Variable Vector Countermeasure Suit (V2Suit) for Space Habitation and Exploration

NASA Innovative Advanced Concepts (NIAC)

Phase I Final Report

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Executive Summary

The "Variable Vector Countermeasure Suit (V2Suit) for Space Habitation and Exploration" is a visionary system concept that will revolutionize space missions by providing a platform for integrating sensors and actuators with daily astronaut intravehicular activities to improve human health and performance. The V2Suit uses control moment gyroscopes (CMGs) within a miniaturized module placed on body segments to provide a "viscous resistance" during movements – a countermeasure to the sensorimotor and musculoskeletal adaptation performance decrements that manifest themselves while living and working in microgravity and during gravitational transitions during long-duration spaceflight, including post-flight recovery and rehabilitation. Through an integrated design, system initialization, and control systems approach the V2Suit is capable of generating this "viscous resistance" along an arbitrarily specified direction of "down." When movements are made, for example, parallel to that "down" direction a resistance is applied, and when the movement is perpendicular to that direction no resistance is applied. The V2Suit proposes to be a countermeasure to this spaceflight-related adaptation and de-conditioning and the unique sensorimotor characteristics associated with living and working in 0-G, which are critical for future long-duration space missions.

This NIAC Phase I project focused on detailing several aspects of the V2Suit concept, including human-system integration, system architecture, computer aided design (CAD) modeling, and closed-loop simulation and analysis. In addition, early-stage breadboard prototyping of several aspects of the V2Suit system modules enabled characterization of expected performance and identified areas for further research and development to enable operational implementation of the V2Suit. In particular, potential challenges with integration of commercial-off-the-shelf components were identified. The key enabler for operational use and adoption of the V2Suit is a low-profile body worn form factor that does not interfere with normal, everyday movements and interfaces adequately with the body as to provide the generated gyroscopic torque for the perceptions of movement with a "viscous resistance." These aspects were investigated through mockups using a life-size mannequin, and through body attachment mechanisms on the breadboard prototype. Through the evaluation and investigation of commercially-available components, as well as an identification of desirable form factors, CAD models of the V2Suit modules were developed. These models included all of the required elements – spin motors, flywheel masses, gimbal motors, slip rings, inertial measurement units, motor controllers, and the required mounting brackets/hardware and cabling. The configuration and orientation of the control moment gyroscopes (CMGs) was specified according to results from the modeling, simulation and analysis. Two revisions of the CAD model were investigated through closed-loop simulation of the CMGs, and their ability to generate a resultant reaction force during movement and null undesirable torques due to changes in the direction of the angular momentum vector as a result of the normal body movements. The simulation architecture was based on the V2Suit system architecture, including the ability to initialize the system, track the position, orientation, and movement of the modules, and command the CMGs to provide the required direction and magnitude of the gyroscopic torque. These simulations demonstrated that the feasibility of the concept, and validated aspects of the design, including the CMG orientation and that the spin and gimbal rates required can be provided using commercially available components. Finally, a breadboard prototype was developed, which included several aspects of the V2Suit system. Custom flywheels were integrated with commercially available motors, a three axis accelerometer, and motor controllers – all packaged into a body-worn form factor. Data from the accelerometer could be read, and motor speed commands sent to the unit through a computer interface. This enabled and identification of the perceptual magnitudes of the gyroscopic torque and detailed the tangible aspects of the V2Suit. The integrated approach, and multiple design cycles provided an opportunity to investigate, in detail many aspects of the V2Suit system, assess their performance, and identify key technology areas to investigate for future development.

The successful development, integration and operation of the V2Suit will be a be an enabler for space exploration mission technologies, including human health and adaptation countermeasures, autonomous health monitoring, human robotic interfaces, and adaptation and operations during artificial gravity. An integrated and comprehensive countermeasure system has a measurable impact in human performance following a space mission, and mass and volume savings in the spacecraft itself. This type of countermeasure suit also has earth benefits, particularly in gait or movement stabilization for the elderly, or rehabilitating individuals – the gyroscopes could be programmed to provide a kinematic envelope of least resistance during walking. Therefore, providing tactile feedback to the appropriate biomechanical coordination either to assist in gait correction or facilitate recovery following spaceflight.

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1.0 Introduction, Motivation and Objectives

The "Variable Vector Countermeasure Suit (V2Suit) for Space Habitation and Exploration" is a novel concept for integrating spaceflight adaptation countermeasures with daily intravehicular activities, and testing the interactions between countermeasures to assure astronaut health, performance and safe operations (Figure 1). The V2Suit integrates control moment gyroscopes (CMGs) within a wearable module on the major segments of the body to provide a "viscous resistance" during movements – a countermeasure to the sensorimotor and musculoskeletal adaptation performance decrements that manifest themselves during gravitational transitions associated with long-duration spaceflight. The V2Suit addresses the "Human Health, Life Support and Habitation Systems" Technology Area (TA06) within NASA's Office of the Chief Technologist Space Technology Roadmaps, specifically the area within "Human Factors and Performance" (6.3.4). The successful development and integration of the V2Suit will be a be an enabler for space exploration mission technologies, including human health and adaptation countermeasures, autonomous health monitoring, human robotic interfaces, and adaptation and operations during artificial gravity. In addition to the measurable impact an integrated and comprehensive countermeasure system has on human performance following a space mission, it also has the potential to enable significant mass and volume savings of required countermeasure equipment within the spacecraft itself.

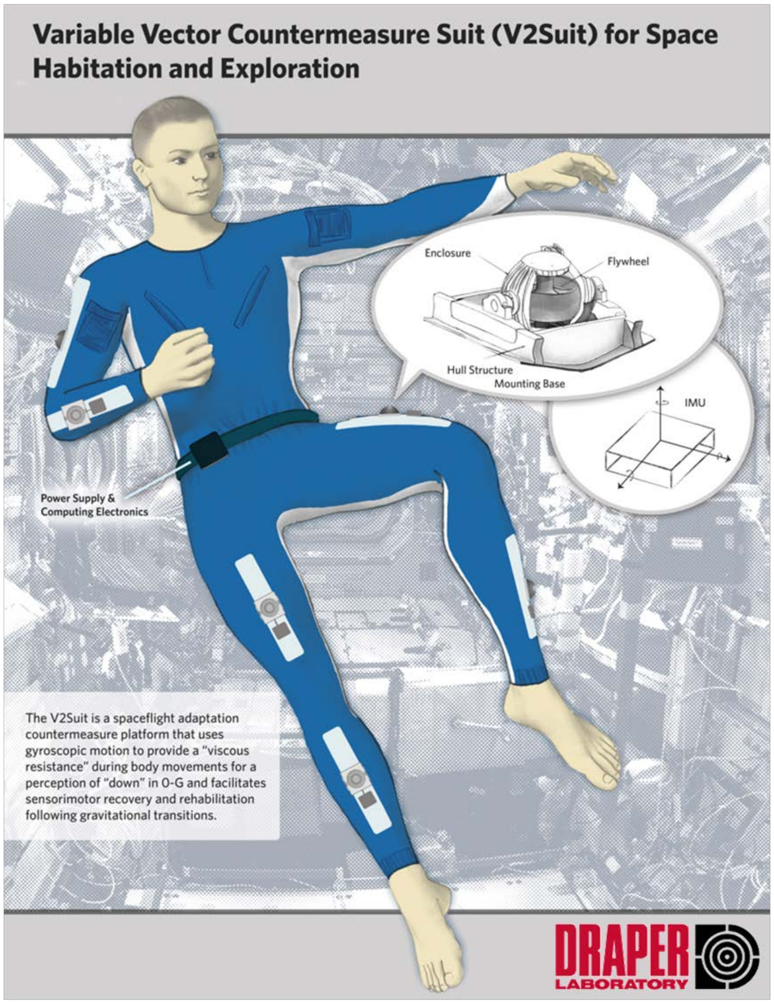


Figure 1 – Variable Vector Countermeasure Suit (V2Suit)

Exposure to the weightless environment of spaceflight is known to result in sensorimotor adaptation and physiological de-conditioning that includes spatial disorientation, space motion sickness, reductions in muscle volume, muscle strength, and bone mineral density [4, 5]. Most astronauts report that the effects related to sensorimotor adaptation are the most obvious and prevalent (NSBRI Sensorimotor Research Team Annual Report, 2009). It has been noted that these changes – postural instability, gait ataxia, eye-head-hand control – typically manifest themselves during gravitational transitions and during post-flight activities [6-8]. Gravitational transitions also often coincide with the time critical maneuvering phases of a mission, just when physical and cognitive performance must be high to ensure mission safety and success. Launch, rendezvous and docking with orbiting platforms or bodies, and return to a gravitational environment requires precise, time-critical interactions with complex vehicle systems. In addition, self-orientation perception in 0-G is dynamic since gravitational "down" cues are absent, and visual cues may be ambiguous [1]. Teleoperation and docking tasks are three dimensional and require integration of sensory information from multiple reference frames (NSBRI Sensorimotor Research Team Annual Report, 2009), and performance may be affected due to sensorimotor adaptation.

Anecdotally, one of the ISS Expedition 6 crewmembers was paraphrased following the off-nominal return that they "completed about thirty minutes of work in six hours…since there wasn't any real rush" (Soyuz TMA-1 re-entry and descent was a ballistic trajectory landing approximately 300 miles short of the planned area). However, given a long-duration space mission to a solar system destination without ground-based support personnel the outcome of an off-nominal scenario could be significantly different and even jeopardize mission safety.

The NASA Human Research Program has identified a "Risk of Impaired Control of Spacecraft, Associated Systems and Immediate Vehicle Egress Due to Vestibular/Sensorimotor Alterations Associated with Space Flight" which states that, "*Given that there is an alteration in vestibular/sensorimotor function during and immediately following gravitational transitions manifested as changes in eye-head-hand control, postural and/or locomotor ability, gaze function, and perception, there is a possibility that crew will experience impaired control of the spacecraft during landing along with impaired ability to immediately egress following a landing on a planetary surface (Earth or other) after long-duration spaceflight*" [9]. Currently, there are no in-flight countermeasures directly targeting the physiologic changes that affect the sensorimotor system, and the V2Suit system offers a promising solution.

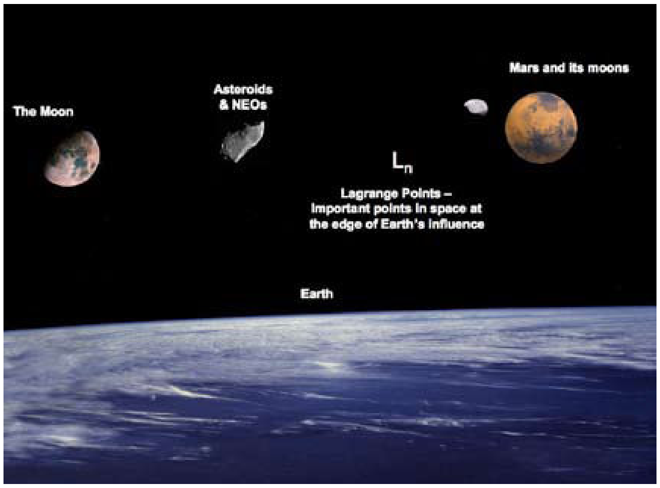


Figure 2 – Potential destinations for the U.S. human spaceflight program [2]

Missions to future solar system destinations – the moon, asteroids and near earth objects, Lagrange points, and Mars and its moons (Figure 2) [2] – will all have varying mission durations, gravitational transitions during entry, descent, and landing or rendezvous maneuvers, and operational requirements upon arrival. These missions will likely include exercise protocols to mitigate the physiologic adaptation and enable operational performance immediately upon arrival. The V2Suit aims to target the sensorimotor system adaptation that results in postural instability, gait ataxia, and eye-head-hand coordination. However, the V2Suit system and wearable sensors are designed to enable the integration of countermeasures against bone and muscle loss, provide radiation protection using novel active and passive materials, and continuously monitor astronaut health and status – all required for deep-space exploration missions. Integrating these countermeasures with daily activities and operations without requiring specialized equipment, may eliminate as much as 2.5 hours per day in allocated exercise time [4, 10] and would significantly reduce the required mass and volume for exercise equipment. Mars missions may utilize artificial gravity via centrifugation, and the V2Suit's sensorimotor adaptation capabilities may be used to counter Coriolis accelerations, and therefore eliminate the need for biomechanical adaptation or compensation within a rotating environment [11].

The V2Suit is an integrated platform for spaceflight-related physiological adaptation and de-conditioning countermeasures and training through the use of wearable control moment gyroscopes to produce a torque that results from the change in direction of the angular momentum vector of the flywheels. This Phase I project investigated the human-system integration challenges of interfacing the wearable modules with human to transmit the gyroscopic torque, as well as developed a system architecture for initializing the modules, tracking their movement, and commanding the flywheels to generate the required gyroscopic torque. The properties of the control moment gyroscopes and module packaging were investigated through modeling and simulation, and the results are documented. Collectively, this analysis has led to the identification of key enabling technologies, the challenges associated with each, and the identification of alternate uses and Earth benefits.

2.0 Background

2.1 Spaceflight-related Physiologic Adaptation and De-conditioning

All future long-duration space missions will result in physiologic adaptation and deconditioning, that include, but are not limited to, bone loss, muscle atrophy, cardiovascular alterations, sensorimotor adaptation [5], and the recent identification of potential changes to the visual system [12]. Each system adapts with a qualitatively different time course. Some have been quantified during space flights up to 6-months in duration, whereas others have no known "0-G Set Point." Each system also recovers to their "1-G Set Point" after returning to Earth at a different pace, ranging from days (sensorimotor) to years (bone). Crewmembers on the International Space Station (ISS) spend approximately 2.5 hours per day exercising in an attempt to prevent this physiological de-conditioning, but have not been completely successful [4, 10].

The muscular system, used for locomotion, postural control, and balance is affected by spaceflight due to the gravitational unloading, the lack of a need for balance, and changes in locomotor strategies in a weightless environment [13]. The major effect of microgravity is muscle atrophy with an accompanying loss of peak force and power [13]. At the whole-muscle level, the maximum power of the lower limbs was reduced to 67% of the preflight levels in astronauts after 31 days in space, and to 45% after 180 days [14]. Head-down bed rest studies, a spaceflight analog, have reported strength losses between 0.4% and 0.6% per day in the arms and lower extremities [15]. Another complication occurs because muscle contractions are also a major source of bone loading. Loss of muscle strength could exacerbate bone loss, so it is necessary to develop countermeasures that address musculoskeletal de-conditioning.

Bone mineral density reductions following spaceflight have been reported as high as 1-2% per month in the lower spine and hip, with smaller losses in the upper body [4, 16, 17]. Studies of Russian Mir cosmonauts found bone losses of up to 1.7% per month in weight bearing areas such as the spine, pelvis, and proximal femur, but no loss in the upper extremities [16]. Similar studies performed on ISS astronauts revealed reductions of 1% per month in the spine, and up to 1.5% a month in the hip. While astronauts lose bone at a rapid rate, they are slow to recover it when they return to earth, and it is unknown whether they ever fully recover. A follow up study on Skylab astronauts showed that not all bone lost during the mission had been recovered even five years after flight [18]. These results are similar to those seen on earth due to immobilization or spinal cord injury [4], which suggests that research into physiological de-conditioning seen in space could have earth benefits.

Changes to the sensorimotor system typically manifest themselves during gravitational transitions and during post-flight activities, which can be observed in terms of postural instability [6] and gait ataxia [7, 8]. The balance system relies on information from the otoliths, semi-circular canals, vision, proprioception, as well as local reflex arcs [19]. Results from spaceflight suggest that when astronauts enter weightlessness, arm movements are altered and may be inappropriate and inaccurate [20-23] with increased movement variability, reaction time, and duration [24]. Changes in neuromuscular function (e.g., muscle fiber changes, activation potential changes), muscle atrophy, and orthostatic intolerance may also contribute to post-flight posture and stability. The sensorimotor system, however, does recover rapidly. The initial rapid re-adaptation has a time constant on the order of 2.7 hours, whereas the slower, secondary, re-adaptation phase shows a time constant of approximately 100 hours (4 days) [6]. Even though the sensorimotor system appears to re-adapt rather quickly, many critical tasks must occur during the gravitational transition (e.g.,

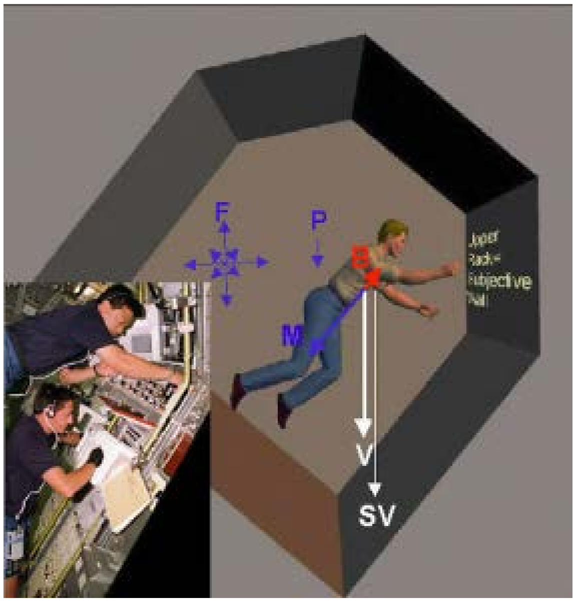


Figure 3 – A human visual orientation model for working with a canted rack in a spacecraft [1].

piloting tasks) or immediately following it (e.g., landing, vehicle egress).

Vision plays a critical role in maintaining spatial orientation in weightlessness [1]. On Earth we experience no orientation illusions because our sensory systems all agree on the same interpretation of our orientation with respect to the surrounding environment [1]. In space the semi-circular canals and vision continue to provide accurate information, but the otoliths no longer have a tonic input signaling gravity or body tilt, and the feet are rarely in contact with a surface. Cumulatively, this results in a conflict between the senses. During flights, one of the perceptions that can change dramatically is "one's perception of static orientation with respect to the cabin and the environment beyond" (see Figure 3) [1], which manifest themselves in the form of 0-G inversion illusions [25, 26] and visual reorientation illusions [25]. There are no countermeasures to these illusions in weightlessness. Providing an external cue to the direction of down may alleviate them, which could have operational benefits for navigation/emergency egress as well as mental rotations and reference frame coordination during teleoperation, docking or berthing operations.

2.2 Countermeasure Suits

A number of countermeasures have been developed and used in an attempt to prevent muscle and strength loss during spaceflight. In addition to treadmills, cycle ergometers, and resistive exercise devices, the Russian Cosmonauts have used passive stretch garments (Russian "Penguin Suit") and electrical stimulation. The "Penguin Suit" has "rubber bands woven into the fabric, extending from the shoulders to the waist and from the waist to the lower extremities, to produce tension on antigravity muscles [15]" (Figure 4, Left). More recently, a Gravity Loading Countermeasure Skinsuit (GLCS) was prototyped and evaluated in parabolic flight [27] (Figure 4, Right). This type of suit, as well as the "Penguin Suit," is an example platform for integrating with the sensorimotor aspects of the V2Suit. Despite these types of intravehicular suits having been developed, and to a limited extent used operationally, none have proposed to integrate multiple countermeasures (e.g., sensorimotor, bone, muscle, or radiation). These devices also have been completely passive – not containing or requiring any electrically powered components to achieve their intended purpose. The integration and use of intermittent powered components within the V2Suit stands to improve countermeasure systems being developed as well as in-flight training systems for sensorimotor adaptation.

http://www.globaleffects.com/C_pages/Rental/Wardrobe/SpaceSuits/Historical/Russian/Penguin755_hi.jpg

http://www.cnn.com/2010/TECH/innovation/11/05/gravity.space.suit/index.html

Figure 4 – Left: Russian "Penguin Suit", Right: MIT Gravity Loading Countermeasure Skinsuit

2.3 *Gyroscopic Motion*

Due to the conservation of angular momentum, a flywheel resists changes in the direction and magnitude of its spin axis [28]. During reach activities, for example, this may manifest itself as perturbations in the limbs during angular movements [29]. The magnitude of the perturbing torque is proportional to the time rate of change of the total angular momentum about a reference point plus the vector cross product of the limbs rotational velocity and the flywheel's spin velocity. For mechanical systems this torque can be easily computed, however due to uncertainties in biomechanical movements, the approximate torque can only be estimated (the exact torque must be measured; it cannot easily be estimated *a priori*) [29]. A control moment gyroscope (CMG) is a special type of flywheel that takes advantage of the conservation of angular momentum. CMGs consist of a spinning flywheel and one or more motorized gimbals that change the angular momentum vector, which causes a gyroscopic torque to be imparted on the attached mass [30]. Using a CMG in conjunction with the V2Suit could apply a torque in the same inertial direction regardless of the orientation of the body segment. With a CMG, there are three key parameters that can be varied to generate the gyroscopic torque – mass moment of inertia of the flywheel, mass

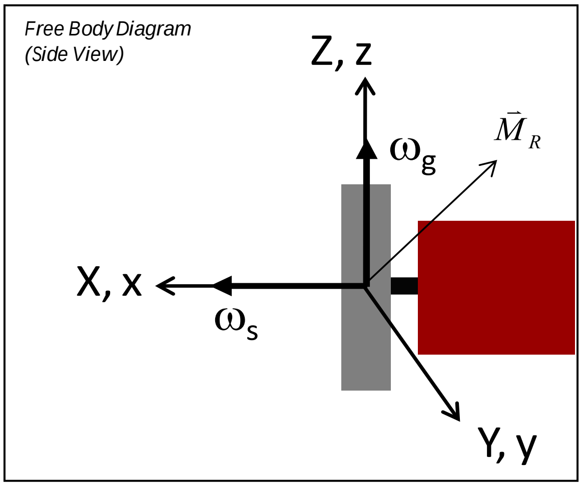


Figure 5 – 2-Axis CMG Free Body Diagram

spin rate, and mass gimbal rate. The following analysis demonstrates the gyroscopic torque that can be generated from a 2-axis CMG (1 spin axis, 1 gimbal axis) while holding the flywheel mass constant. Consider the free body diagram where the spin axis of the flywheel is along the x-axis, and the gimbal axis is aligned with the Z-axis (Figure 5). The active gimballing of the spin vector (i.e., changing the direction of the spin vector in the X-Y plane) results in a gyroscopic torque about the y-Axis (see Figure 6 for calculations). If we consider a fixed flywheel mass, and parametrically vary the spin rate and gimbal rate, the resulting gyroscopic torque is proportional to the product of the spin and gimbal rates (Figure 7). Subsequently, as a result of the attachment points of the CMG to the surrounding structure, a reaction force may result that is proportional to the positioning of the spinning mass relative to those attachment points.

