Wearable CMG Design for the Variable Vector Countermeasure Suit

Rebecca A. Vasquez
The Charles Stark Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA 02139
(617) 258-2620
rvasquez@draper.com

Mitchell L. Hansberry
The Charles Stark Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA 02139
(617) 258-1272
mhansberry@draper.com

Kevin R. Duda
The Charles Stark Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA 02139
(617) 258-4385
kduda@draper.com

Akil J. Middleton
The Charles Stark Draper Laboratory, Inc.
555 Technology Square
Cambridge, MA 02139
(617) 258-1413
amiddleton@draper.com

Dava J. Newman
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
(617) 258-8799
dnewman@mit.edu

***Abstract*—The Variable Vector Countermeasure Suit (V2Suit) is a countermeasure suit for sensorimotor adaptation and musculoskeletal deconditioning in microgravity. The V2Suit consists of wearable modules containing arrays of control moment gyroscopes (CMGs) that provide a viscous resistance to motions made against a specified direction. To reduce the movement coordination and sensorimotor problems seen during and following gravity level transitions, this resistance will be felt in the direction of "down" to mimic gravity.**

Control moment gyroscopes are commonly used for spacecraft stabilization. The V2Suit uses a miniaturized CMG array in a body-worn system to apply torque to the wearer's musculoskeletal joints. Miniaturizing a CMG array while still generating enough gyroscopic torque for suitable resistance is a main challenge in the design of the V2Suit system. The initial specification for the torque magnitude output was set to 0.1 Nm. Various candidate CMG arrays were analyzed to determine the appropriate architecture for the array inside a V2Suit module, as well as flywheel parameters for the chosen array. The selected array is a 4 CMG pyramid array, chosen for a combination of torque output performance and size and hardware considerations.

A mechanical design for the V2Suit 4 CMG pyramid array was developed using a combination of off the shelf and custom manufactured components. Minimizing the size of the array drove many design decisions; the final module design has a 6.5 inch square footprint and is 3.5 inches tall. A brassboard prototype has been fabricated based on this design.

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1. INTRODUCTION

Future long-duration space flight missions will expose astronauts to long periods of microgravity. For example, a mission to Mars as outlined by NASA in Design Reference Architecture (DRA) 5.0 would involve a 180 day microgravity transit time for the crew and a 500 day long stay on Mars at 3/8 G and would include 4 gravitational transitions [1]. The physiological changes caused by microgravity exposure include, but are not limited to, adaptation of the sensorimotor system and musculoskeletal and cardiovascular deconditioning [2, 3].

The Variable Vector Countermeasure Suit (V2Suit) is an in-vehicle countermeasure suit system targeting sensorimotor adaptation and bone and muscle loss due to exposure to microgravity [4]. The V2Suit will provide viscous resistance to motion when movements are made against a specified direction of "down". The V2Suit will consist of small wearable modules, one located on each major body segment that will act in a coordinated manner. Each module will contain an inertial measurement unit (IMU) and software that will track body motions and the direction of “down” as the wearer moves [5]. This information will be used to determine when the wearer’s motions are against the direction of “down” as well as to control the direction in which the viscous resistance should be applied.

Each V2Suit module will contain an array of miniature control moment gyroscopes (CMGs), that, when actuated, generate a gyroscopic torque to provide the viscous resistance during movements that are against the specified direction of “down”. Gyroscopic torque has been previously shown to be able to affect biomechanics by perturbing arm motions, and the goal of the V2Suit is to generate a perceptible resistance to act as an additional input to the sensorimotor system [6]. The objective is for the CMG generated torque perceived at each musculoskeletal joint to be in the same direction as a gravitational torque on Earth (or other planetary body). This will reinforce the direction of “down” and thus the wearer’s orientation with respect to their specified reference frame. An additional benefit of this CMG-generated resistance is to provide loading to the musculoskeletal system, which is significantly affected by prolonged exposure to microgravity [2, 3].

The microgravity environment in space means that the otolith organs of the vestibular system do not have a gravitational input signaling body tilt. Visual cues are also used to estimate body orientation, and without the influence of gravity on the vestibular system they become more critical in maintaining spatial orientation in a weightless environment [7, 8]. One’s perception of their orientation in their environment can change dramatically based on a number of factors, from the specific room they are in to what they are doing at the time. This can cause spatial disorientation illusions including 0g inversion illusions, visual reorientation illusions, and illusory self-motion perception [9-11]. In space, there is no obvious direction of “down” because of the absence of gravity; it is hypothesized that providing an additional external cue to the direction of “down” with the V2Suit may alleviate some spatial disorientation illusions associated with microgravity [4].

