and adaptable data collection opportunities. For example, by incorporating the force plate into the end effector of a robot arm, the force data collection throughout the EVA reach envelope could be automated, and the grid size changed to get maximum data discrimination in regions of primary interest. This system could also be used to move beyond static force applications, and investigate pressure suited control



**Figure 6**  
**Instrumented Work Station for Force Mapping**

bandwidth as a function of various design parameters such as restraint type and location.[16]

#### SUIT-COMPATIBLE LOW-PROFILE WEARABLE PRESSURE OR FORCE SENSORS

As described above, low-profile pressure/force sensors could be beneficially placed on the pressure suit wearer's body to directly measure applied forces, or to monitor pressure points as a function of suit design. Conceptually, these sensors might be mounted at significant locations of the liquid cooling garment, to simplify the interfaces to the wearer.

Although the SSL has never attempted to integrate this type of sensor into a pressure suit, they have been used effectively with a robotic hand model to assess pressure loads in space suit gloves. This test apparatus, originally designed to test mechanical counterpressure gloves, has demonstrated the utility of this type of sensor, and shown that integration into an actual pressure suit would not be a difficult task.[17]

## PULMONARY FUNCTION METABOLISM MEASUREMENTS

In laboratories around the world, metabolic workload measurements are routinely made using VO<sub>2</sub> instrumentation. These systems measure pulmonary tidal volume, and monitor partial pressures of oxygen and carbon dioxide in the inhaled and exhaled air streams. Using this information, physiological workload can be calculated.

Since parallels to these measurements are available in pressure suit portable life support systems, metabolic workload measurements have been available post-flight in some operational EVAs.[6] However, since surface-supplied breathing gases are used in neutral buoyancy facilities, no corresponding underwater metabolic workload measurement is available. This is severely limiting, as this data would be invaluable for correlation of neutral buoyancy simulations to flight EVAs.

The problem with simply purchasing and integrating a VO<sub>2</sub> instrumentation system into a neutral buoyancy life support system is the fact that suits are provided with a constant air flow (typically at six cubic feet per minute); there is therefore no way to directly measure tidal volume. However, in the development of the MX-2 underwater suit simulator [Figure 7], the SSL has integrated a set of air constituent sensors into the suit life support systems at appropriate places to provide sufficient information to infer tidal volume, and thereby obtain a metabolic workload measurement in the pressure suit. Initial tests of this system should occur in the summer of 2003.

## THERMAL BALANCE MONITORS

An alternative means of measuring metabolic workload is to directly monitor the heat exchange rates of the human body. Because of the thickness and multiple layers of a pressure suit, the heat transfer rate through the suit itself is quite low, and subject to experimental measurement. Body cooling is effected by a liquid cooling garment, which circulates cold water through tubes held against the surface of the subject's skin. By measuring inlet and outlet water temperatures, as well as water flow rates, an estimate may be obtained of total metabolic workload; the accuracy of this is enhanced by including data on air cooling (measuring inlet and outlet air temperature and humidity, along with air flow rate). Ideally such a system should be used in conjunction with the pulmonary metabolic sensor system described above.



**Figure 7**  
**Maryland Advanced Research/Simulation (MARS)**  
**Suit MX-2**

## ELECTROMYOGRAPHIC MONITORING SYSTEM

Critical muscle groups, such as the hands and forearms, control how much useful work an EVA crew may perform, and even limit the extent of safe EVA operations. Laboratories have been able for decades to directly measure muscle involvement and the rate of fatigue onset through the use of electromyographic (EMG) sensors. These surface-mounted electrodes pick up the muscle activation signals of nearby muscle groups, and can be used to measure the fatigue and estimate the remaining work limitations of the muscles.

The SSL as part of its Joint Angle and Muscle Signature (JAMS) experiment, developed and operated a self-contained EMG sensor system inside NASA EMUs in neutral buoyancy simulations. [Figure 8] Techniques were developed for this testing which allowed direct inference of muscle state at arbitrary times, as opposed to common laboratory protocols in which the muscle under study had to be relaxed and static to take an EMG reading.[18] This system has been demonstrated in neutral buoyancy operations at repeated intervals, and



**Figure 8**  
**Final Installation of Joint Angle and Muscle**  
**Signature (JAMS) Data Recorder inside EMU**

is ready for incorporation today into advanced EVA testbeds.

## CONCLUSIONS AND RECOMMENDATIONS

The listed measurement systems have been developed by the University of Maryland Space Systems Laboratory over the past 25 years of research. Taken individually, they have allowed a wealth of experimental investigation of EVA capabilities, and the effects of technology upgrades on pressure suit design.

However, there has never been an occasion wherein all of these component instrumentation systems were brought together into a single testbed setup. This would allow a wealth of data on EVA capabilities and pressure suit design to be obtained. For example, reach and force capabilities could be obtained in three-dimensional space throughout the reach envelope, as a function of local gravity and various competing suit component. Tasks which in the past were only used to generate time-based performance metrics could provide correlated numerical data on physiological workload, applied forces and moments, muscular activation and fatigue, and body motions. Data would be available to sort out exactly how much energy the test subject was using to perform the task, and how much goes into the suit. Since all of these instrumentation systems are compatible with neutral buoyancy testing, a much larger data base can be accumulated than would be available if limited to flight data. And, since the systems are (generally) EMU compatible and flight qualifiable, flight data could be obtained from operational EVAs without additional work load on the flight crew which would

produce a wealth of data for correlation of neutral buoyancy (or other ground-based) simulation to actual flight data.

The intersection of all of these sensor systems, with the inclusion of modern technologies in scene generation and immersive virtual reality, offer the tantalizing possibility of high fidelity dynamic VR training. An EVA crew might train in the neutral buoyancy environment to obtain the benefit of realistic body motions in the microgravity environment. Rather than produce an expensive and high-maintenance high fidelity mockup of the entire spacecraft, however, the only physical hardware would be a series of human interfaces (such as hand rails) positioned and manipulated by robotic actuators. Position sensors (such as 3DAPS) and body joint sensors would be combined to produce a model of how the subject is moving; force-torque sensors would record external forces and provide the input to reference models on how the subject and pressure suit would be responding in actual microgravity. An immersive head-mounted display would show the subject not the underwater pool environment, but a three-dimensional image of whatever space environment to which the training task is applicable. Actively controlled interfaces would produce high-fidelity motion for any component planned for manipulation in space, from small orbital replacement units to large modules or truss segments. This underwater immersive reality would provide much higher fidelity training than is currently available in neutral buoyancy and virtual reality laboratories, and would minimize "negative training" artifacts of the environment.

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