ω_s = Flywheel spin rate

ω_g = Flywheel gimbal rate

$\vec{M}_R$ = Resulting gyroscopic moment

H = Angular Momentum

I = Moment of Inertia

Assume the coordinate system is fixed to the flywheel: $\vec{\Omega} = \vec{\omega}$

The angular velocity of the flywheel, as observed from a fixed coordinate system (X, Y, Z) that is coincident with the x, y, z axes at the instant shown:

$$\vec{\omega} = \vec{\omega}_s + \vec{\omega}_g$$

$$\vec{\omega} = \omega_s \hat{i} + \omega_g \hat{k}$$

$$\omega_x = \omega_s, \omega_y = 0, \omega_z = \omega_g$$

Since $\vec{\Omega} = \vec{\omega}, \dot{\vec{\omega}} = \left(\dot{\vec{\omega}}\right)_{x,y,z}$

$$\dot{\vec{\omega}} = \vec{\omega}_g \times \vec{\omega} = \vec{\omega}_g \times \left(\vec{\omega}_s + \vec{\omega}_g\right)$$

$$\dot{\vec{\omega}} = \omega_g \hat{k} \times \omega_s \hat{i} = \omega_g \omega_s \hat{j}$$

$$\dot{\omega}_x = 0, \dot{\omega}_y = \omega_g \omega_s, \dot{\omega}_z = 0$$

From the Equations of Motion:

$$\sum \vec{M}_O = \left(\dot{\vec{H}}_O\right)_{x,y,z} + \vec{\omega} \times \vec{H}_O$$

Representing as scalar equations:

$$\sum M_x = I_x \dot{\omega}_x - \left(I_y - I_z\right)\omega_y \omega_z$$

$$\sum M_y = I_y \dot{\omega}_y - \left(I_z - I_x\right)\omega_z \omega_x$$

$$\sum M_z = I_z \dot{\omega}_z - \left(I_x - I_y\right)\omega_x \omega_y$$

Substituting known parameters:

$$\sum M_x = I_x(0) - \left(I_y - I_z\right)(0)\omega_z$$

$$\boxed{\sum M_x = 0}$$

$$\sum M_y = I_y\left(\omega_g \omega_s\right) - \left(I_z - I_x\right)\omega_g \omega_s$$

$$\sum M_y = \left(I_y - I_z + I_x\right)\omega_g \omega_s$$

$$\boxed{\sum M_y = I_x \omega_g \omega_s}$$

$$\sum M_z = I_z(0) - \left(I_x - I_y\right)\omega_x(0)$$

$$\boxed{\sum M_z = 0}$$

Figure 6 – Nomenclature and Calculation of Gyroscopic Torque

The V2Suit design incorporates several 2-axis CMGs to generate the specified magnitude and direction of the gyroscopic torque. The gimbal motor actively changes the direction of the angular momentum of the flywheel. However, movement of the body limb on which the CMG is attached also changes the direction of the flywheel angular momentum. The active control of the spin and gimbal rates of the CMGs within the V2Suit module enables the system to both generate the specified magnitude and direction of gyroscopic torque to generate a “viscous resistance” to movement, and counter the gyroscopic torque generated due to body movement.

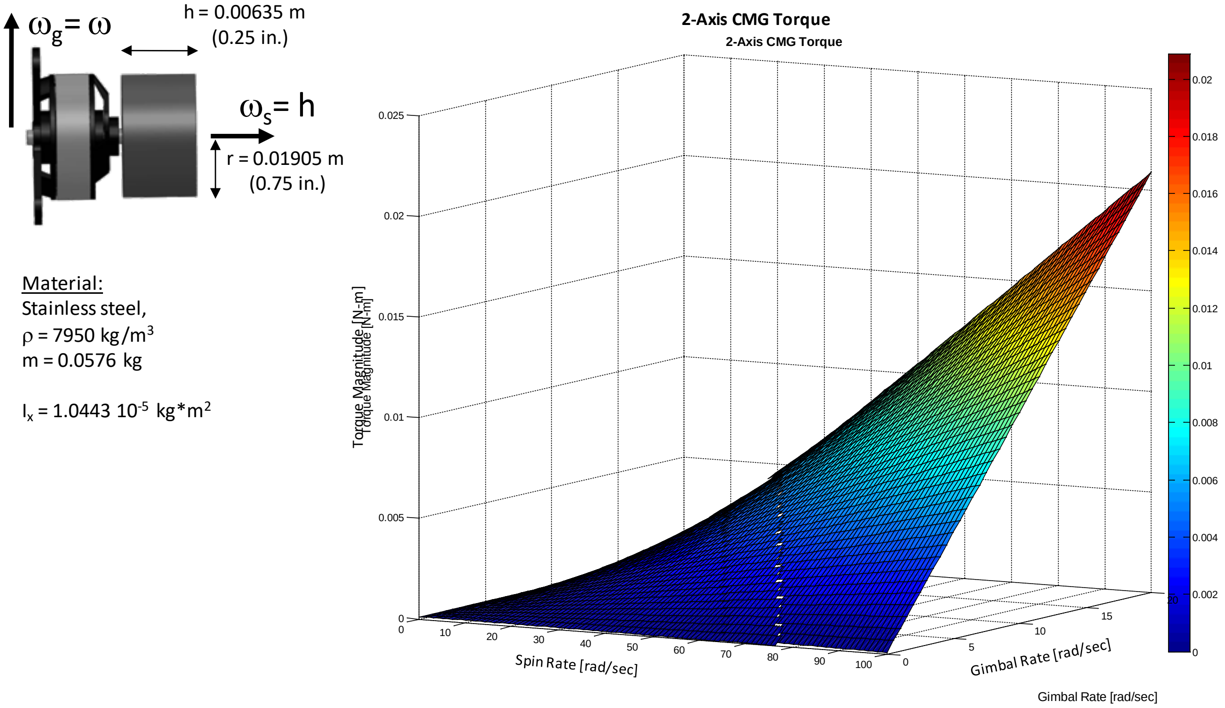


Figure 7 – 2-Axis CMG Torque Tradespace. Fixed flywheel mass and vary spin (ω_s) and gimbal (ω_g) rates.

3.0 V2Suit System Design and Analysis

3.1 Human-System Integration

The interface with the human wearer is important for the operational implementation of the V2Suit. Existing countermeasure suits (e.g., Russian "Penguin Suit" or GLCS) do not have a rigid component along the major axis of the bones within the various limb segments. (They were designed for elastic resistance and therefore did not require it.) However, for the V2Suit to be effective as a countermeasure system, it requires this infrastructure. The ability of the gyroscope to both resist changes in angular momentum and as a result affect the body segment during movements requires that the module be rigidly attached to the limb. This is the key to providing the coordinated "viscous response" with a specific magnitude and direction.

To develop an operational system the V2Suit must be easily put on, comfortable to wear, and small and low-profile as to not interfere with normal movements -- all while providing the desired functionality. In addition, the modules must not interfere with normal, daily activities when worn and non-operational. This requires a small form factor that can be integrated with normally worn garments – either as an add-on to existing equipment or designed to be an integral part of the garment.

The V2Suit module sizing, placement and interface to the human body was investigated through computer aided design (CAD) modeling (Figure 8), form-factor analysis using a life-size mannequin (Figure 9) and through limited evaluations through members of the V2Suit team. The modules were sized according to the anticipated final form factor through technology selection, component miniaturization, and packaging. They were placed near each body segments center-of-mass (e.g., [31]) in an effort to maximize the resulting "viscous resistance" perceptual magnitudes. The CAD modeling (Figure 8) provided an initial opportunity to visualize the sizing estimates relative to the anthropometrics, as well as the position and orientation with respect to the individual limbs. Subsequent analysis using a life-size mannequin (Figure 9) enabled the visualization of various V2Suit module form factors, the position and orientation of them including the power and processing module, as well as the required cabling to connect the modules to one another. In addition, the V2Suit module interface with the mannequin/garment, as well as the attachment points for the cabling was investigated.

In this analysis, the modules did not have a contoured backplate (to accommodate the body segment anthropometrics) or a rigid plate interwoven in the garment itself. The module mockups were attached to the body segments using Velcro. Through inspection of the mannequin interface and limited evaluations using team members, this provided several design recommendations for future iterations of the V2Suit module form factor. Near-term design recommendations include a combination of a contoured backplate – single lengthwise concavity to align with the major axis of the body segments – and a Velcro strap for firm attachment. This would enable the interface with all types of body-worn garments, as well as interface directly with the body (e.g., bare forearm). Additionally, it enables rapid sizing and positioning adjustment for proper fit and comfort. Power and communication cabling would remain exterior to the garment. Longer-term design recommendations include the integration of a module with a contoured backplate with a skinsuit garment, such as the GLCS. The module itself would be an integral part of the form-fitting garment, and the power and communication cabling also part of the garment. There is less option for placement customization, but it does allow for a quick don and doff of the V2Suit. Both design recommendations will likely be desired, based on the operational use of the system. However, given the operational requirements and existing customization for spaceflight systems it is envisioned that the modules will be integrated with the garment for a spaceflight countermeasure system.

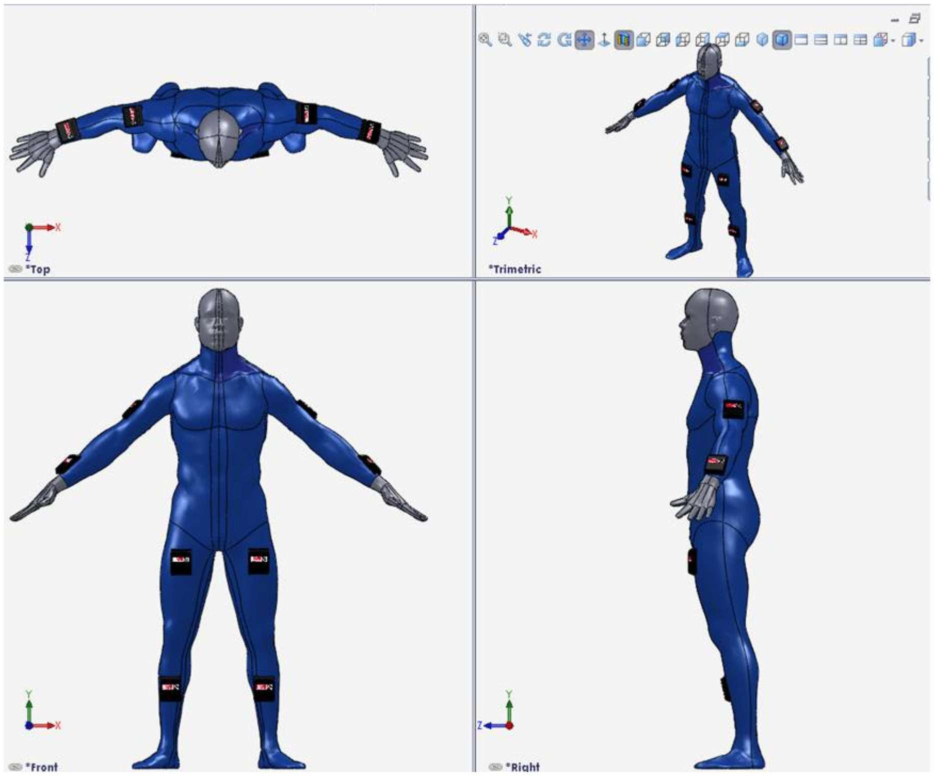


Figure 8 – CAD modeling of V2Suit module sizing and placement

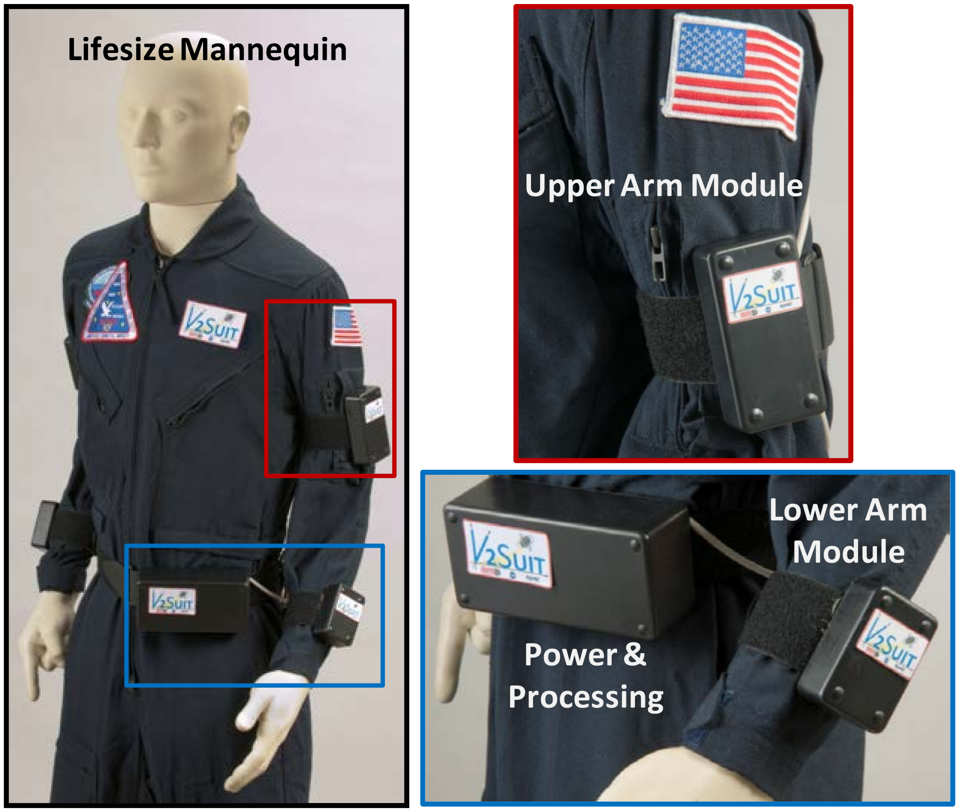


Figure 9 – V2Suit module form factor sizing and placement analysis using life-size mannequin

3.2 System Architecture

The V2Suit system is comprised of two main elements: 1) the wearable modules that can be placed on various body segments, and 2) central processing and commanding to coordinate the tracking and actuation of each module (Figure 10). At the highest level, data is received from the modules, and commands are sent to them, both through the inter-module cabling.

Each V2Suit module includes an inertial measurement unit (IMU) to measure linear accelerations and angular velocities of each module, the control moment gyroscopes (CMGs) to generate the specified direction and magnitude of the desired torque, and the spin and gimbal motor controllers. These modules receive power through the cabling from the central processing and commanding module, as well as specified flywheel spin and gimbal rates. The data from the IMU, flywheel spin rate and gimbal rates are transmitted to the central processing and commanding module.

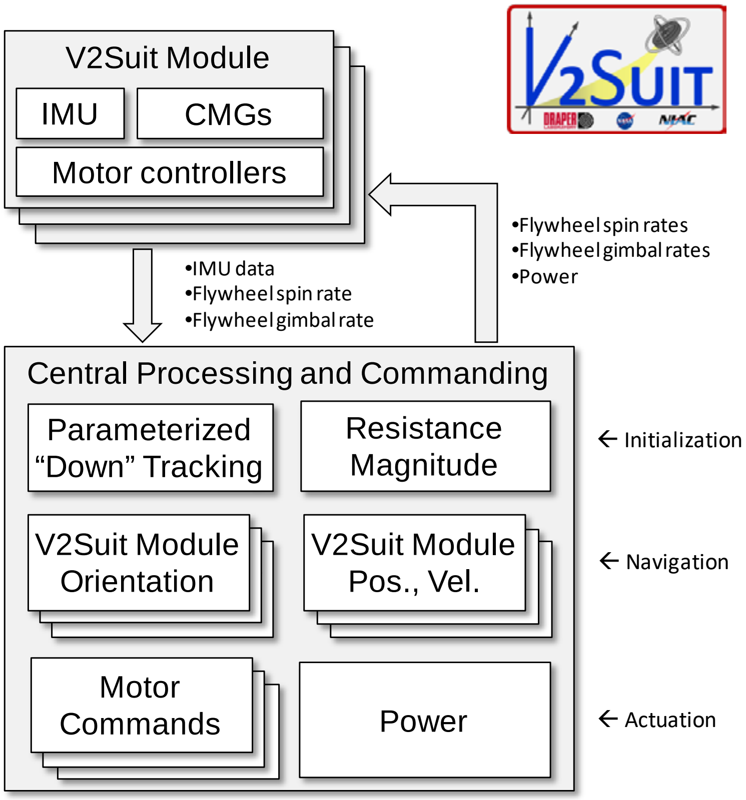


Figure 10 – V2Suit High Level System Architecture

The central processing and commanding module contains three sub-elements – initialization, navigation and actuation. Initialization enables parameters within the system to be specified, including the direction of "down" and the magnitude of the commanded resistance during body segment movements that are parallel to the specified "down" vector. The IMU data from each module is processed to determine its orientation with respect to a specified coordinate system, as well as track is position and velocity. To provide a whole-body coordinated resistance during movements, knowledge of the relative orientation, position, and velocity of each module with respect to one another is required. The processing of the IMU data to generate this information is part of the Navigation element. Finally, with the system initialized, and knowledge of the module position, orientation, and velocity, the appropriate commands can be sent to the CMG spin and gimbal motors to generate the appropriate gyroscopic torque during body movements.

3.3 Modeling and Simulation

Three dimensional computer aided design (CAD) models using representative commercially available equipment were created to visualize the component layout, and identify opportunities for packaging improvement. In addition, simulations were run with a representative configuration to demonstrate the ability to create a constant reaction force (due to the gyroscopic torque) parallel to the specified direction of "down" while simultaneously nulling perturbations induced from the body movement.

3.3.1 CAD Modeling

Two major revisions of the CAD models were developed – Rev1 (Figure 11) and Rev2 (Figure 12). Rev1 was based on the hardware specified in the breadboard prototype (see Section 3.4). This included commercially available spin motors, gimbal motors, and slip rings, as well as the custom flywheel masses. Each CMG included two spin motors and a single gimbal motor and slip ring; the gimbal axis is along an axis parallel to the height dimension of the CMG cylinder. The orientation of the CMGs was based on initial analyses of the packaging to generate gyroscopic toque in three dimensions. Initial closed loop simulation found that this configuration could not command a gyroscopic torque about an arbitrary direction and magnitude; therefore Rev2 design was initiated. Rev1 was also not focused on compact packaging – it was demonstrating the integration of commercially available components. In addition to the CMGs, a representative IMU and motor control electronics are included in the packaged concept.

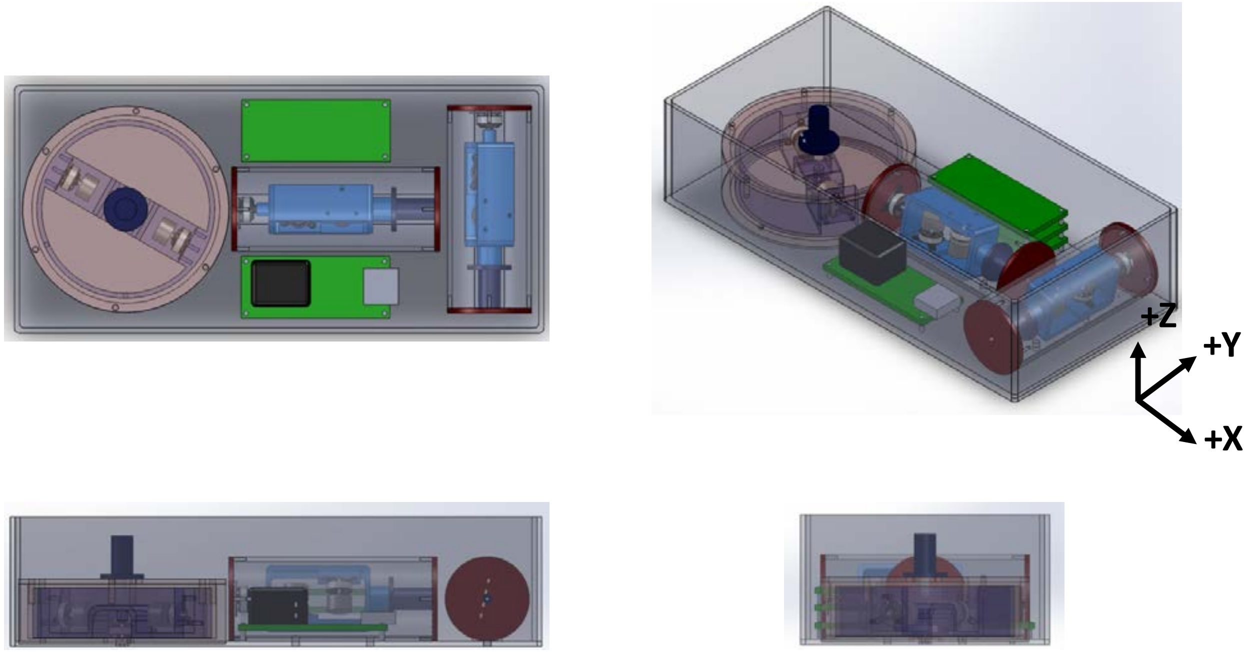


Figure 11 – V2Suit Module Design Rev1

The Rev2 design (Figure 12) was based on initial simulation results, and also focused on compact packaging of commercially available components. Rev2 consists of four CMGs, each canted 10-degrees towards the center of the module (that is, CMGs 1 and 3 are rotated 10-deg about the module y-axis, and CMGs 2 and 4 are rotated 10-deg about the x-axis). The 10-degree canting was chosen to enable full three-dimensional generation of the gyroscopic torque, and limited to 10-degrees to minimize the height dimension of the V2Suit module. Each of the CMGs has four spin motors (and flywheel masses), a gimbal motor, and a slip ring. This design was revised based on packaging using commercially available components, including 0.12 in. (3 mm) diameter spin motors (MICROMO), a commercially available gimbal motor from model aircraft components (AEO-RC C10 Micro 8g Brushless Motor), and a MOOG 12-channel slip ring. Commercially available MEMS IMUs (9-DOF Razor IMU, Sparkfun.com), and representative motor controllers (Phoenix-25, Dragonfly Innovations, Inc.) are also included within the module design. This CMG orientation was used in the subsequent closed-loop simulation, and will be the baseline for future research and development of the V2Suit modules.