On Earth, bones and muscles are constantly loaded by gravity during motion and this (among other things) keeps them strong and functioning properly. Currently, astronauts on the International Space Station are required to spend 2.5 hours a day exercising in an attempt to mitigate the effects of microgravity but deconditioning still occurs [12, 2]. The addition of the V2Suit during daily tasks in microgravity would load the user’s limbs and may reduce or eliminate the required exercise time for the V2Suit user. The magnitude of resistance necessary, as well as the amount of time that the suit must be worn to have any significant beneficial effects on sensorimotor adaptation or musculoskeletal deconditioning is unknown and must be determined [13].

2. CMG Background

CMGs are momentum actuators that are commonly used on a large scale for spacecraft stabilization and attitude control. A CMG consists of a spinning mass gimbaled about one or more axes to change the direction of the angular momentum vector and thereby generate a gyroscopic torque (Figure 1). In the majority of CMG designs, the magnitude of the angular momentum vector is constant; that is, the flywheel spin rate is held constant. Variable speed CMGs may also be considered for some applications, but they introduce system complexities and inefficiencies. In this paper, any reference to a CMG will imply a single gimbal CMG (SGCMG) – meaning that it gimbals only about one axis and has a constant spin rate.

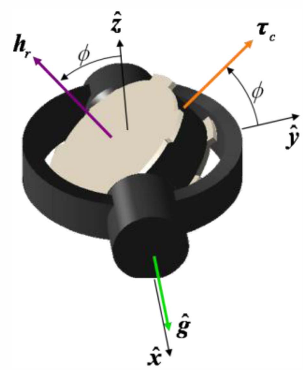

Figure 1- Control moment gyroscope diagram [14].

The V2Suit uses a miniaturized CMG array in a body-worn form factor to apply torque to the wearer’s musculoskeletal joints. The smallest commercially available CMGs are used on cube satellites and are too large to be incorporated into such a system. The exact size requirement for a body-worn CMG module has yet to be determined, but consideration must be taken to ensure that the V2Suit modules do not encumber the wearer or inhibit normal motion in any way. The goal of this research was to develop a custom CMG array for the V2Suit in an as-small-as-possible form factor. This module will be used in further testing and development of the V2Suit system. There are two main challenges associated with the development of a miniature CMG array for the V2Suit: 1) minimizing the form factor while still maintaining the capability to generate the required torque, and 2) development of control algorithms that can maintain the required torque magnitude and direction. Both of these challenges must be addressed simultaneously. In this paper we detail an analysis of various candidate CMG arrays to determine the appropriate architecture inside each V2Suit module, as well as flywheel size, flywheel spin rate, and spin assembly gimbal rate – using a candidate implementation of the control algorithms. A detailed mechanical design, using a combination of off-the-shelf and custom components, for the selected architecture – a 4 CMG pyramid array – is summarized. A prototype module was developed using this design to test the control algorithms, and identify improvements in the steering laws to avoid singularities and re-setting of the gimbal angles during motion to prevent saturation.

Gimballing the spinning mass within the CMG changes the direction of its angular momentum vector, which generates an internal torque on the system. The magnitude of the torque from a SGCMG is dependent on the angular momentum of the spinning mass as well as the gimbal rate. The direction of the torque vector for a SGCMG is dependent on the gimbal angle and is always perpendicular to the gimbal axis. The torque from a SGCMG can be approximated as shown in Equation 1 where $\vec{\omega}_g$ is the gimbal rate vector and $\vec{h}_r$ is the angular momentum vector of the spinning mass.

$$\tau = -\vec{\omega}_g \times \vec{h}_r \quad (1)$$

This is simplified from taking the time derivative of the SGCMG angular momentum vector and is valid under the assumption that the angular velocity of the body on which the CMG is mounted (typically a spacecraft) is small in comparison to the gimbal rate of the CMG. This is referred to as the base rate. In the case of the V2Suit CMG, the base rate is the angular velocity of the body segment on which the module is located. The effect of the base rate, given in Equation 2, might become significant in this case.

$$\tau_B = -\vec{\omega}_B \times \vec{h}_r \quad (2)$$

Therefore, the total torque generated by a CMG is $\tau + \tau_B$. In order for the V2Suit to generate the desired torque in the appropriate direction, the base rate effects caused by the motion of the wearer's limbs must be accounted for. In the ideal scenario, the base rate torque is in the desired direction for the specified resistance torque, but this is rarely the case. The base rate torque must be nulled through active gimballing to prevent undesired perceptions.