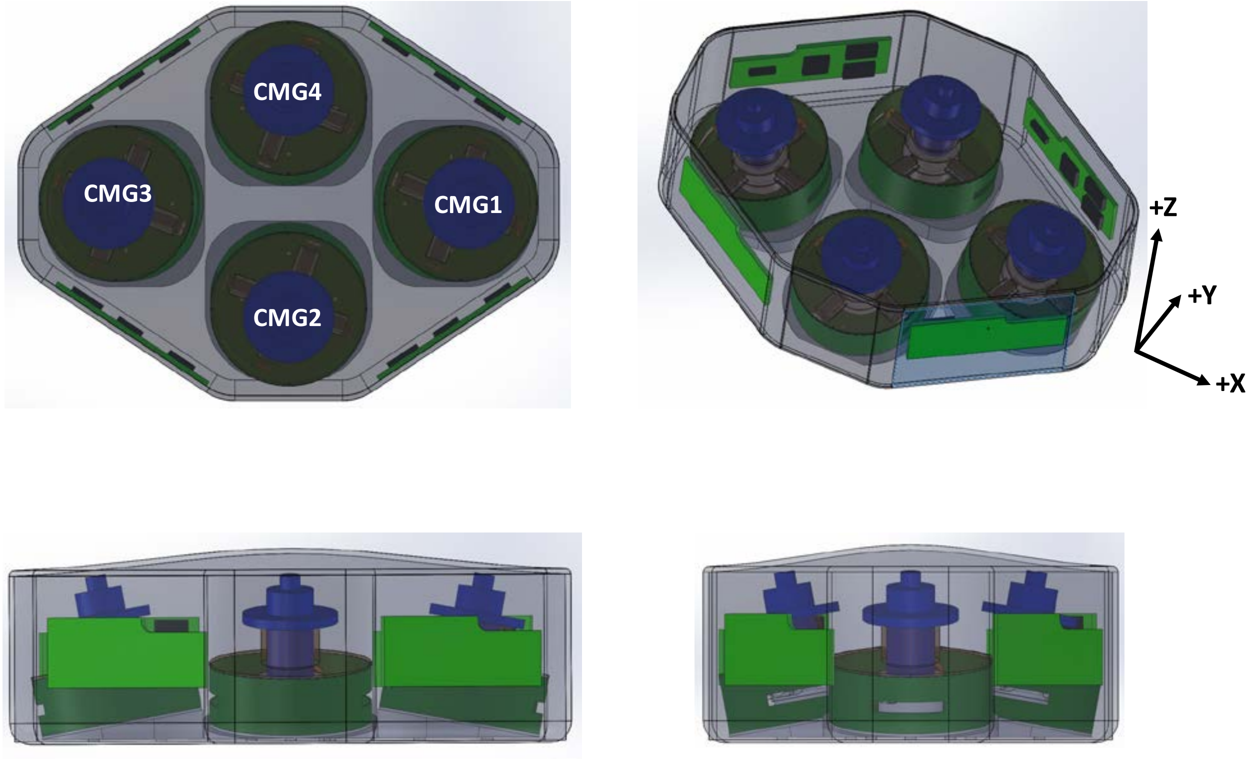


Figure 12 – V2Suit Module Design Rev2

3.3.2 *Closed-Loop Simulation*

A closed-loop simulation was developed to demonstrate the ability of the CMGs within the Rev2 module design to generate a gyroscopic torque (and resulting reaction force based on the attachment points) at a specified magnitude, along a specified direction of "down", and reject perturbations induced from body kinematics. The simulation consisted of a single module mounted on the arm, and the kinematics included raising and lowering the arm through 90-degrees in a single continuous motion (Figure 13 and Figure 14).

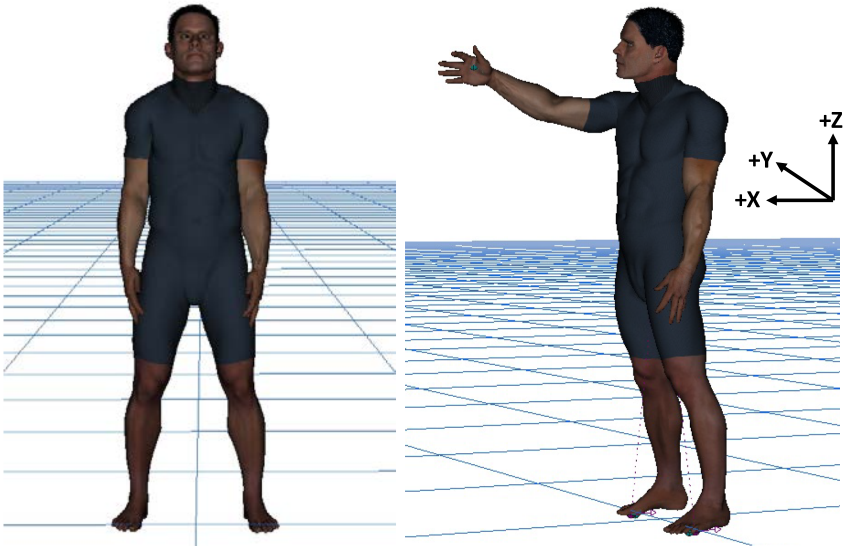


Figure 13 – Simulated kinematics: Start with arm at side (left), raise straight up 90-degrees (right), and then lower to side again (left) in one continuous motion.

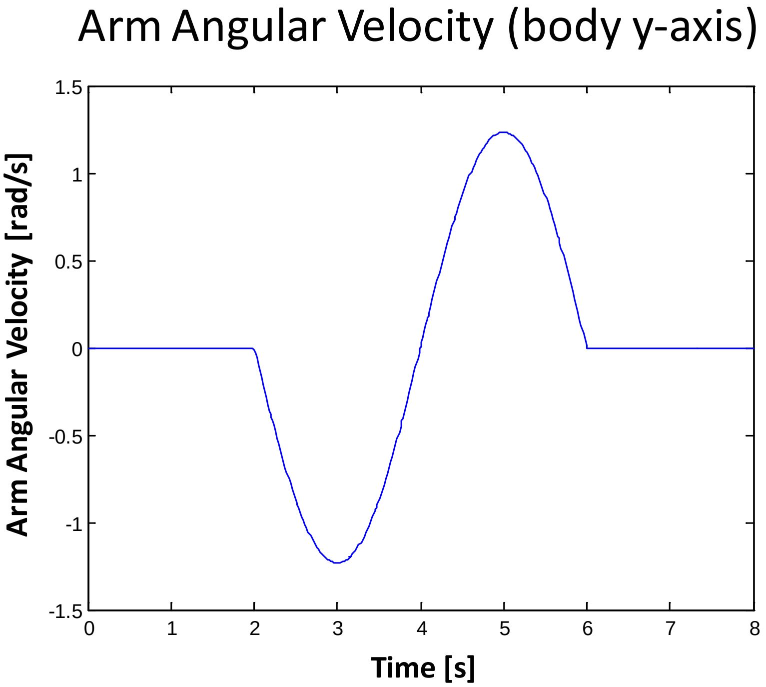


Figure 14 – Arm angular velocity about the body y-axis, demonstrating the raising and lowering of the arm 90-degrees in a single continuous motion.

Several aspects of the simulation architecture (see Figure 10) were implemented in MATLAB/Simulink to demonstrate the V2Suit concept of generating a viscous resistance during movement. Three simulation cases were run using the flywheel mass properties shown in Figure 7, to maintain a constant reaction force along the module z-axis during body movements. Converting, from module axes to body/inertial axes is easily done through a quaternion integrator given knowledge of the position and orientation of the module, as well as an initialize position and orientation. Simulation Case 1 was run open loop to illustrate the perturbations induced from changes in the angular momentum vector due to body movement kinematics. Simulation Case 2, also run open loop, but the flywheel spin rates were modulated to command a specified reaction force. Finally, Simulation Case 3 was run closed-loop to meet a specified reaction force and reject the arm kinematics-induced perturbations. Each of the plots show the resulting reaction force at the center of the V2Suit module based on the CMG flywheel mass at a distance of 1.0 in. (2.54 cm) from the gimbal motor axis of rotation.

Simulation Case 1

Simulation Case 1 was run open loop with two of the four flywheels (a single opposite pair) within each of the four CMGs set to 955 rpm (100 rad/s). The gimbal rate was set to 48 rpm (5 rad/s). Figure 15 illustrates the resulting three axis reaction forces due to the active gimballing and body kinematics-induced gimballing of the CMG flywheels. By running open loop with a set spin and gimbal rate, the module z-axis reaction force remains constant. However, there are transverse reaction forces induced from the arm kinematics and the magnitudes are likely above the perceptible threshold.

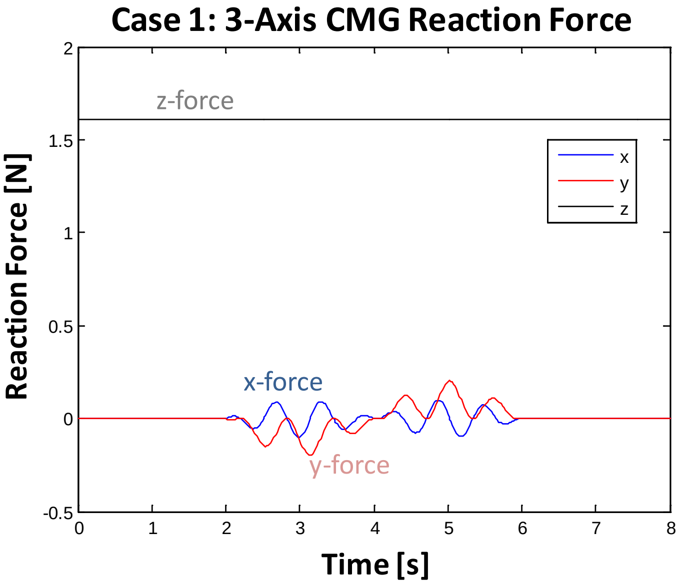


Figure 15 – Simulation Case 1 open loop CMG reaction force.

Simulation Case 2

Simulation Case 2 was run open loop with two of the four flywheels (a single opposite pair) within each of the four CMGs set to 592 rpm (62 rad/s) to generate a module z-axis reaction force of 1 N. The gimbal rate was again set to 48 rpm (5 rad/s). Figure 16 illustrates the resulting three axis reaction forces due to the active gimballing and body kinematics-induced gimballing of the CMG flywheels. As in Case 1, by running open loop with a set spin and gimbal rate, the module z-axis reaction force remains constant (at the value specified). However, the transverse reaction forces induced from the arm kinematics are slightly attenuated as compared to Case 1, but they are also likely above the perceptible threshold.

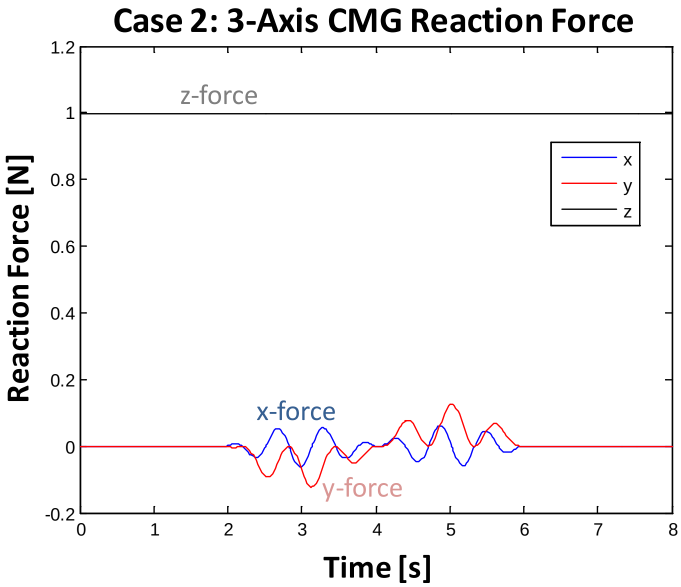


Figure 16 – Simulation Case 2 open loop CMG reaction force.

Simulation Case 3

Simulation Case 3 was run closed-loop to generate a set module z-axis reaction force of 1 N and reject perturbations due to the arm kinematics (Figure 17). A single opposite pair (two of the four flywheels) within each CMG was initially spun to 487 rpm (52 rad/s) and the other opposite pair (two of the four flywheels) was initially spun to 95 rpm (10 rad/s) (Figure 18). This resulted in a module z-reaction force of 1 N. Figure 17 illustrates the resulting three-axis forces due to the active gimballing and body kinematics induced gimballing of the CMG flywheels. Contrasted with Cases 1 and 2, where there are transverse forces that are likely perceptible, the transverse forces in Case 3 (Figure 17) are likely below the perceptible threshold and would not negatively impact any sensorimotor protocols. Figure 18 illustrates the modulation of the spin rates to generate the desired reaction force and reject the transverse perturbations. For the kinematics specified, it is encouraging to see that the required spin rates (1050 rpm = 110 rad/s) are within the limits of commercially available motors, and given the simulated arm kinematics, the required spin motor acceleration does not appear to be prohibitive. Further analysis into the required acceleration and that which can be provided given the available torque of commercially available micro-motors will be required. Collectively, the demonstration of the ability of the Rev2 V2Suit module design to generate a reaction force along a specified direction and reject perturbations due to body kinematics illustrates the feasibility of the concept.

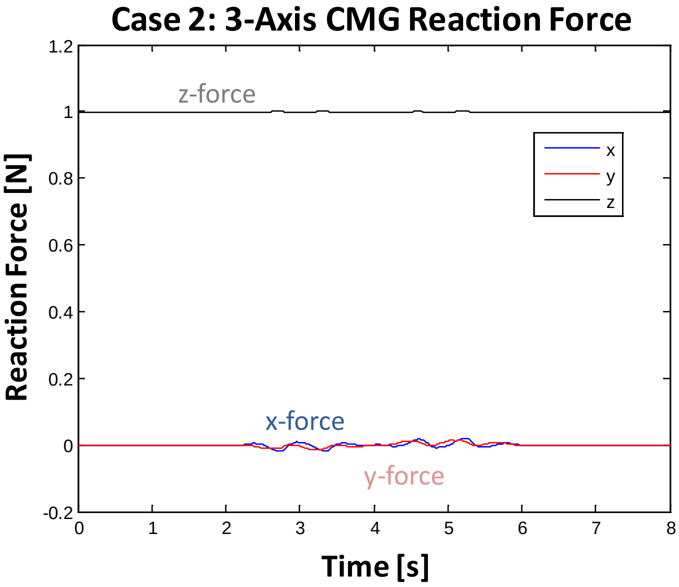


Figure 17 – Simulation Case 3 closed loop CMG reaction force

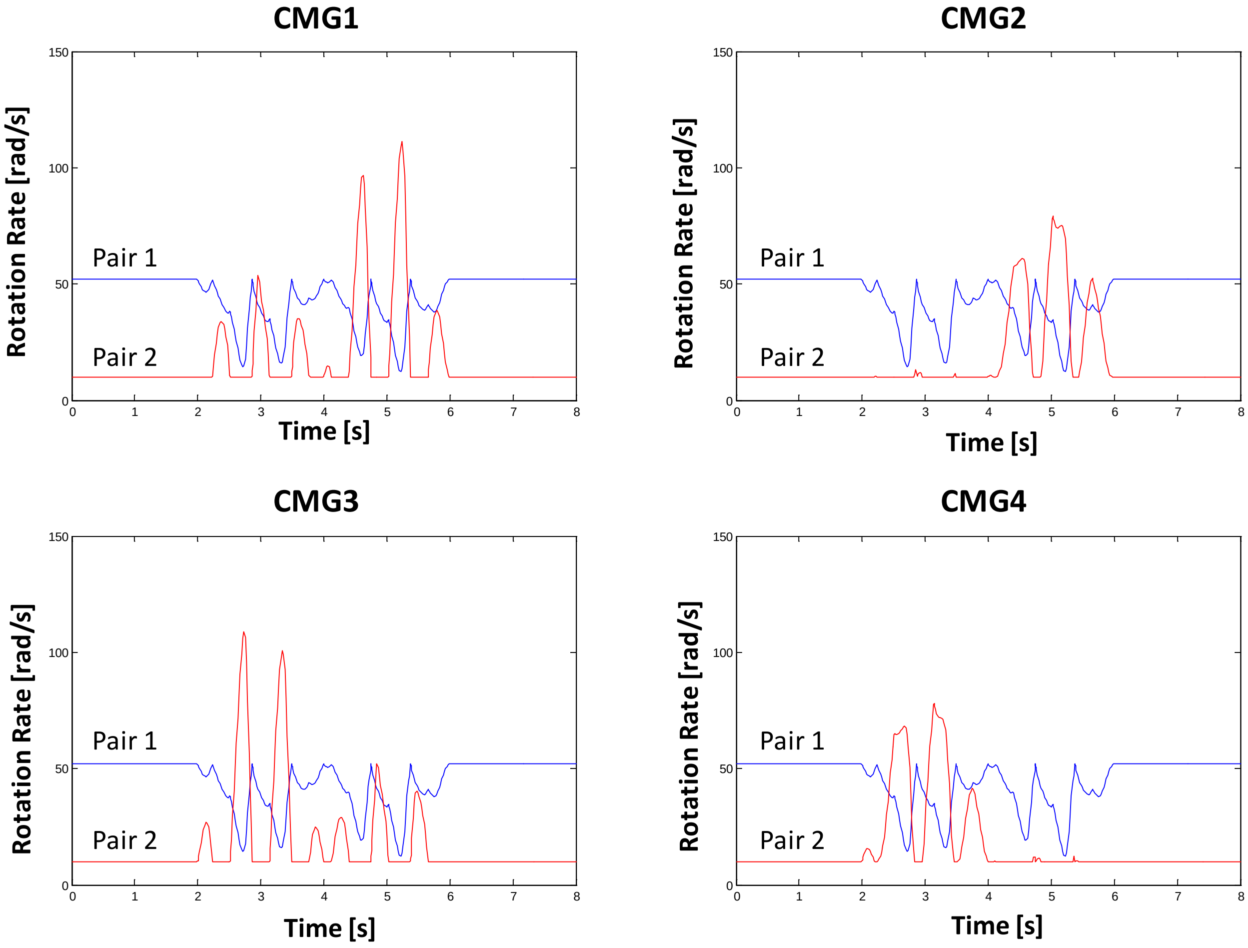


Figure 18 – Simulation Case 3 CMG flywheel pair spin rates.

3.4 Concept Prototyping

Aspects of the V2Suit system were breadboarded to demonstrate proof of concept, and initial form factor sizing (Figure 19). It also provided the V2Suit team with tangible perceptions for the gyroscopic torque that can be generated from changing the direction of the angular momentum vector. The breadboard unit was primarily assembled from commercial off the shelf model aircraft / helicopter components. Custom 1 in. (25.4 mm) diameter stainless steel disks were attached to brushless DC motors (AEO-RC C10 Micro 8g Brushless Motor), which were connected to a motor controller (Phoenix-25) through the power and communications wire bundle. Additionally, a 3-axis accelerometer was mounted on the enclosure to sense linear motion and tilt in three dimensions. The data from the accelerometer was read and recorded through a National Instruments controller and LabVIEW, and motor commands were sent through the same equipment (Figure 20).

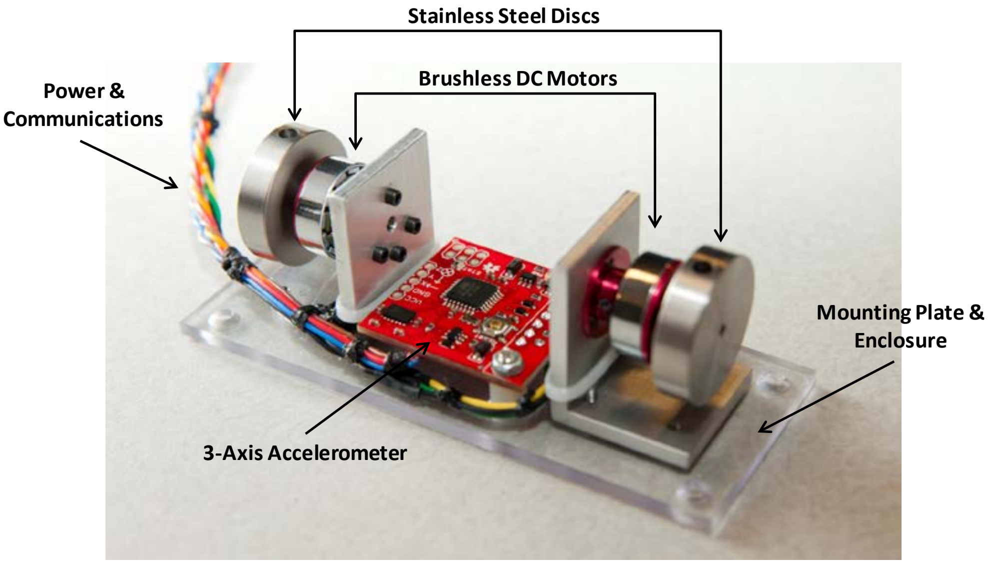


Figure 19 – Breadboard V2Suit Module

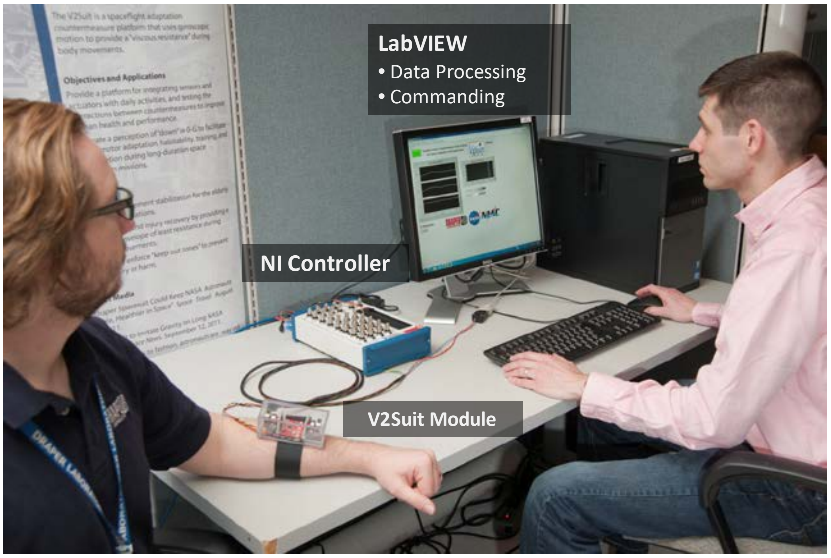


Figure 20 – V2Suit breadboard module worn and interfacing with a command and control computer.

The ability to rapidly and cost-effectively prototype aspects of the V2Suit system enabled the identification of risks and assessment of key system technologies early in the research and development process. With the commercial off the shelf equipment and breadboard assembly (Figure 19), we were able to identify potential issues with the motor / motor controller response time and power consumption. Several issues identified include:

- *Vibrations* – With the selected motors and custom flywheel masses, vibrations were encountered when rotation rates approached 1,000 rpm (105 rad/s) (the rotation rate required for a perceptible gyroscopic torque during body movements). These vibrations are likely due to slight off-axis rotation of the motors. There is also the possibility of unbalanced flywheels due to an asymmetry in the set-screws, which is amplified at high rotation rates.
- *Control* – The combination of the commercial off the shelf motors and motor controllers, National Instruments controller and LabVIEW, and standard desktop computer resulted in approximately a 50 - 250 ms delay from the time a speed change command was sent to the motor until it responded. The range in delay was not constant and was not always repeatable. Future designs must identify the cause of this and minimize the delay. Delayed or inappropriate commands due to body movements while wearing the V2Suit modules could lead to negative (sensorimotor) training, and reduce the effectiveness of the countermeasure system.
- *Power* – The power consumption of the two brushless DC motors and single motor controller was approximately 2 Watts in the steady state, with an observed 12 Watt spike. This is likely due to the motor controller electronics, which we did not have insight into. Additionally, a continuous 2 Watt power draw for two motors is undesirable for a full system, which may have 16 spin motors and 4 gimbal motors, and operated from an internal battery. Custom electronics, which are designed specifically for the CMG motors may reduce the continuous power consumption.
- *Packaging* – Enclosing the CMGs, IMUs, and motor controller electronics within a low-profile body-worn package will be a challenge. The breadboard does not include a gimbal motor or slip ring, which will only increase the form factor dimensions with the currently selected equipment. Miniaturized spin motors and gimbal motors, along with miniaturized slip rings will need to be considered to meet the packaging requirement.
- *Human-System Interface* – The breadboard module was attached to a team member using Velcro (similar to the life-size mannequin). The lack of a contoured backplate identified several challenges for a snug, but comfortable fit which did not move relative to the body. These evaluations motivated the near-term design recommendation to include a concave backplate, combined with Velcro, to pseudo-rigidly attach to the body and conform to varying anthropometrics.

3.5 Key Enabling Technologies

There are two key enabling technologies on the research and development roadmap for the V2Suit – Wearable Kinematic Systems and Miniaturized Packaging. Additional technologies, such as high-density batteries or wireless power systems and external or alternative position/orientation/motion sensing systems, will need to be leveraged for an operational implementation of the V2Suit. However, they are not seen as being critical for implementation and demonstration of the V2Suit system.

3.5.1 Wearable Kinematic Systems

Miniaturized inertial measurement units (IMUs), composed of accelerometers and/or gyroscopes, enables local sensing in small wearable devices to measure human motion, without the encumbrances of wires, heavy electronics, and dozens of permanently mounted video cameras. Kinematic measurements (e.g., limb velocities, body angles) derived from wearable IMU sensors offer tremendous opportunities to study the biomechanics of human motion outside of laboratory and clinical settings, such as those required when using state of the art optical motion capture systems [32, 33]. In particular, tilt and orientation may be accurately estimated using gyroscopes, accelerometers, and complementary filtering, as has been achieved for implementation in assistive devices to improve balance [34]. The accuracy of integration may be further improved with fusion algorithms that use quaternion-based representation of orientation. Such algorithms allow for efficient real-time operation while effectively preventing “gimbal lock" – a problem seen when Euler angles are used [35]. Nonlinear Kalman filters, such as the extended Kalman filter (EKF) [36] and the unscented Kalman filter (UKF) [37], represent a class of fusion algorithms that can correct for the drift exhibited by inertial sensors, while providing absolute unit estimation. Recent work has demonstrated the effectiveness of this technique for tracking orientation of the torso [38] and orientation of the hand [39].

MIT has recently implemented a wearable IMU and EKF to study human gait and astronaut space-suited kinematics, for which accurate measurement of lower body kinematics was desired [3, 40, 41]. Knee and ankle joint angles may be obtained using three IMUs: one IMU (measuring 3D acceleration and 3D angular velocity) mounted on each of the three limb segments of the leg. Using the inertial data from these devices as inputs to the EKF, the 2D orientation of each limb segment is estimated and these results are then combined to obtain the joint angles in the sagittal and coronal planes [41, 42]. Comparisons between the joint angle results obtained by the IMU approach to those obtained by the traditional "gold standard" approach using optical motion capture and inverse kinematics software shows

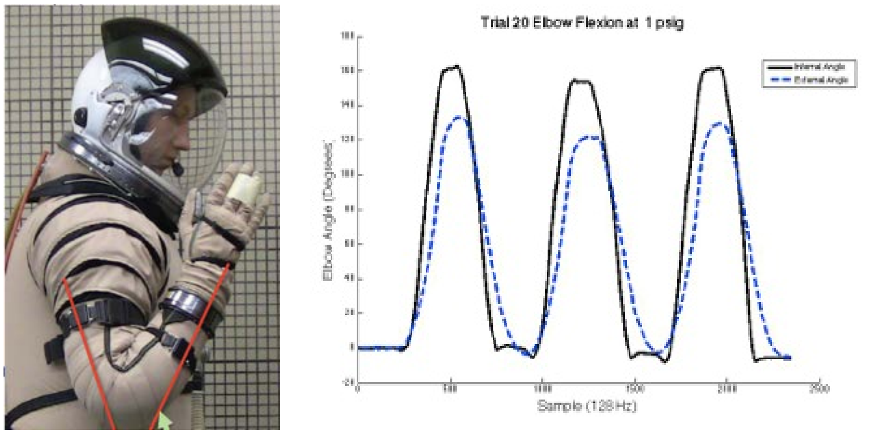


Figure 21 – CHAPS elbow flexion angle data (solid line: internal angle, dashed line: external angle) [3]

data agreement within a few percent. However, the IMU wearable system is an order of magnitude more cost effective and provides for measurements in operational settings rather than being constrained to laboratory use.

3.5.2 Miniaturized Components and Packaging

In order to meet the requirement for a low-profile, unobtrusive body-worn system, the V2Suit must include miniaturized components that are densely packaged. As shown in Figure 12, the V2Suit module includes commercial off the shelf components that are packaged in a custom form factor. These include the spin motors, gimbal motors, slip rings, IMUs, motor controllers and the required cabling and mounting hardware. There are a number of micro electromechanical system (MEMS) IMUs that are available, as well as motor controllers – these are not viewed as limiting components in the miniaturization. Not only do the individual form factors of the spin motors, gimbal motors, and slip rings need to be considered, but their size of their final integrated form factor.

Spin and Gimbal Motors

Miniature brushless DC motors (MICROMO, www.micromo.com) offer the smallest commercially available spin motors for the V2Suit. The MICROMO Series 0308 model (Figure 22) – dimensions of 0.12 in. (3 mm) in diameter and 0.31 (8 mm) in length, while still being able to spin at 15,000 rpm – is included in the Rev2 model (see Figure 12). However, the small form factor does have limitations. The stall torque is 0.024 mNm, which provides upper bounds on the size of the flywheel mass. Since the ability of the V2Suit to generate a viscous resistance to movement is enabled by the gyroscopes tendency to resist changes in the angular momentum vector, a small flywheel mass can be spun at high rotation rates. The analysis of the V2Suit system (see Section 3.3.2) only required rotation rates as high as 1,050 rpm, which is considerably less than the capability of the MICROMO motors. High rotation rates, however, require careful balancing and mounting of the spin motors and flywheel masses to minimize counterproductive vibrations.

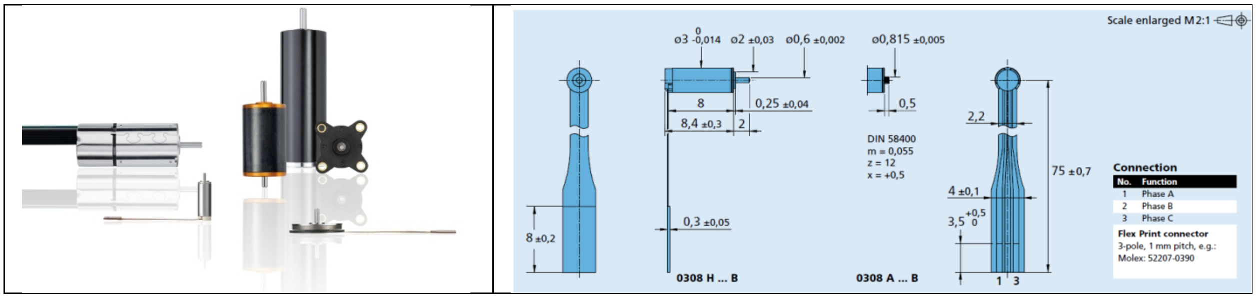


Figure 22 – MICROMO Series 0308 brushless DC motor

The Rev2 V2Suit module design includes a micro RC airplane brushless DC motor as the gimbal motor (Figure 23; AEO-RC C10 Micro 8g Brushless Motor, www.hobbypartz.com). The AEO-RC C10 offers a small form factor (0.70 in. (17.8 mm) in diameter, 0.59 in. (15 mm) in length), and can operate over 10,000 rpm with enough torque to both spin the currently designed flywheel masses. The upper limit rotation rate, however, is over-specified for the capabilities of the slip rings (typically, max 250 rpm). The design of the AEO-RC C10 motor does offer several benefits for packaging. In addition to the rotation of the motor shaft, the outer casing rotates as well. This offers the benefit for attaching the spin motors at the mid-point of the motor length and minimizing the packaged height. There are a number of commercially available motors in this size and torque class. Subsequent designs of the V2Suit CMGs will require the evaluation of these motors in terms of their power consumption, reliability, and manufacturing precision to avoid vibrations due to imbalances.

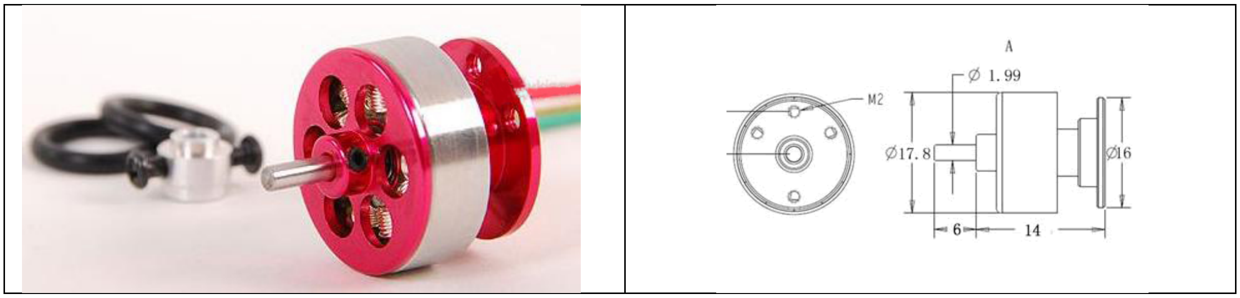
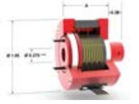


Figure 23 – AEO-RC C10 Micro 8g Brushless Motor

Slip Rings

Slip rings are required for sending the spin motor commands on-board the rotating platform from the external, stationary V2Suit module housing and power and communications assembly. There are a number of commercially available slip rings, with enough channels to send power and speed commands. In Rev2, there are four spin motors per CMG and each brushless DC motor requires three leads, thus 12 channels per slip ring is required. Table 1 summarizes commercially available slip rings. MOOG offers the smallest form factor at 0.44 in. (11.2 mm) in length, and 0.44 in. (11.2 mm) in diameter, and supporting 12 channels and rotation rates up to 250 rpm. However, other small form factors do exist. The challenge with the V2Suit is integrating it with the gimbal motor and maintaining the low-profile form factor.

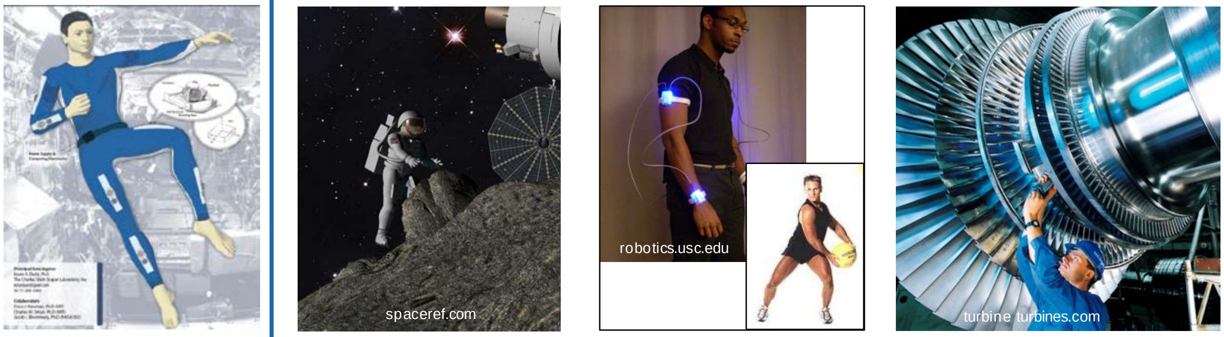
Table 1 – Commercially Available Slip Rings

Vendor	P/N	Dimensions	Notes	Image
MOOG	SRA-73540	0.44 in. (Dia) x 0.44 in. (L)	6,12 circuits; 2A; 250 RPM http://www.moog.com/products/slip-rings/commercial-industrial-slip-rings/compact-slip-ring-capsules/sra-73540/	
Rotary Systems Inc.	SR008-10008	2.0 in. (Dia) x 2.0 in. (L)	8 rings, 3 A; Available for slip ring customization; http://rotarysystems-sr.com/sr008	
Senring Electronics	SNM012A-06	0.47 in. (Dia) x 0.65 in. (L)	6 rings, 2A; 250 RPM http://www.senring.com/SNM012A-06.html (12 rings has length of 1.12 in.)	
DSTI	ES6A	0.58 in. (L)	6 circuits, 2A http://www.dsti.com/products/slip-rings/es/#spec (12 circuits has length of 0.83 in.)	
Michigan Scientific	Short S	1.6 in. (Dia) x 1.05 in. (L)	8 circuits, 500 mA; 12,000 RPM http://www.michsci.com/Products/sliprings/eos/short_s-series.htm	
Aeroflex	Cay-1398	0.37 in. (Dia) x 0.8 in. (L)	12 rings, 1A, 1,000 RPM http://www.aeroflex.com/ams/motion/motion-airflyte-rings.cfm	

4.0 Earth Benefits and Alternate Uses

The current research, analysis, and concept design of the V2Suit has focused on a wearable system to prevent the physiological adaptation and de-conditioning that is associated with long-duration spaceflight. There are other spaceflight applications of the V3Suit technology (see Figure 24). Wearable CMGs could be integrated with a spacewalking astronaut and commanded to provide a "stable" work platform, or counter reaction torques during movement, while operating on or near a low-gravity body such as an asteroid. This type of countermeasure suit also has earth benefits, particularly in gait or movement stabilization for the elderly, or physical therapy/rehabilitation (see Figure 24). For example, the V2Suit CMGs could be programmed to provide a kinematic envelope of least resistance during walking – "keeping within stability zones." Therefore providing tactile feedback to the appropriate biomechanical coordination – either to assist in gait correction or facilitate recovery following spaceflight or traumatic injuries. A potential advancement to drop foot gait (a neuromuscular disorder, often occurring after a stroke, where the anterior muscles of the lower leg are weaker) could be made with a wearable device with embedded sensors and programmable network of actuators, such as with the V2Suit modules. With the appropriately sized CMG, it is possible that the gyroscopic torque could prevent falls – a significant contributor to hip fractures in the elderly. In addition, with knowledge of the environment and the planned task, the CMGs could be commanded to enforce "keep out zones" – spatial regions that if encroached with a body limb could cause harm to either the person or the equipment.

- **Spacecraft Interior**
  - Sensorimotor
  - Musculoskeletal
- **Low-G EVA**
  - Stabilization
  - Orientation control
- **Exercise/Rehabilitation**
  - Movement trajectories
  - Posture stabilization
- **Industrial**
  - Keep-out zones
  - Safety zones



Platform Technology for Space- and Earth-based Applications

Figure 24 – V2Suit Alternate Uses

5.0 References

1. Oman, Charles M., *Chapter 19: Human Visual Orientation in Weightlessness*, in *Levels of Perception*, L.R. Harris and M. Jenkin, Editors. 2003, Springer-Verlag: New York. p. 375-395.
2. Augustine, Norman R., et al., *Review of U.S. Human Spaceflight Plans Committee: Seeking a Human Spaceflight Program Worthy of a Great Nation*. 2009.
3. Kobrick, R. L., et al. *Using inertial measurement units for measuring spacesuit mobility and work envelope capability for intravehicular and extravehicular activities*. in *International Astronautical Congress*. 2012. Naples, Italy.
4. Buckey, Jay C., Jr., *Space Physiology*. 2006, New York: Oxford University Press.
5. NSBRI. *Research Areas: National Space Biomedical Research Institute*. 2011 [cited 2011 April 19]; Available from: http://www.nsbri.org/Research/index.html.
6. Paloski, William H., et al., *Recovery of Postural Equilibrium Control Following Space Flight (DSO 605)*, in *Extended duration orbiter medical project final report 1989-1995. NASA SP-1999-534*, C.F. Sawin, G.R. Taylor, and W.L. Smith, Editors. 1999. p. 5.4-1 - 5.4-16.
7. Bloomberg, Jacob J. and Ajitkumar P. Mulavara, *Changes in Walking Strategies after Spaceflight.* IEEE Engineering in Medicine and Biology Magazine, 2003(March/April): p. 58-62.
8. Bloomberg, J.J., et al. *Locomotion after long-duration spaceflight: Adaptive modulation of a full-body head and gaze stabilization system*. in *Bioastronautics Investigators' Workshop*. 2001. Galveston, Texas.
9. NASA-HRP. *Risk of Impaired Control of Spacecraft, Associated Systems and Immediate Vehicle Egress Due to Vestibular/Sensorimotor Alterations Associated with Space Flight*. 2012a [cited 2012 April 27]; Available from: http://humanresearchroadmap.nasa.gov/risks/.
10. Coolahan, James E., Andrew B. Feldman, and Sean P. Murphy. *Integrated Physiological Simulation of an Astronaut Exercise Protocol*. in *55th International Astronautical Congress*. 2004. Vancouver, Canada.
11. Duda, Kevin R., Thomas Jarchow, and Laurence R. Young, *Squat Exercise Biomechanics During Short-Radius Centrifugation.* Aviation, Space, and Environental Medicine, 2012. 83(2): p. 102-110.
12. NASA-HRP. *Risk of Microgravity-Induced Visual Impairment/Intracranial Pressure*. 2012b [cited 2012 May 18]; Available from: http://humanresearchroadmap.nasa.gov/risks/?i=105.
13. LeBlanc, A., et al., *Muscle volume, MRI relaxation times (T2), and body composition after spaceflight.* Journal of Applied Physiology, 2000. 89(6): p. 2158-64.
14. Gopalakrishnan, R., et al., *Muscle volume, strength, endurance, and exercise loads during 6-month missions in space.* Aviat Space Environ Med, 2010. 81(2): p. 91-102.

15. Convertino, Victor A., *Exercise as a countermeasure for physiological adaptation to prolonged spaceflight.* Medicine and Science in Sports and Exercise, 1996. 28(8): p. 999-1014.
16. LeBlanc, A., et al., *Bone mineral and lean tissue loss after long duration space flight.* J Musculoskelet Neuronal Interact, 2000. 1(2): p. 157-60.
17. Oganov, V. and V. S. Schneider, *Skeletal system*, in *Space Biology and Medicine*, A. Nicogossian and O.G. Gazenko, Editors. 1996, American Institute of Aeronautics and Astronautics: Reston, VA. p. 247-266.
18. Bikle, D. D., T. Sakata, and B. P. Halloran, *The impact of skeletal unloading on bone formation.* Gravit Space Biol Bull, 2003. 16(2): p. 45-54.
19. Astrand, Per-Olof, et al., eds. *Textbook of Work Physiology: Physiological Bases of Exercise, 4th Edition*. 2003, Human Kinetics: Champaign, IL.
20. Gazenko, O. G., A.M. Gernin, and A.D. Egorov, *Major Medical Results of the Salyut-6 Soyuz 18 5day Space Flight.* 1981.
21. Johnson, R.S., L.F. Dietlein, and C.A. Berry, *Biomedical Results of Apollo*. 1975, Washington, D.C.: NASA.
22. Nicogossian, A.W., C. Leach-Huntoon, and S.L. Pool, *Space Physiology and Medicine*. 1989, Philadelphia: Lea & Febiger.
23. Paloski, William H., et al., *Risk of Sensory-Motor Performance Failures Affecting Vehicle Control During Space Missions: A Review of the Evidence.* Journal of Gravitational Physiology, 2008. 15(2): p. 1-29.
24. Bock, O., S. Abeele, and U. Eversheim, *Human adaptation to rotated vision: interplay of a continuous and a discrete process.* Exp Brain Res, 2003. 152(4): p. 528-32.
25. Oman, C. M. *Etiologic role of head movements and visual cues in space motion sickness on Spacelabs 1 and D-1*. in *7th IAA Man in Space Symposium: Physiologic Adaptation of Man in Space*. 1986. Houston, TX.
26. Gazenko, O. G., *Medical studies on the cosmic spacecrafts "Vostok" and Voskhod"*. 1964.
27. Waldie, James M. and Dava J. Newman, *A gravity loading countermeasure skinsuit.* Acta Astronautica, 2011. 68(7-8): p. 722-730.
28. Hibbeler, R.C., *Chapter 21: Three-Dimensional Kinetics of a Rigid Body*, in *Engineering Mechanics: Dynamics*. 1998, Prentice-Hall: Saddle River, NJ.
29. Flanders, M., et al., *Using arm configuration to learn the effects of gyroscopes and other devices.* J Neurophysiol, 2003. 89(1): p. 450-9.
30. Wikipedia. *Control Moment Gyroscope*. 2011 [cited 2011 April 8].
31. Yeadon, M. R., *The simulation of aerial movement--II. A mathematical inertia model of the human body.* Journal of Biomechanics, 1990. 23(1): p. 67-74.
32. Brodie, Matthew, Alan Walmsley, and Wyatt Page, *Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing.* Sports Technology, 2008. 1(1): p. 17-28.

33. Lapinski, Michael, et al. *A Distributed Wearable, Wireless Sensor System for Evaluating Professional Baseball Pitchers and Batters*. in *International Symposium on Wearable Computers*. 2009: IEEE.
34. Weinberg, M. S., et al., *Tilt determination in MEMS inertial vestibular prosthesis.* J Biomech Eng, 2006. 128(6): p. 943-56.
35. Favre, J., et al., *Quaternion-based fusion of gyroscopes and accelerometers to improve 3D angle measurement.* Electronic Letters, 2006. 42(11).
36. Brown, R. G. and P. Y. C. Hwang, *Introduction to Random Signals and Applied Kalman Filtering*. 1997, New York: John Wiley & Sons.
37. Julier, Simon J. and Jeffrey K. Uhlmann. *A New Extension of the Kalman Filter to Nonlinear Systems*. in *Int. Symp. Aerospace/Defense Sensing, Simul. and Controls*. 1997. Orlando, FL.
38. Luinge, H. J. and P. H. Veltink, *Measuring orientation of human body segments using miniature gyroscopes and accelerometers.* Med Biol Eng Comput, 2005. 43(2): p. 273-82.
39. Sabatini, A. M., *Quaternion-based extended Kalman filter for determining orientation by inertial and magnetic sensing.* IEEE Trans Biomed Eng, 2006. 53(7): p. 1346-56.
40. Young, D. and D. J. Newman, *Augmenting Exploration: Aerospace, Sea and Self*, in *Wearable Monitoring Systems*, A. Bonfiglia and D. De Rossi, Editors. 2011, Springer Science.
41. Young, D., et al. *Estimation of Lower Limb Joint Angles During Walking Using Extended Kalman Filtering* in *6th World Congress on Biomechanics*. 2010. Singapore.
42. Young, D., et al. *Inertial Sensing for Estimating Human Kinematics*. in *15th International Conference on Perception and Action (ICPA)*. 2009. Minneapolis, MN.