A single SGCMG is capable of generating a torque vector that may lie anywhere on a 2 dimensional surface at a given instant. While one CMG may occasionally be able to generate the desired torque for an attitude control system, at least 3 CMGs are generally necessary to direct torque in 3 dimensions. The resultant torque is from a combination of the CMGs. Groups of CMGs controlled together to generate torque are referred to as arrays.

Candidate Arrays

Scissored Pairs Array— A scissored pair is a grouping of two SGCMGs that act together to generate torque in one direction. They are gimbaled at equal and opposite rates which results in a net torque vector from the pair in a constant direction. Figure 5 shows an array of 3 scissored pairs and the directions in which they generate torque.

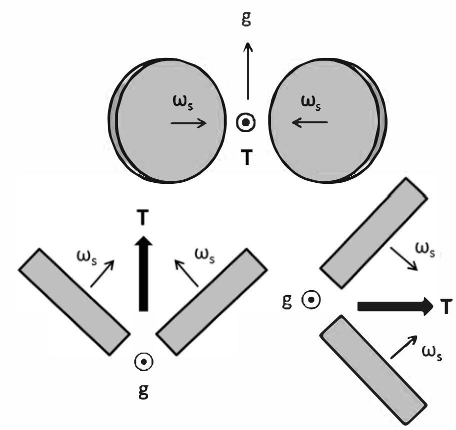

Figure 2- In a 3-scissored pairs array, each pair controls torque along one module axis. This array is singularity robust within its operating capabilities of +/- 90 degrees of gimbal displacement.

Pyramid Arrays— Pyramid arrays consist of a group of SGCMGs arranged so that their gimbal axes are perpendicular to the faces of a pyramid with a skew angle of α. Two pyramid arrays were examined for potential use in the V2Suit: a 4-CMG pyramid and a 5-CMG pyramid (Figure 3). The skew angle was set to 54.73 degrees, which creates a nearly spherical momentum envelope for the 4 CMG pyramid array [15].

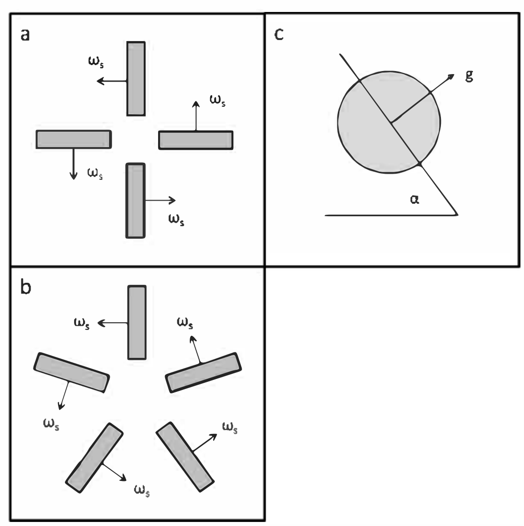

Figure 3- 4-CMG Pyramid (a) and 5-CMG Pyramid (b) arrays. The gimbal axes of the CMGs are perpendicular to a pyramid with a skew angle of α=54.73 degrees.

Variable Speed CMGs— The analysis included two variable speed CMG arrays, each consisting of 16 total small CMGs (see Figure 4). The CMGs are gimbaled at a constant rate and the speed of each flywheel is varied. The combination of gimballing and speed control is what generates the output torque from the variable speed CMG array.

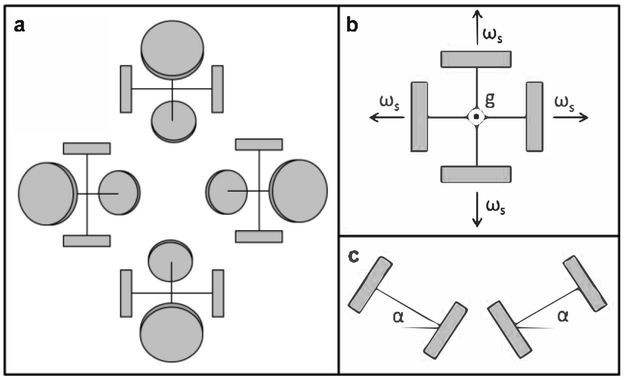

Figure 4- Variable speed CMG array with 16 CMGs arranged into groups of 4 (a). Within each group, the CMGs are gimbaled at a constant rate around a central axis (b). Each grouping is canted at an angle α (c).

The dynamics of variable speed CMGs differs from those of constant speed CMGs because both the changing of both the gimbal angle and the spin rate of the CMG contribute to torque generation.

3. V2SUIT CMG ARRAY ANALYSIS

Detailed analysis of each of the candidate arrays was conducted in order to select an appropriate array and design parameters for use in the V2Suit. Simulations of each of the candidate arrays were created in MATLAB and Simulink. The goal of the analysis was to narrow down the candidate arrays so that a more detailed parameterized simulation study could be conducted to determine the appropriate CMG array architecture and specifications for use in the V2Suit. The performance of the arrays in terms of generating the desired torque to apply resistance to movements against the specified "down" direction was quantified. Additional criteria used to down-select the array candidates included considerations for the required spin and gimbal rates of the CMGs as well as the overall size of the array. The size of the array will ultimately be a major factor to down-select from among arrays that are all able to successfully generate the desired resistance. The array needs to be as small as possible to enable a wearable form factor for the V2Suit module.

Simulation Design

The basic simulation architecture for the SGCMGs is shown in Figure 5. The simulation is for a single CMG array mounted on the V2Suit user's arm. In Figure 5, the boxes outlined in red represent aspects of the simulation that are unique to each individual CMG array.

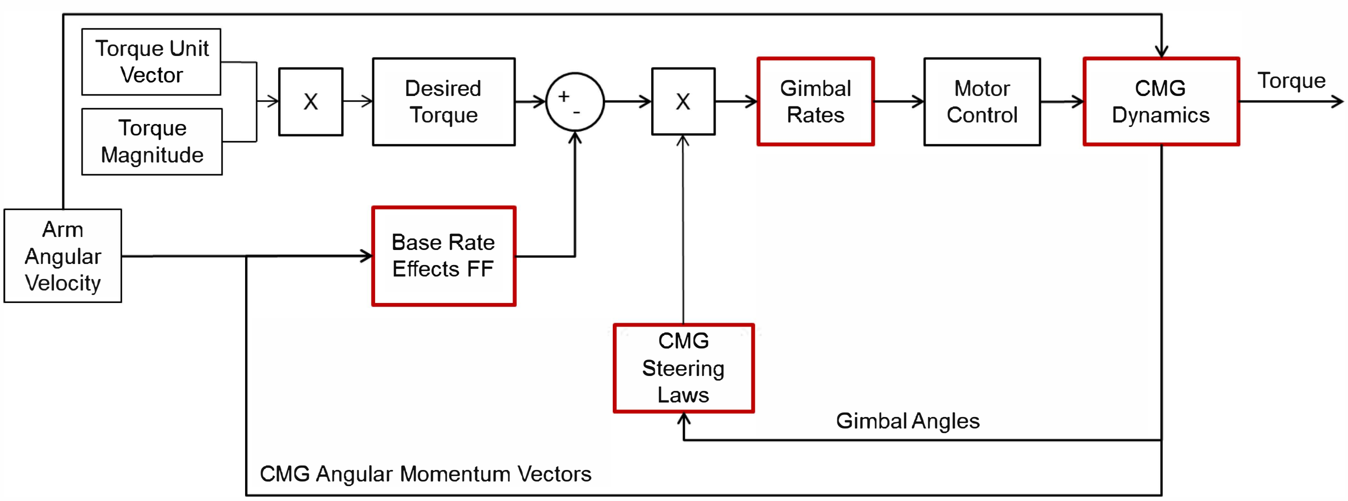

Figure 5- SGCMG simulation architecture to select an array for the V2Suit. The CMG simulation begins at the end of the initialization phase. The inputs to the simulation are the direction of the torque vector in the module coordinate frame (determined by "down" tracking), the desired torque magnitude, and the angular velocity of the arm. The red boxes indicate aspects of the simulation that are unique to each array.

For the SGCMG architectures the simulation uses basic steering laws to determine the appropriate gimbal rate commands. These commands are sent to simulated CMG dynamics. Note that in this simulation motor dynamics were not included. The output of the simulation is the torque that a user would perceive while using the V2Suit.