6.0 Appendices

6.1 V2Suit Module CAD Designs

Rev1 – with dimensions

Rev2 – with dimensions

6.2 NIAC Fellows Orientation Poster

VARIABLE VECTOR COUNTERMEASURE SUIT (V2SUIT) FOR SPACE HABITATION AND EXPLORATION

V2Suit Overview

The V2Suit is a spaceflight adaptation countermeasure platform that uses gyroscopic motion to provide a "viscous resistance" during body movements.

Objectives and Applications

Provide a platform for integrating sensors and actuators with daily activities, and testing the interactions between countermeasures to improve human health and performance.

Generate a perception of "down" in 0-G to facilitate sensorimotor adaptation, habitability, training, and rehabilitation during long-duration space exploration missions.

Earth Benefits

Walking or movement stabilization for the elderly or clinical populations.

Rehabilitation and injury recovery by providing a kinematic envelope of least resistance during preferred movements.

Specify and enforce "keep out zones" to prevent bodily injury or harm.

Select Media

"Draper Spacesuit Could Keep NASA Astronauts Stable, Healthier in Space" *Space Travel.* August 24, 2011.

"Spacesuit to Imitate Gravity on Long NASA Missions." *Space News.* September 12, 2011.

"When it comes to fashion, astronauts are way out there" *The Washington Post.* September 20, 2011.

Principal Investigator
Kevin R. Duda, Ph.D.
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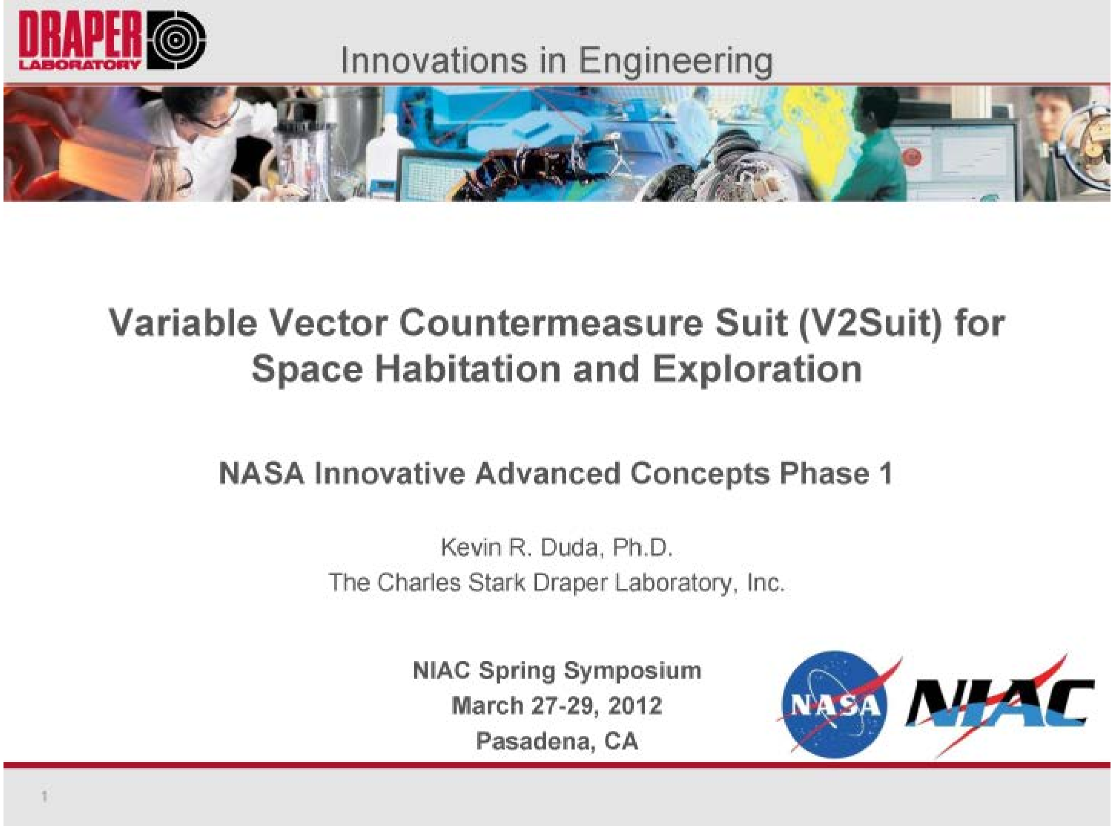
(617) 258-4385

Colaborators
Dava J. Newman, Ph.D (MIT)
Charles M. Oman, Ph.D (MIT)
Jacob J. Bloomberg, Ph.D (NASA/JSC)

NIAC Fellows Orientation Meeting
November 16-17, 2011
Washington, DC

6.3 NIAC Spring 2012 Symposium Presentation



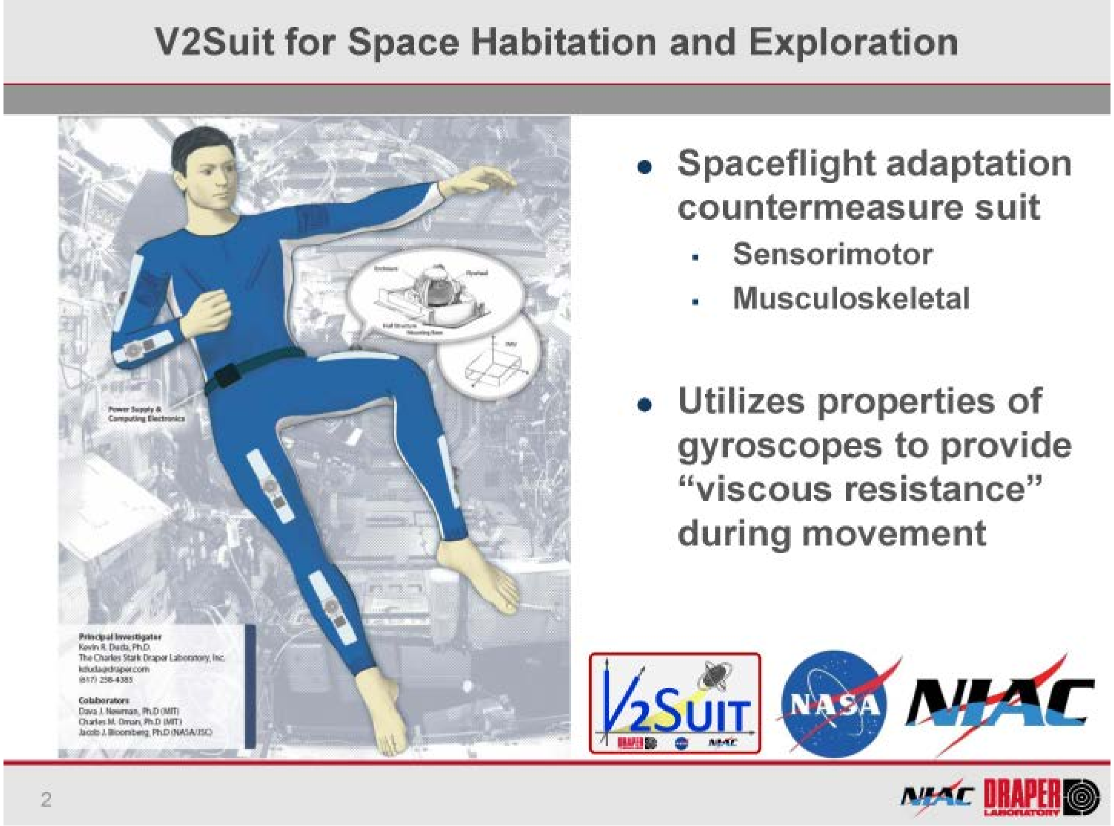
Innovations in Engineering

Variable Vector Countermeasure Suit (V2Suit) for Space Habitation and Exploration

NASA Innovative Advanced Concepts Phase 1

Kevin R. Duda, Ph.D.
The Charles Stark Draper Laboratory, Inc.

NIAC Spring Symposium
March 27-29, 2012
Pasadena, CA



V2Suit for Space Habitation and Exploration

Principal Investigator
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Collaborators
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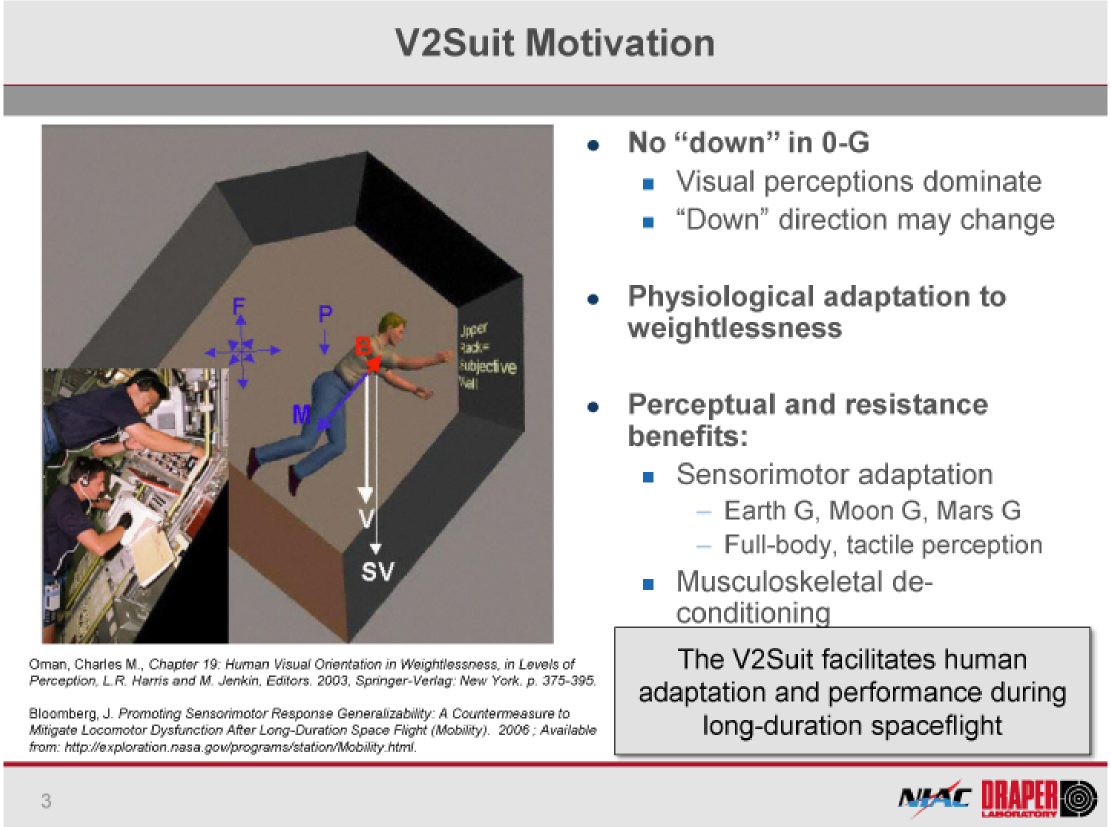
Charles M. Oman, Ph.D (MIT)
Jacob J. Bloomberg, Ph.D (NASA/JSC)

- Spaceflight adaptation countermeasure suit
  - Sensorimotor
  - Musculoskeletal
- Utilizes properties of gyroscopes to provide "viscous resistance" during movement



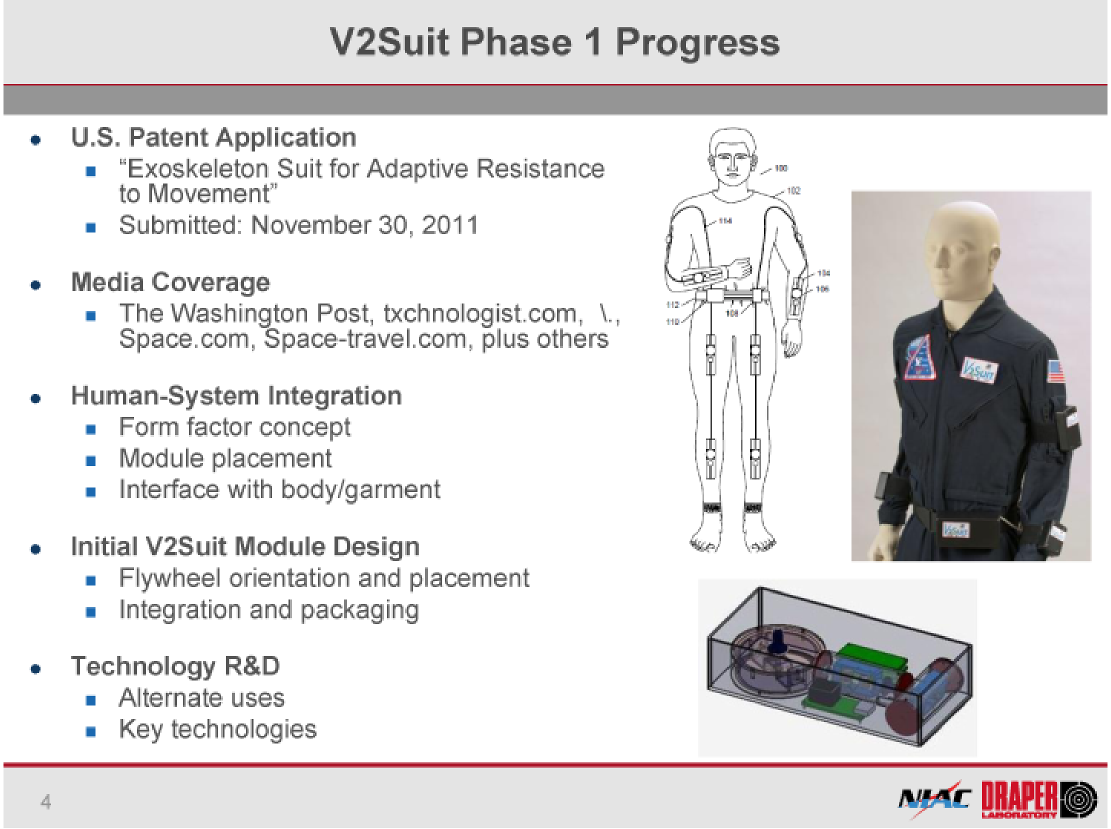
V2Suit Motivation

- **No “down” in 0-G**
  - Visual perceptions dominate
  - “Down” direction may change
- **Physiological adaptation to weightlessness**
- **Perceptual and resistance benefits:**
  - Sensorimotor adaptation
    - Earth G, Moon G, Mars G
    - Full-body, tactile perception
  - Musculoskeletal de-conditioning

The V2Suit facilitates human adaptation and performance during long-duration spaceflight

Oman, Charles M., *Chapter 19: Human Visual Orientation in Weightlessness, in Levels of Perception, L.R. Harris and M. Jenkin, Editors. 2003, Springer-Verlag: New York. p. 375-395.*

Bloomberg, J. *Promoting Sensorimotor Response Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-Duration Space Flight (Mobility). 2006 ; Available from: http://exploration.nasa.gov/programs/station/Mobility.html.*

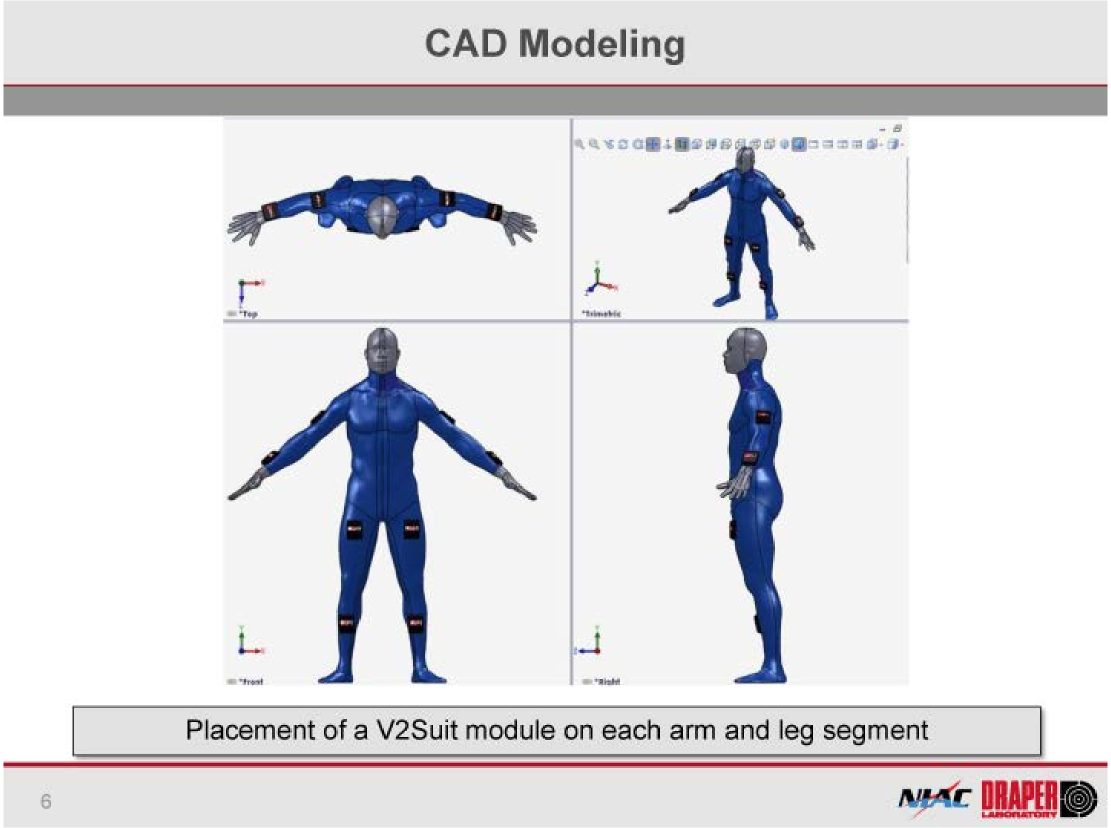


V2Suit Phase 1 Progress

- **U.S. Patent Application**
  - “Exoskeleton Suit for Adaptive Resistance to Movement”
  - Submitted: November 30, 2011
- **Media Coverage**
  - The Washington Post, txchnologist.com, \., Space.com, Space-travel.com, plus others
- **Human-System Integration**
  - Form factor concept
  - Module placement
  - Interface with body/garment
- **Initial V2Suit Module Design**
  - Flywheel orientation and placement
  - Integration and packaging
- **Technology R&D**
  - Alternate uses
  - Key technologies

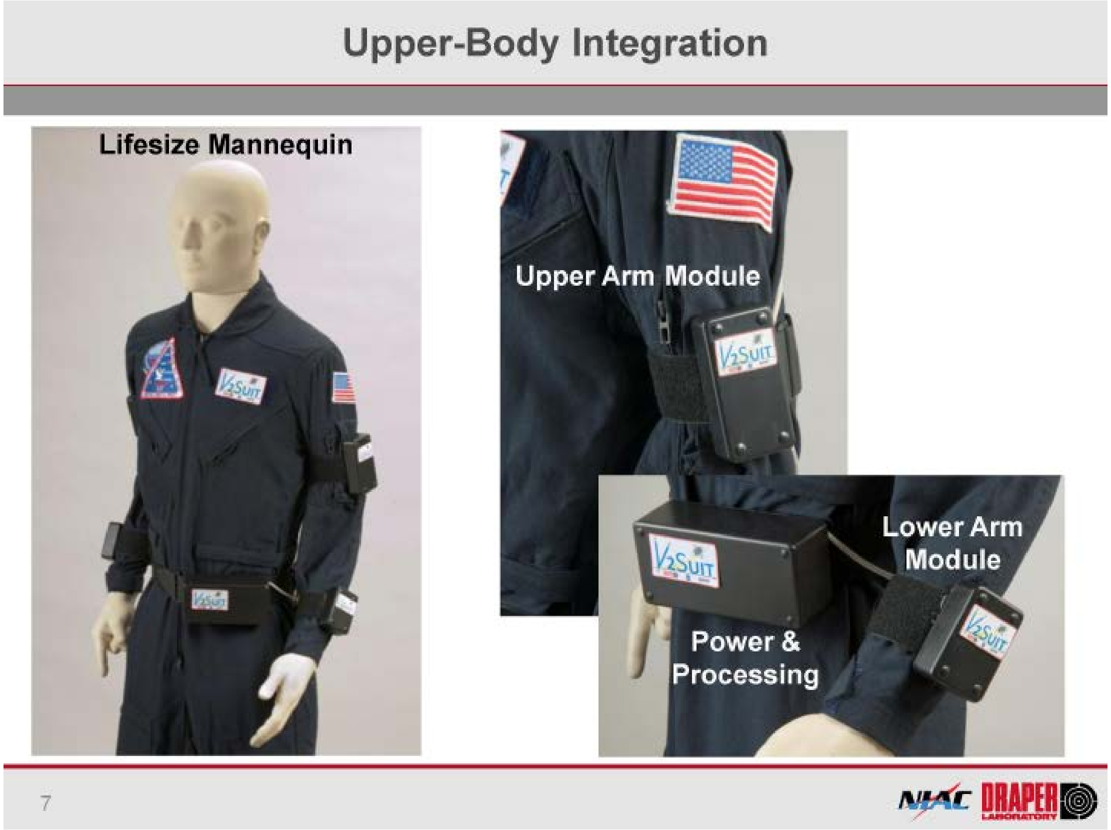
Innovations in Engineering

Human-System Integration



CAD Modeling

Placement of a V2Suit module on each arm and leg segment



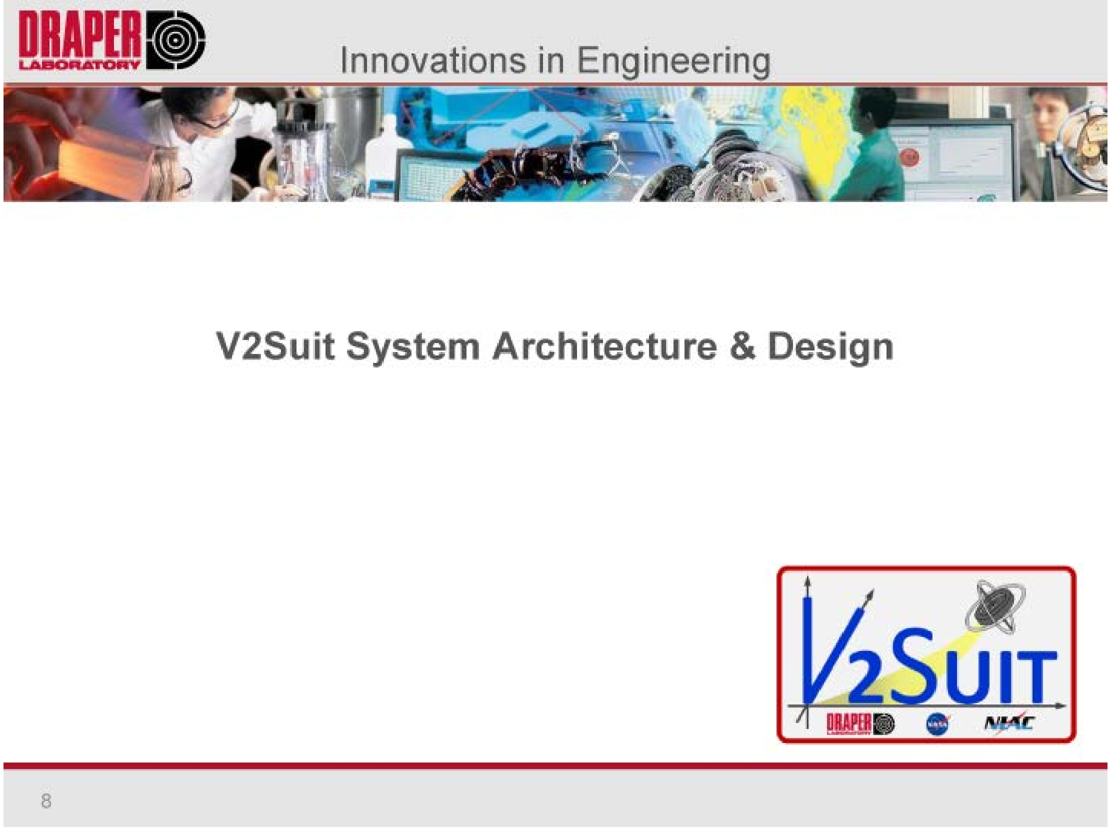
Upper-Body Integration

Lifesize Mannequin

Upper Arm Module

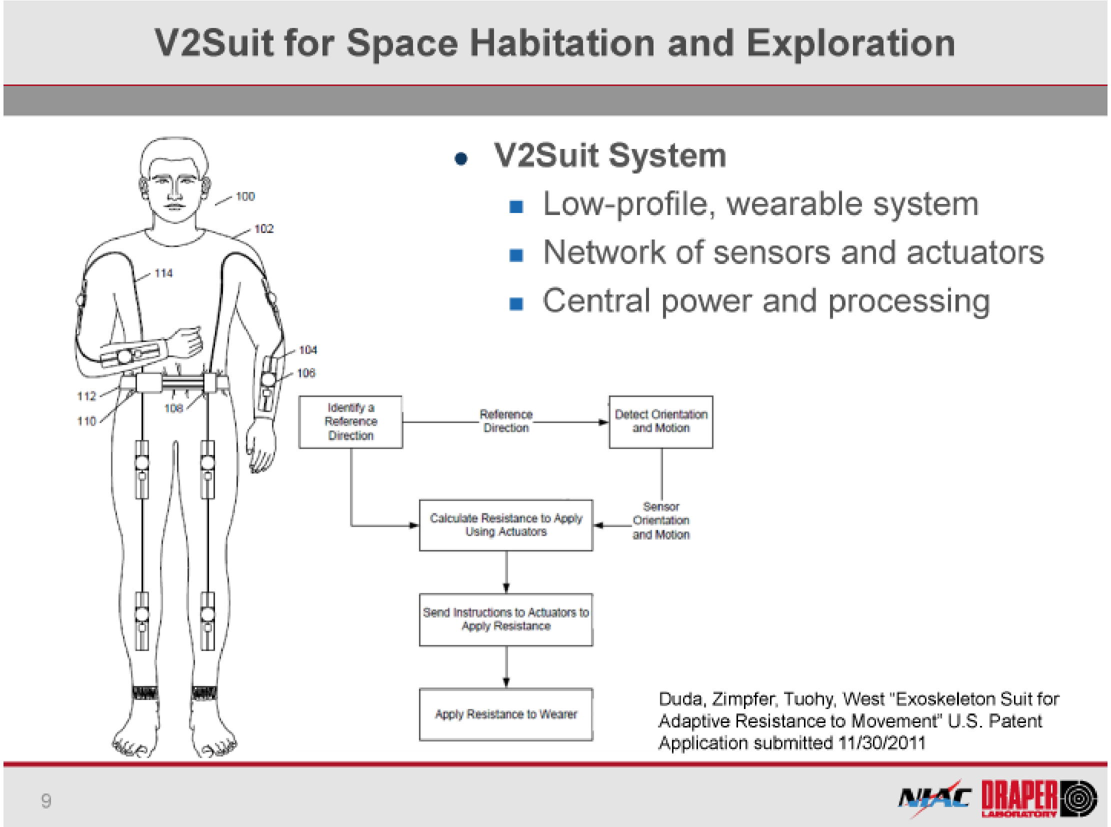
Lower Arm Module

Power & Processing



Innovations in Engineering

V2Suit System Architecture & Design



V2Suit for Space Habitation and Exploration

- **V2Suit System**
  - Low-profile, wearable system
  - Network of sensors and actuators
  - Central power and processing

Identify a Reference Direction

Reference Direction

Detect Orientation and Motion

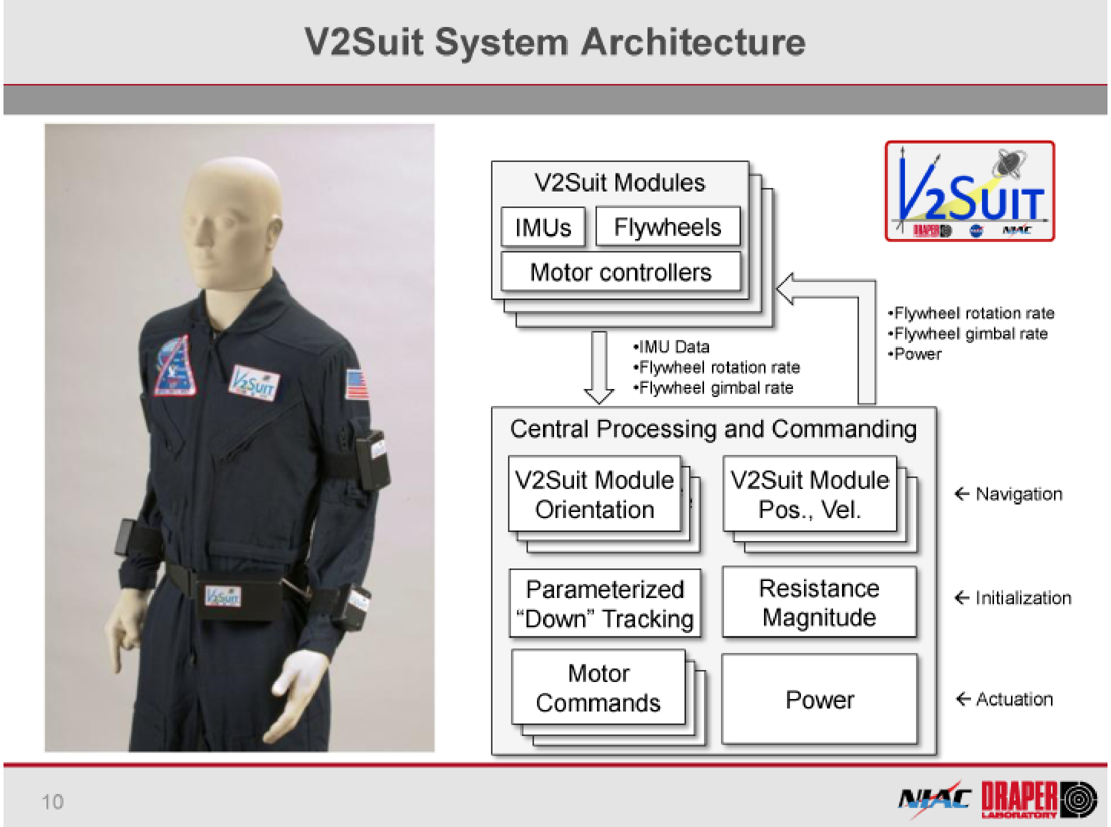
Sensor Orientation and Motion

Calculate Resistance to Apply Using Actuators

Send Instructions to Actuators to Apply Resistance

Apply Resistance to Wearer

Duda, Zimpfer, Tuohy, West "Exoskeleton Suit for Adaptive Resistance to Movement" U.S. Patent Application submitted 11/30/2011



V2Suit System Architecture

V2Suit Modules

IMUs

Flywheels

Motor controllers

- •IMU Data
- •Flywheel rotation rate
- •Flywheel gimbal rate

- •Flywheel rotation rate
- •Flywheel gimbal rate
- •Power

Central Processing and Commanding

V2Suit Module Orientation

V2Suit Module Pos., Vel.

Parameterized "Down" Tracking

Resistance Magnitude

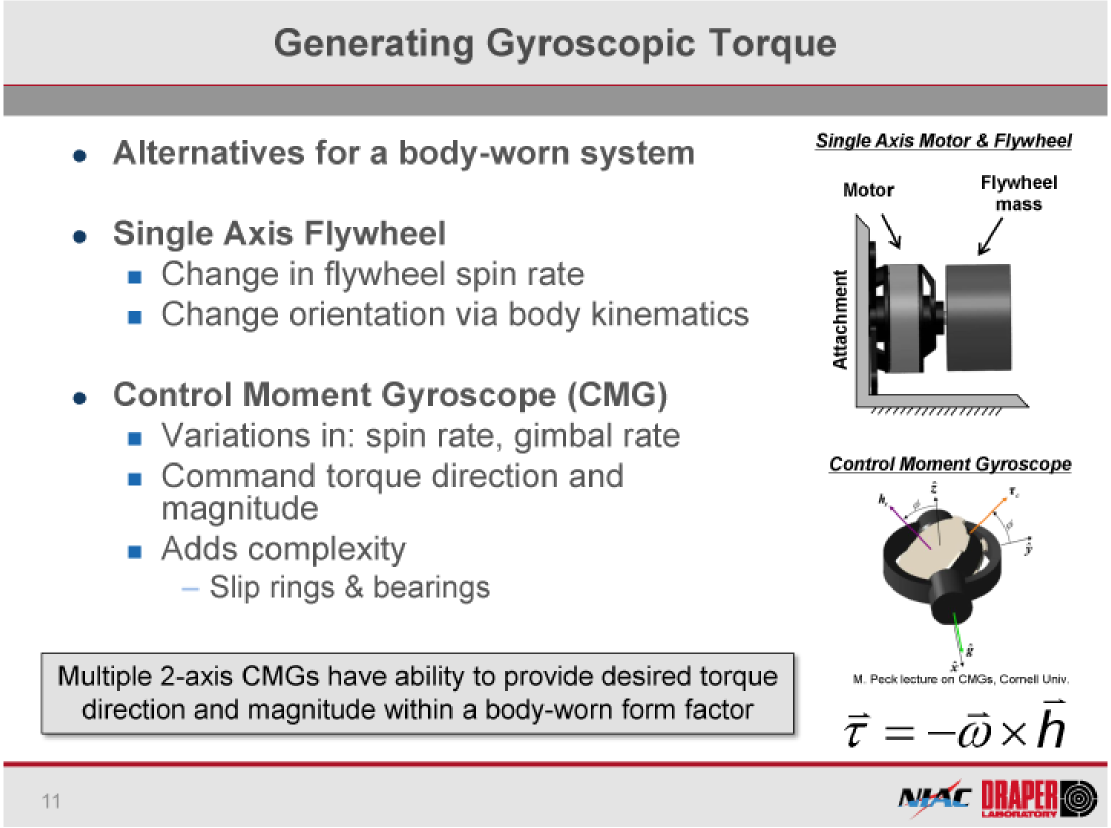
Motor Commands

Power

← Navigation

← Initialization

← Actuation



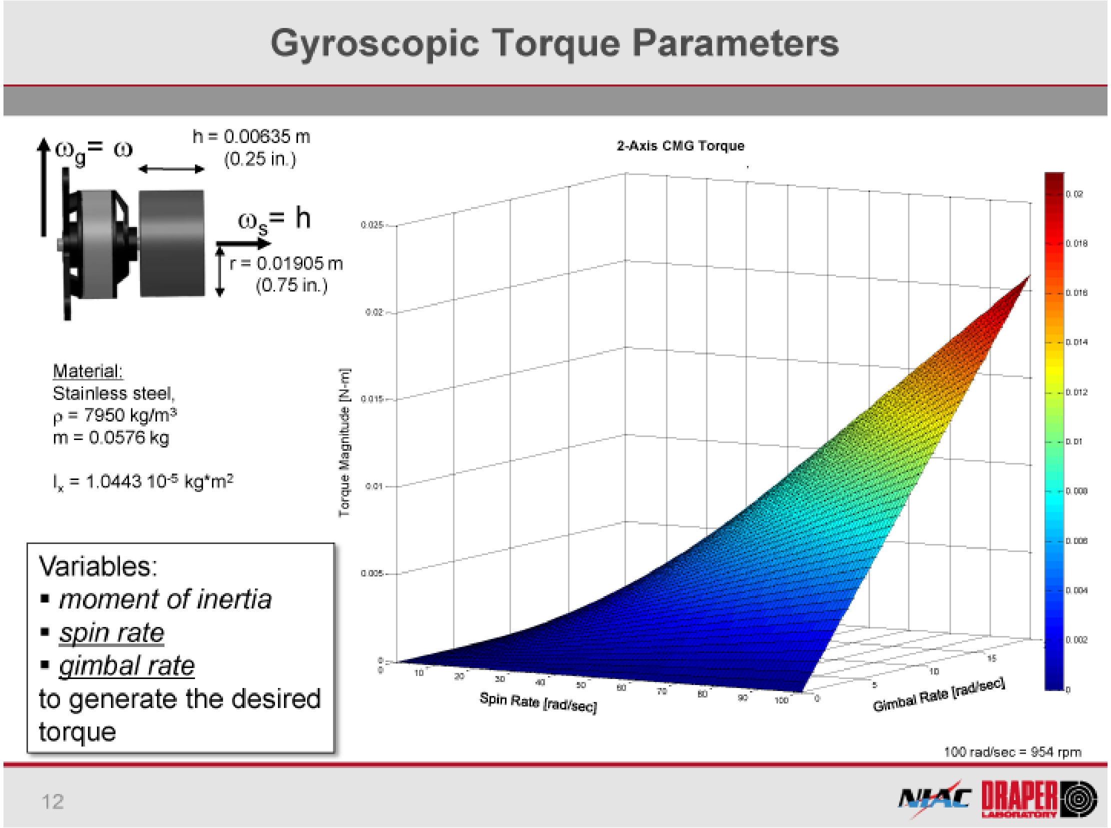
Generating Gyroscopic Torque

- **Alternatives for a body-worn system**
- **Single Axis Flywheel**
    - Change in flywheel spin rate
    - Change orientation via body kinematics
- **Control Moment Gyroscope (CMG)**
    - Variations in: spin rate, gimbal rate
    - Command torque direction and magnitude
    - Adds complexity
        - Slip rings & bearings

Multiple 2-axis CMGs have ability to provide desired torque direction and magnitude within a body-worn form factor

M. Peck lecture on CMGs, Cornell Univ.

$$\vec{\tau} = -\vec{\omega} \times \vec{h}$$



Gyroscopic Torque Parameters

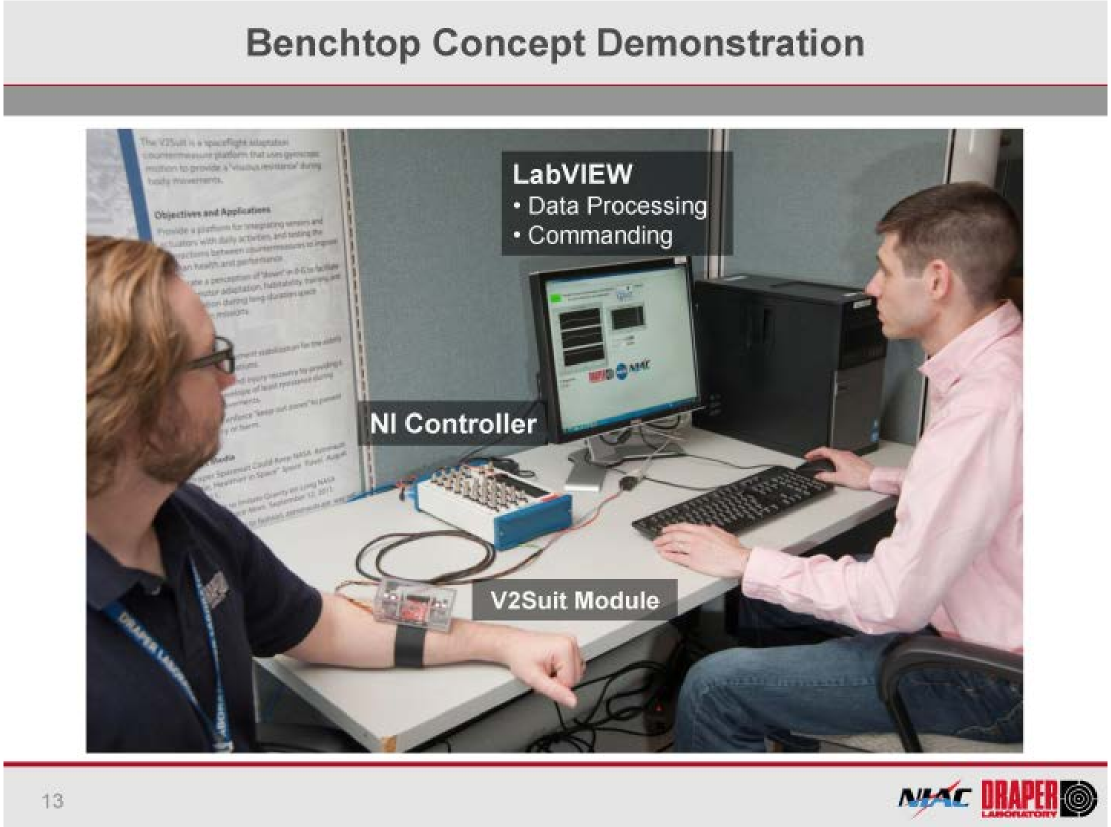
Material:
Stainless steel,
ρ = 7950 kg/m^3
m = 0.0576 kg

I_x = 1.0443 10^{-5} kg*m^2

Variables:
- *moment of inertia*
- *spin rate*
- *gimbal rate*

to generate the desired torque

100 rad/sec = 954 rpm

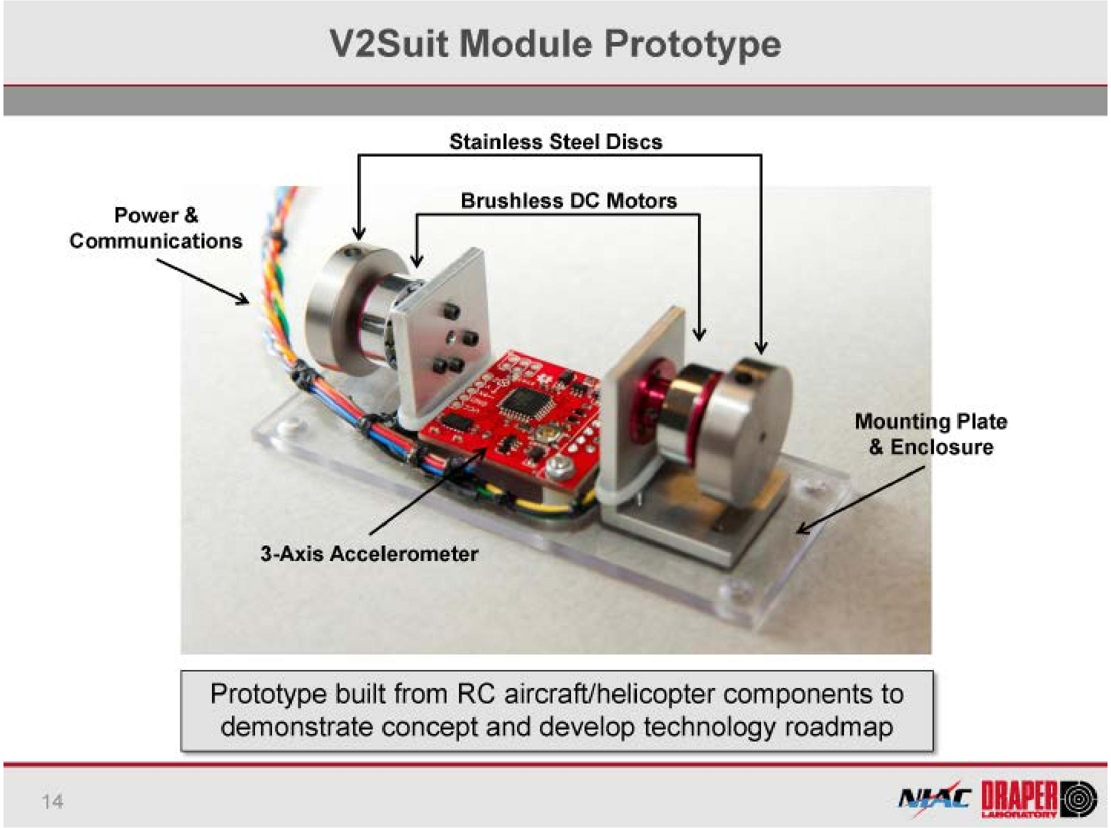


Benchtop Concept Demonstration

LabVIEW
- Data Processing
- Commanding

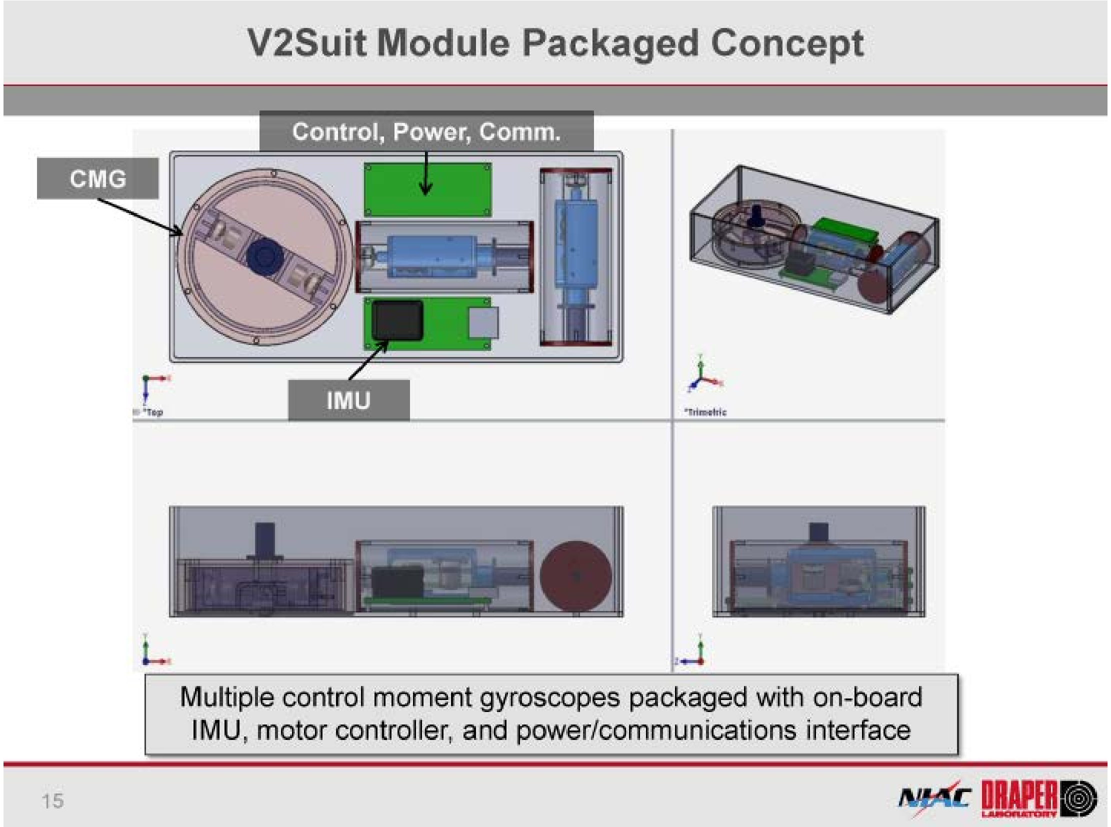
NI Controller

V2Suit Module



V2Suit Module Prototype

Prototype built from RC aircraft/helicopter components to demonstrate concept and develop technology roadmap



V2Suit Module Packaged Concept

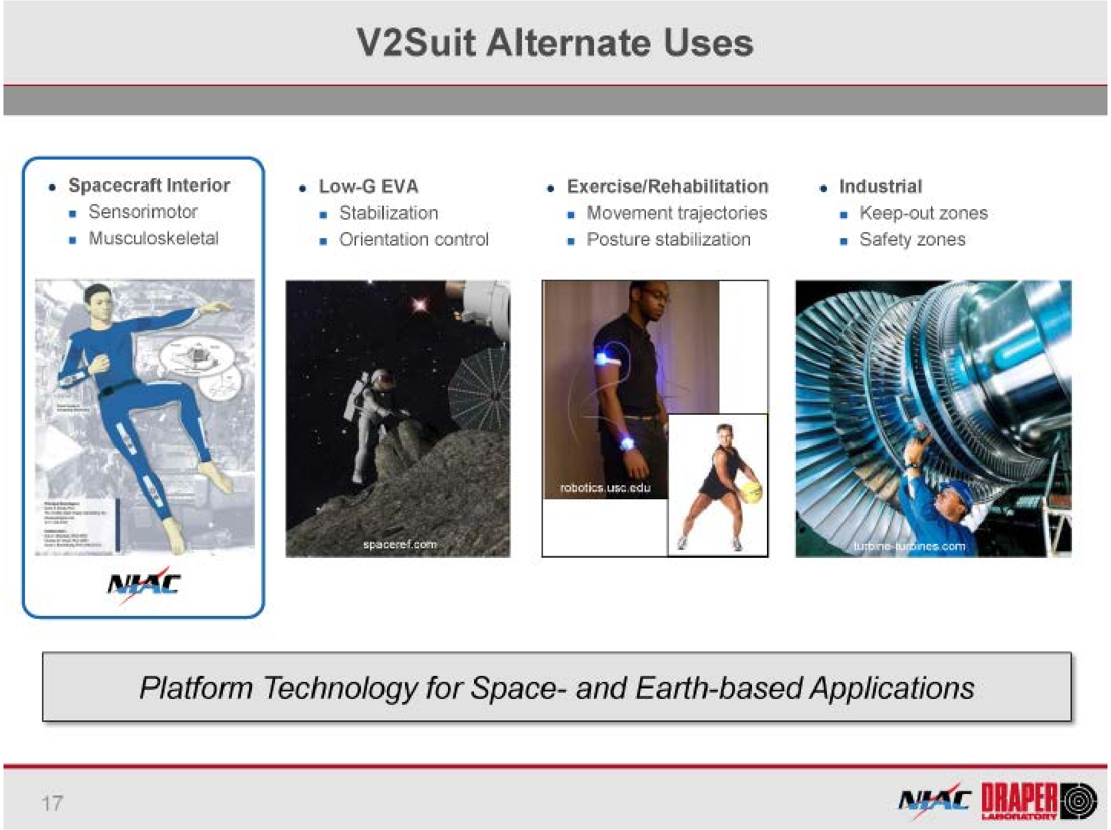
Multiple control moment gyroscopes packaged with on-board IMU, motor controller, and power/communications interface

15

Innovations in Engineering

Technology R&D

16



V2Suit Alternate Uses

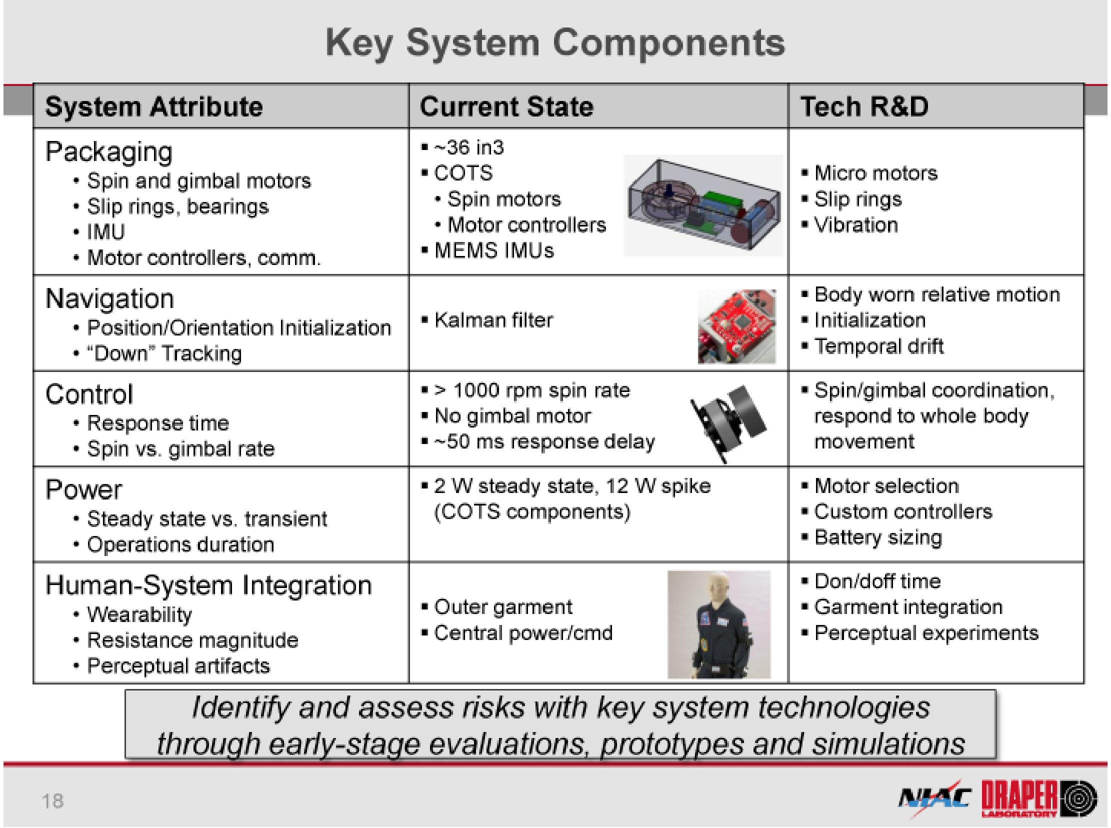
- **Spacecraft Interior**
  - Sensorimotor
  - Musculoskeletal
- **Low-G EVA**
  - Stabilization
  - Orientation control
- **Exercise/Rehabilitation**
  - Movement trajectories
  - Posture stabilization
- **Industrial**
  - Keep-out zones
  - Safety zones

spaceref.com

robotics.usc.edu

turbine-turbines.com

Platform Technology for Space- and Earth-based Applications



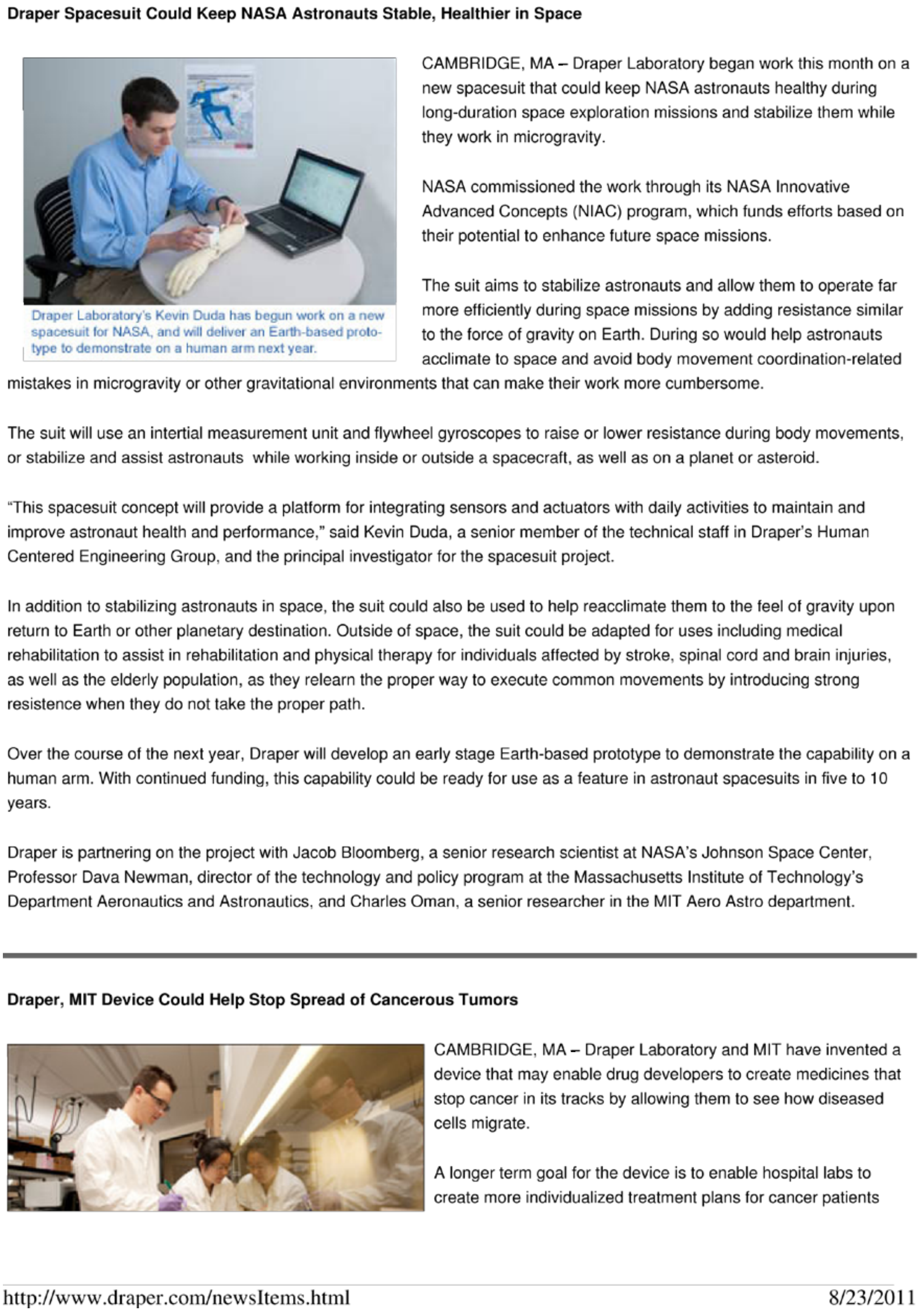
Key System Components

System Attribute	Current State	Tech R&D
Packaging • Spin and gimbal motors • Slip rings, bearings • IMU • Motor controllers, comm.	▪ ~36 in3 ▪ COTS • Spin motors • Motor controllers ▪ MEMS IMUs	▪ Micro motors ▪ Slip rings ▪ Vibration
Navigation • Position/Orientation Initialization • "Down" Tracking	▪ Kalman filter	▪ Body worn relative motion ▪ Initialization ▪ Temporal drift
Control • Response time • Spin vs. gimbal rate	▪ > 1000 rpm spin rate ▪ No gimbal motor ▪ ~50 ms response delay	▪ Spin/gimbal coordination, respond to whole body movement
Power • Steady state vs. transient • Operations duration	▪ 2 W steady state, 12 W spike (COTS components)	▪ Motor selection ▪ Custom controllers ▪ Battery sizing
Human-System Integration • Wearability • Resistance magnitude • Perceptual artifacts	▪ Outer garment ▪ Central power/cmd	▪ Don/doff time ▪ Garment integration ▪ Perceptual experiments

Identify and assess risks with key system technologies through early-stage evaluations, prototypes and simulations

6.4 Select News & Media Coverage

Draper Laboratory News Release



Draper Spacesuit Could Keep NASA Astronauts Stable, Healthier in Space

Draper Laboratory's Kevin Duda has begun work on a new spacesuit for NASA, and will deliver an Earth-based prototype to demonstrate on a human arm next year.

CAMBRIDGE, MA – Draper Laboratory began work this month on a new spacesuit that could keep NASA astronauts healthy during long-duration space exploration missions and stabilize them while they work in microgravity.

NASA commissioned the work through its NASA Innovative Advanced Concepts (NIAC) program, which funds efforts based on their potential to enhance future space missions.

The suit aims to stabilize astronauts and allow them to operate far more efficiently during space missions by adding resistance similar to the force of gravity on Earth. During so would help astronauts acclimate to space and avoid body movement coordination-related mistakes in microgravity or other gravitational environments that can make their work more cumbersome.

The suit will use an intertial measurement unit and flywheel gyroscopes to raise or lower resistance during body movements, or stabilize and assist astronauts while working inside or outside a spacecraft, as well as on a planet or asteroid.

"This spacesuit concept will provide a platform for integrating sensors and actuators with daily activities to maintain and improve astronaut health and performance," said Kevin Duda, a senior member of the technical staff in Draper's Human Centered Engineering Group, and the principal investigator for the spacesuit project.

In addition to stabilizing astronauts in space, the suit could also be used to help reacclimate them to the feel of gravity upon return to Earth or other planetary destination. Outside of space, the suit could be adapted for uses including medical rehabilitation to assist in rehabilitation and physical therapy for individuals affected by stroke, spinal cord and brain injuries, as well as the elderly population, as they relearn the proper way to execute common movements by introducing strong resistence when they do not take the proper path.

Over the course of the next year, Draper will develop an early stage Earth-based prototype to demonstrate the capability on a human arm. With continued funding, this capability could be ready for use as a feature in astronaut spacesuits in five to 10 years.

Draper is partnering on the project with Jacob Bloomberg, a senior research scientist at NASA's Johnson Space Center, Professor Dava Newman, director of the technology and policy program at the Massachusetts Institute of Technology's Department Aeronautics and Astronautics, and Charles Oman, a senior researcher in the MIT Aero Astro department.

Draper, MIT Device Could Help Stop Spread of Cancerous Tumors

CAMBRIDGE, MA – Draper Laboratory and MIT have invented a device that may enable drug developers to create medicines that stop cancer in its tracks by allowing them to see how diseased cells migrate.

A longer term goal for the device is to enable hospital labs to create more individualized treatment plans for cancer patients

http://www.draper.com/newsItems.html 8/23/2011

The Washington Post

URBAN JUNGLE

The changing natural world at our doorsteps.

Troubled urban streams

When hurricanes or tropical storms pass through the Washington area, flash flooding can become a problem, not just for houses and businesses in the flood plain, but also for the organisms that live in the waterways being flushed with storm water.

The flow can cause serious disturbances in streambeds, "uprooting aquatic plants, rolling rocks and killing many bottom-dwelling organisms," says N. LeRoy Poff, an ecology professor at Colorado State University.

Heavy rains can also flush pollutants and soil sediments into streams. Although too much sediment in a stream can cause problems, too little can also be detrimental.

"Many streams inside the Beltway have been urbanized for a long time, and there is no longer available sediment from the watershed due to all the impervious surfaces," says Poff. A loss of sediment cripples an urban stream's ability to deposit new banks and bottoms, so the stream becomes incised, cutting an increasingly deeper groove for itself.

Another problem: Roofs, streets and parking lots prevent rainwater from soaking into the ground, sending it as a "flash" through urban waterways. Sensitive species have trouble finding refuge during such an event.

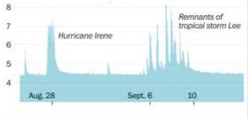
Only species that are pollution-tolerant, have a fast life cycle and are able to handle extremes in flow can survive in such an environment, says Poff.

Asian clams, an exotic invasive species found in local streams, "do very well in extreme flashy environments," says Daren Carlisle, an aquatic ecologist with the U.S. Geological Survey.

Carlisle describes urban-stream fishes, such as the common carp, as generalists: "They can reproduce anywhere and eat anything."

Watts Branch, a deeply incised urban stream, drains almost 3.3 square miles of Northeast Washington and Capitol Heights.

WATER LEVEL IN WATTS BRANCH, in feet



SOURCES: Joel Guyer, USGS Virginia Water Science Center; USGS National Water Information System
PATTERSON CLARK/THE WASHINGTON POST *clarkp@washpost.com* *washingtonpost.com/urbanjungle*

HOW & WHY

Brian Palmer

When it comes to fashion, astronauts are way out there

Some people like runway fashion. Not me. I'm much more interested in function than form. From that perspective, no one has a more interesting closet than an astronaut. While they look very much like painter's smocks — their sloppy draping would probably make Michael Kors faint — spacesuits are fascinating, high-tech threads.

Astronaut clothes really boil down to indoor wear and outdoor wear. Let's start with the outdoor ensemble. To state the obvious, space is an inhospitable environment. There's no air. Astronauts are constantly bombarded by ultraviolet-C rays, the high-energy solar radiation that ozone blocks from the Earth. The weather is terrible. A spacewalker's suit can confront freezing temperatures on the front and burning-hot conditions on the back, because the difference between sun and shade is around 275 degrees in space.

Then there's the pressure difference. Space is nearly a vacuum. If an astronaut stepped into the void with lungs full of oxygen in ordinary clothes, the air would expand enough to rupture the lungs. The pressure is also so low that the boiling point of blood drops below human body temperature, a condition that can kill in an instant. Space is also full of micro-meteoroids, tiny projectiles that threaten to pierce an astronaut's armor.

Spacesuits protect astronauts against all these challenges. They have multiple layers to provide insulation and prevent a puncture of the inner coating, which is filled with pure oxygen at a livable pressure. (The pressure difference between the suit and the external environment is daunting, though. Without the improvement in modern spacesuit joints, bending your knee in a spacesuit would be like trying to bend an inflated football.)

A layer of water circulates throughout the suit, interacting with a layer of ice near the outer surface, to moderate the temperature. A ventilation system removes excess body heat when the sun threatens to warm the astronaut too much. For the most part, the temperature remains fairly comfortable, although some space travelers have noted that their extremities —which aren't covered by the water circulation system —can get chilly.

Modern suits have built-in life support systems, so the astronaut can function outside a spacecraft without being tethered to a much larger machine. (Earlier astronauts had to remain attached to their shuttles by large tubes.) The suits are so self-contained that some refer to them as the universe's smallest space vehicles.

Until recently, an astronaut's indoor outfit hasn't had nearly the same sophistication. The international space station, which is still operating despite the end of the shuttle program, has regulated temperature and pressure, plus breathable air. It also protects astronauts from nasty space projectiles.

But this environment has its own challenges. Living in a small orbiting object requires astronauts to adjust to microgravity. It's not just a matter of overcoming the initial clumsiness of movement as they float around the ISS. Since there's very little to resist an astronaut's motion, muscles become deconditioned over months of space life. Bone density also drops, and faces puff up as fluid that is normally pulled toward the feet floats into the head.

To deal with all this, engineers at Draper Labs, an MIT spinoff, are working on a spacesuit that creates the sensation of gravity.

To understand how it works, consider this experiment: If you sit still in a swivel chair holding an upright, spinning bicycle wheel by its axle, then tilt the wheel to the left or right, the chair begins to turn. (Watch the BBC's "office chair fun" on YouTube to see the experiment in action.)

"A flywheel or spinning mass doesn't like to change its orientation," says Kevin Duda. He's leading the Draper team that's developing the spacesuit. "When you tilt the spinning wheel, it exerts a force against your body."

The engineers at Draper think they can use this effect to create a suit that resists an astronaut's attempts to move, in the same way gravity resists us on Earth.

Imagine that an astronaut working in the space station reaches for an instrument on a nearby shelf. As soon as he begins to lift his arm, a computer system inside the suit would order flywheels located along the suit's forearm to begin spinning in a direction that would exert a force against the arm's motion, The faster the flywheel spins, the more the suit would push back against the astronaut.

If it works, the suit would offer a number of benefits. It could ease the transition to life on the space station, and the return to living on Earth. The suit could reduce some of the muscle deconditioning that happens in space.

Beyond the space station, the suit could be used to prepare astronauts for the long, low-gravity trip to Mars and for maneuvering on the Martian surface, whose gravity is only about 40 percent as strong as Earth's.

There may even be uses on Earth. Since the flywheels can make movement more difficult in any environment, Duda thinks the technology could be useful for rehabilitation.

"Some patients have trouble with repetitive movements, such as walking," he says. "The flywheels could train the body to walk by making it difficult for the patient's legs to stray from a proper gait."

Duda hopes Draper Labs will have the spacesuits ready in five years. That should be several years before NASA's first manned mission to Mars, which probably won't come before 2025.

health-science@washpost.com

Space News

www.spacenews.com SPACE NEWS 9
September 12, 2011

Hispasat Picks Ariane 5 To Launch Amazonas 3

Europe's Arianespace consortium will launch Spanish satellite fleet operator Hispasat's Amazonas 3 tri-band telecommunications satellite aboard a European Ariane 5 rocket in late 2012 or early 2013 under a contract Arianespace and Hispasat announced Sept. 7.

Amazonas 3, under construction by Space Systems/Loral of Palo Alto, Calif., will replace the Amazonas 1 satellite now stationed at Hispasat's 61 degrees west orbital slot, where it provides telecommunications in the Americas and between Latin America and Europe. Amazonas 1 was launched in 2004 with an expected 15-year operational life, but a defect in its fuel system has cut its life expectancy by several years.

Given the growing importance of the Americas, especially Central and South America, to Hispasat — the region provided 44 percent of its total 2010 revenue of $214.6 million — the company was forced to order Amazonas 3 sooner than originally expected.

Madrid-based Hispasat also operates the Amazonas 2 satellite at the 61 degrees west slot. Amazonas 2 was launched in October 2009 and is expected to operate for at least 15 years. Amazonas 1 and Amazonas 2 were both built by Astrium Satellites of Europe.

Amazonas 3, based on Loral's 1300 satellite platform, is expected to weigh 6,000 kilograms at launch. It will be equipped with 33 Ku-band transponders, 19 C-band transponders and nine Ka-band spot beams. Hispasat said Amazonas 3 will be the first satellite over Latin America providing substantial Ka-band capacity for broadband Internet connections.

Hispasat is financing Loral's construction of Amazonas 3 through a loan from JPMorgan Chase that was valued at 165 million euros ($236 million) and guaranteed by the U.S. Export-Import Bank. Hispasat said it will be repaying the loan over 10 years.

RapidEye Inks Imagery Deal With NGA Worth $4.6 Million

The U.S. National Geospatial-Intelligence Agency (NGA) has contracted with Canadian-German Earth observation satellite operator RapidEye to purchase up to $4.6 million in RapidEye imagery over the next 18 months, RapidEye announced Sept. 6.

The indefinite-delivery, indefinite-quantity contract is the first NGA purchase of RapidEye data. Brandenburg, Germany-based RapidEye, which was recently purchased by Canada's Iunctus Geomatics of Lethbridge, Alberta, operates a fleet of five identical optical observation satellites, which have been in orbit since mid-2008.

The satellites offer relatively low-resolution imagery but, evenly spaced in low Earth orbit, they are able to cover vast swaths of territory — 4 million square kilometers per day — and offer relatively quick revisits to a given locale.

NGA is the principal U.S. government agency responsible for purchasing satellite imagery from the private sector. It has long-term contracts with high-resolution-satellite operators GeoEye and DigitalGlobe of the United States, and also has purchased radar imagery from Italian and German radar satellite operators.

Comments: Brian Berger, bberger@spacenews.com

Blue Origin Acknowledges Test Flight Failure

Blue Origin, the private entrepreneurial space group backed by Amazon.com founder Jeff Bezos, acknowledged Sept. 2 that it lost its New Shepard suborbital spacecraft during a test mishap in Texas.

"Three months ago, we successfully flew our second test vehicle in a short hop mission, and then last week we lost the vehicle during a developmental test at Mach 1.2 and an altitude of 45,000 feet," or 13,716 meters, Bezos wrote in a statement posted on the Blue Origin website Sept 2.

Bezos' statement appeared several hours after *The Wall Street Journal* first reported on the Aug. 24 test failure.

According to Bezos, a "flight instability" drove an angle of attack that triggered the Blue Origin range safety team to terminate thrust on the vehicle. The vehicle roared skyward from the Blue Origin spaceport, roughly 40 kilometers north of tiny Van Horn, Texas, before the failure.

The tight-lipped Blue Origin space company has been focused on suborbital spaceflight, first using its Goddard vehicle and then migrating to the New Shepard spacecraft design at its facility in Culberson County, Texas. New Shepard is seen by the company as supporting the commercial suborbital tourist market. The Goddard vehicle flew on a short, successful test flight in November 2006.

In April, NASA awarded Blue Origin $22 million in funding under the space agency's Commercial Crew Development program for development of concepts and technologies to support future human spaceflight operations. That award followed $3.7 million in NASA funding the company received in 2010 to develop an astronaut escape system and space capsule for ground tests.

NASA retired its space shuttle fleet in July and plans to rely on U.S. commercial spacecraft like those being developed by Blue Origin and other private space companies to transport American astronauts to low Earth orbit.

While the test vehicle that failed last week was a suborbital vehicle, Blue Origin is also developing an orbital space capsule designed initially to launch on an expendable Atlas 5 rocket, then transition to a reusable booster being developed by the company.

"In case you're curious and wondering 'where is the crew capsule,' the development vehicle doesn't have a crew capsule — just a close-out fairing instead," Bezos added in a postscript to his website update. "We're working on the sub-orbital crew capsule separately, as well as an orbital crew vehicle to support NASA's Commercial Crew program."

BLUE ORIGIN PHOTO

New Shepard during a successful early-summer test

DRAPER LABORATORY PHOTO

Kevin Duda is one of the researchers designing a stabilized spacesuit at the Draper Laboratory

Spacesuit To Imitate Gravity on Long NASA Missions

Researchers at Draper Laboratory in Cambridge, Mass., are working on a NASA-funded concept for a spacesuit that would help astronauts adjust to weightlessness by resisting movement to imitate gravity.

"We would expect the resistance to simulate movements against a gravitational acceleration when in microgravity," said Kevin Duda, senior member of the technical staff in the Draper Laboratory's Human Centered Engineering Group.

An inertial measurement unit would help the suit gauge an astronaut's movement. That in turn could allow flywheel gyroscopes — spinning devices that resist changes in angular momentum caused by motion — to raise or lower spacesuit resistance for every movement, by increasing speed or changing direction.

First-generation versions of the suit mainly would help astronauts working inside the protected habitat of a space station or spacecraft. But if the concept holds up, it might eventually help stabilize astronauts during spacewalks, as well as on low-gravity planets or asteroids.

"Sensing and adapting to exactly what an astronaut wants to do is difficult," Duda said. "We need to analyze the mechanics and prototype the concept before we can accurately quantify the type of performance we can expect."

Wearing such a suit also might help astronauts ease back into life on Earth, because their muscle coordination would not have to readjust from the resistance-free motions in microgravity.

Another side benefit from the suit could take the form of a space technology spinoff that helps people go through physical rehabilitation. Patients suffering from stroke, spinal cord and brain injuries could make use of the device, as could older people.

"A wearable, full-motion device could be programmed to help you learn, or re-learn, specific movements," Duda explained.

Duda's Draper Lab group has partnered on the project with scientists at NASA's Johnson Space Center in Houston and the Massachusetts Institute of Technology in Cambridge. They plan to first create a prototype for a spacesuit arm by 2012, with funding from the NASA Innovative Advanced Concepts program.

If success attracts continued funds, Duda said, a full-body wearable suit could become a reality within a decade — easily within the time frame for NASA's plans targeting the asteroids, Mars and beyond.

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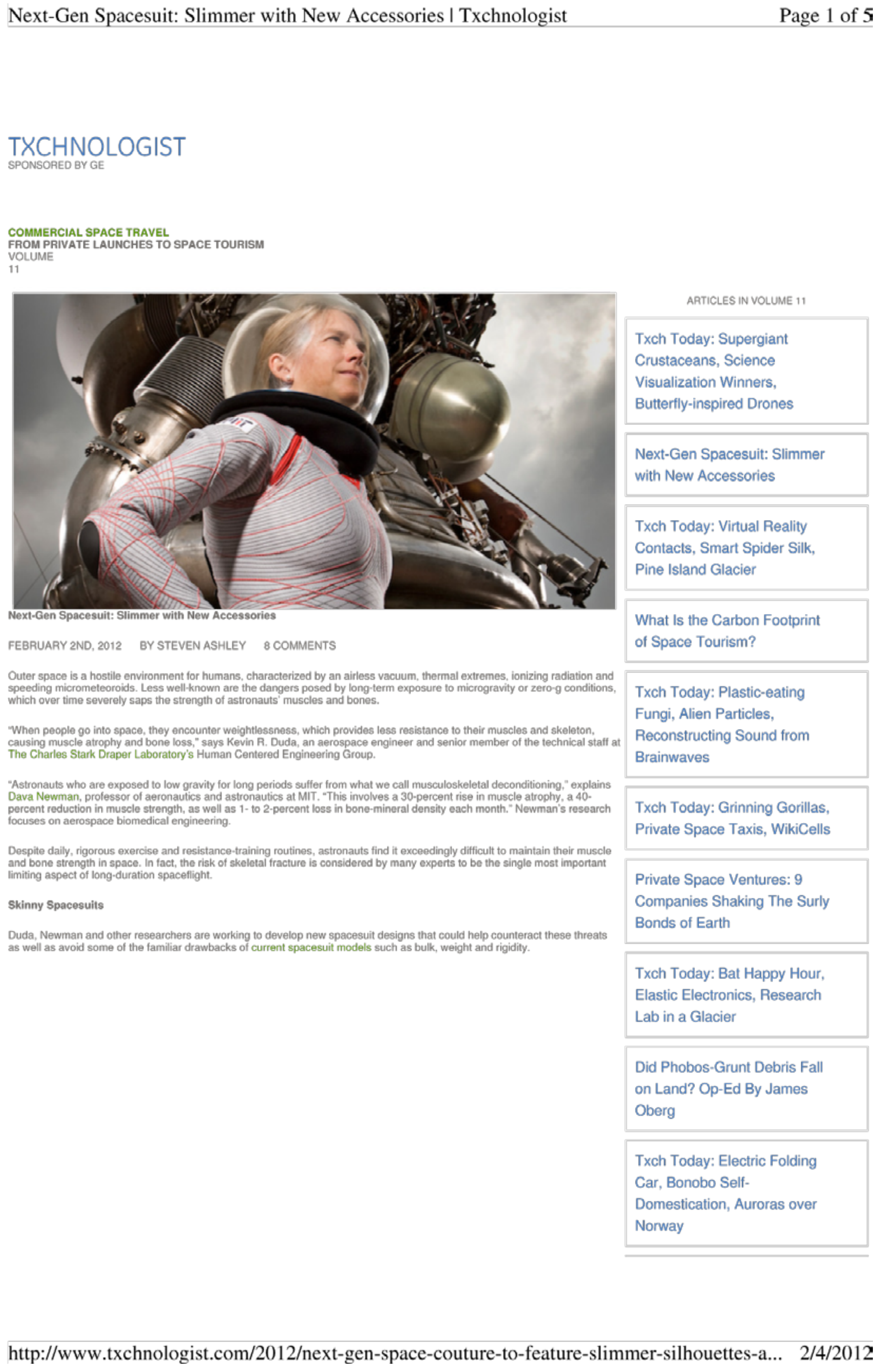

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Next-Gen Spacesuit: Slimmer with New Accessories

FEBRUARY 2ND, 2012 BY STEVEN ASHLEY 8 COMMENTS

Outer space is a hostile environment for humans, characterized by an airless vacuum, thermal extremes, ionizing radiation and speeding micrometeoroids. Less well-known are the dangers posed by long-term exposure to microgravity or zero-g conditions, which over time severely saps the strength of astronauts' muscles and bones.

"When people go into space, they encounter weightlessness, which provides less resistance to their muscles and skeleton, causing muscle atrophy and bone loss," says Kevin R. Duda, an aerospace engineer and senior member of the technical staff at The Charles Stark Draper Laboratory's Human Centered Engineering Group.

"Astronauts who are exposed to low gravity for long periods suffer from what we call musculoskeletal deconditioning," explains Dava Newman, professor of aeronautics and astronautics at MIT. "This involves a 30-percent rise in muscle atrophy, a 40-percent reduction in muscle strength, as well as 1- to 2-percent loss in bone-mineral density each month." Newman's research focuses on aerospace biomedical engineering.

Despite daily, rigorous exercise and resistance-training routines, astronauts find it exceedingly difficult to maintain their muscle and bone strength in space. In fact, the risk of skeletal fracture is considered by many experts to be the single most important limiting aspect of long-duration spaceflight.

Skinny Spacesuits

Duda, Newman and other researchers are working to develop new spacesuit designs that could help counteract these threats as well as avoid some of the familiar drawbacks of current spacesuit models such as bulk, weight and rigidity.

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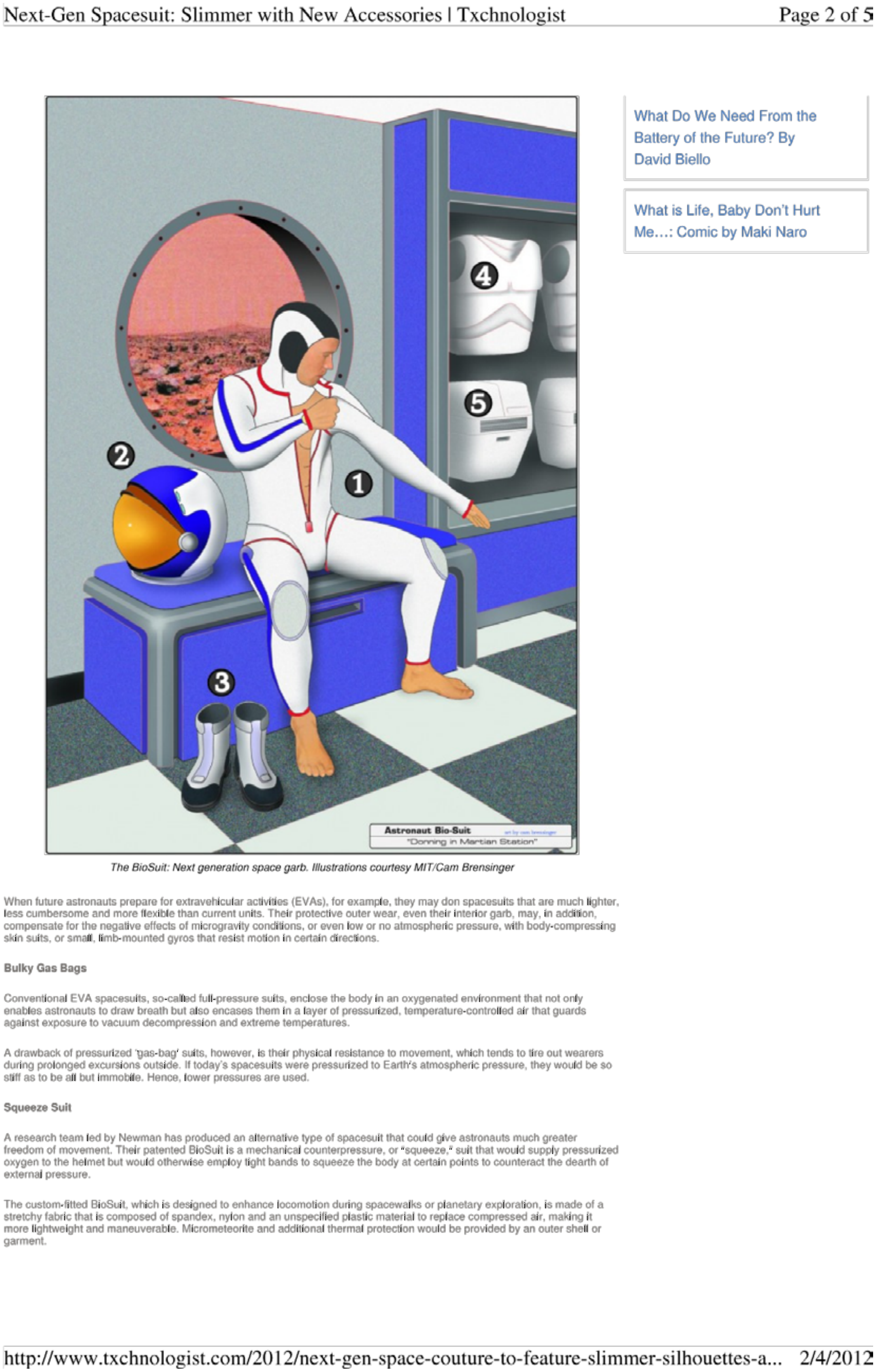


What Do We Need From the Battery of the Future? By David Biello

What is Life, Baby Don't Hurt Me…: Comic by Maki Naro

The BioSuit: Next generation space garb. Illustrations courtesy MIT/Cam Brensinger

When future astronauts prepare for extravehicular activities (EVAs), for example, they may don spacesuits that are much lighter, less cumbersome and more flexible than current units. Their protective outer wear, even their interior garb, may, in addition, compensate for the negative effects of microgravity conditions, or even low or no atmospheric pressure, with body-compressing skin suits, or small, limb-mounted gyros that resist motion in certain directions.

Bulky Gas Bags

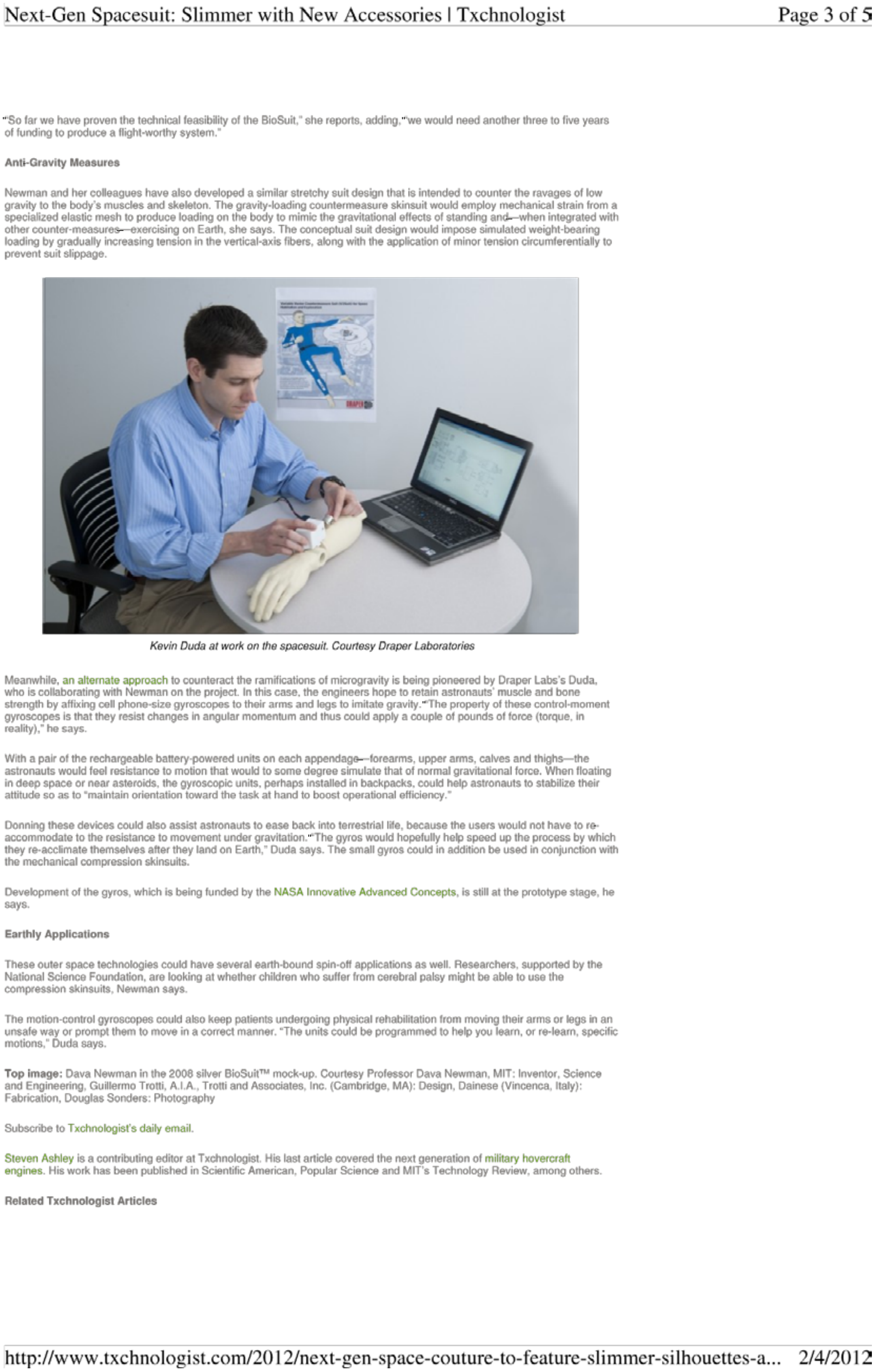
Conventional EVA spacesuits, so-called full-pressure suits, enclose the body in an oxygenated environment that not only enables astronauts to draw breath but also encases them in a layer of pressurized, temperature-controlled air that guards against exposure to vacuum decompression and extreme temperatures.

A drawback of pressurized 'gas-bag' suits, however, is their physical resistance to movement, which tends to tire out wearers during prolonged excursions outside. If today's spacesuits were pressurized to Earth's atmospheric pressure, they would be so stiff as to be all but immobile. Hence, lower pressures are used.

Squeeze Suit

A research team led by Newman has produced an alternative type of spacesuit that could give astronauts much greater freedom of movement. Their patented BioSuit is a mechanical counterpressure, or "squeeze," suit that would supply pressurized oxygen to the helmet but would otherwise employ tight bands to squeeze the body at certain points to counteract the dearth of external pressure.

The custom-fitted BioSuit, which is designed to enhance locomotion during spacewalks or planetary exploration, is made of a stretchy fabric that is composed of spandex, nylon and an unspecified plastic material to replace compressed air, making it more lightweight and maneuverable. Micrometeorite and additional thermal protection would be provided by an outer shell or garment.



"So far we have proven the technical feasibility of the BioSuit," she reports, adding, "we would need another three to five years of funding to produce a flight-worthy system."

Anti-Gravity Measures

Newman and her colleagues have also developed a similar stretchy suit design that is intended to counter the ravages of low gravity to the body's muscles and skeleton. The gravity-loading countermeasure skinsuit would employ mechanical strain from a specialized elastic mesh to produce loading on the body to mimic the gravitational effects of standing and—when integrated with other counter-measures—exercising on Earth, she says. The conceptual suit design would impose simulated weight-bearing loading by gradually increasing tension in the vertical-axis fibers, along with the application of minor tension circumferentially to prevent suit slippage.

Kevin Duda at work on the spacesuit. Courtesy Draper Laboratories

Meanwhile, an alternate approach to counteract the ramifications of microgravity is being pioneered by Draper Labs's Duda, who is collaborating with Newman on the project. In this case, the engineers hope to retain astronauts' muscle and bone strength by affixing cell phone-size gyroscopes to their arms and legs to imitate gravity. "The property of these control-moment gyroscopes is that they resist changes in angular momentum and thus could apply a couple of pounds of force (torque, in reality)," he says.

With a pair of the rechargeable battery-powered units on each appendage—forearms, upper arms, calves and thighs—the astronauts would feel resistance to motion that would to some degree simulate that of normal gravitational force. When floating in deep space or near asteroids, the gyroscopic units, perhaps installed in backpacks, could help astronauts to stabilize their attitude so as to "maintain orientation toward the task at hand to boost operational efficiency."

Donning these devices could also assist astronauts to ease back into terrestrial life, because the users would not have to re-accommodate to the resistance to movement under gravitation. "The gyros would hopefully help speed up the process by which they re-acclimate themselves after they land on Earth," Duda says. The small gyros could in addition be used in conjunction with the mechanical compression skinsuits.

Development of the gyros, which is being funded by the NASA Innovative Advanced Concepts, is still at the prototype stage, he says.

Earthly Applications

These outer space technologies could have several earth-bound spin-off applications as well. Researchers, supported by the National Science Foundation, are looking at whether children who suffer from cerebral palsy might be able to use the compression skinsuits, Newman says.

The motion-control gyroscopes could also keep patients undergoing physical rehabilitation from moving their arms or legs in an unsafe way or prompt them to move in a correct manner. "The units could be programmed to help you learn, or re-learn, specific motions," Duda says.

Top image: Dava Newman in the 2008 silver BioSuit™ mock-up. Courtesy 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

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