The simulations are initiated using MATLAB scripts that allow for parameterization of flywheel dimensions, material properties, spin rate, and gimbal rate. Each simulation scenario is initialized with a direction of the required perceptible torque vector and a desired torque magnitude of 0.1 Nm [6]. Angular velocity profiles of simulated arm movements were used. The arm motions included a test case where there was no motion (i.e., the module was stationary) and two simple motions: 1) raising the arm 90-degrees and 2) a complex reaching motion (e.g., “90-90-90 profile”). These arm motions were previously used in evaluation of the V2Suit “down” tracking algorithm [5]. The plots of the commanded torque vector for each motion are shown in Figure 6. The output torque from the simulated CMG array should closely match the command torque. Comparisons of performance (deviations from commanded torque and required gimbal rates/angles) were made within an arm motion profile.

Simulation Results

SGCMG Results— Sample results from the simulations are shown in Figure 7. The results are for simulations with 4CMG pyramid array with a steel flywheel of radius 2 cm and height 1 cm. Figure 7 simulates the 90-90-90 motion. The upper left plot shows the perceptible torque output from the CMG array (this should match the commanded torque). The upper right plot displays the deviation (in magnitude and direction) of this torque from the command. At a high level, the results show that the 4 CMG pyramid array is successful in generating the desired torque vector in the appropriate direction for this arm motion. The torque deviated negligibly in both magnitude and direction. These deviations are likely to increase when motor dynamics are added to the simulation. The other SGCMG array simulations were also successful with negligibly small torque deviations.

The lower two plots are of the commanded gimbal rates and the resulting gimbal angles for the CMG array during the course of the simulation. For this motion, the gimbal rate to generate the desired torque never exceeded 50 rpm for this array and the CMG never exceeded 1 full revolution in either direction during the simulation. This was also true for the other SGCMG array simulations with this arm motion. The CMGs will have a limited range of motion and will need to be re-set when they reach this limit. This means that there will be periods of time during which the system is not capable of generating the desired torque. Slower gimbal rates and smaller gimbal angles mean that the CMGs can operate for longer periods of time without having to be reset. The required gimbal rate may also have some bearing on the size of the module as larger motors may be necessary to achieve faster gimbal rates.

The variable speed array simulations were found to be unsuccessful with the steering law presented in Equation 7. Gimballing the CMGs interfered with the torque output and the variable speed arrays were being controlled as reaction wheels. In other words, when the gimbal rate was set to 0 RPM the array could generate the desired torque, but when the gimbal rate was increased the torque output deviated from the command. Further investigation into the variable speed CMG was not done due to the implementation challenges of such an array. This result prompted the exploration of a reaction wheel array as a possible alternative to a CMG array for use in the V2Suit.

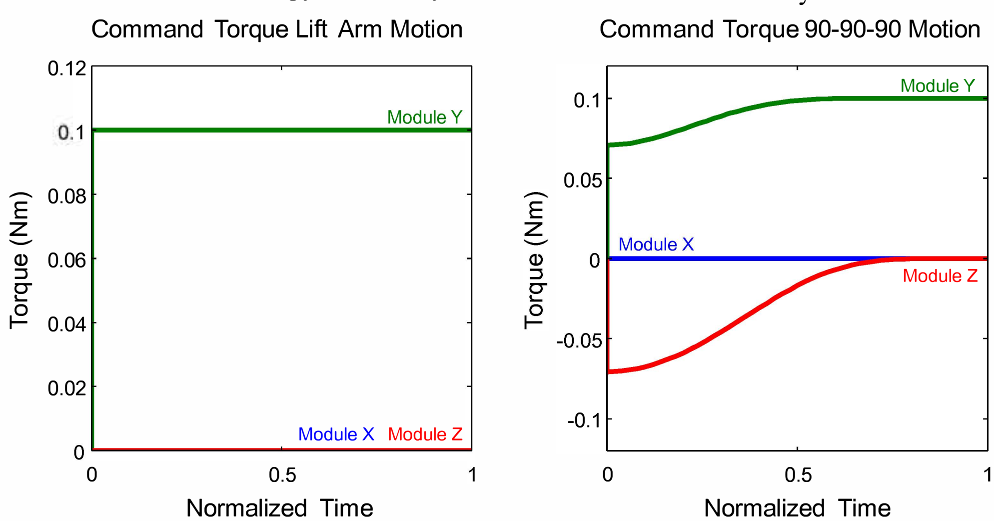

Figure 6- Command Torque for the lift arm motion (left) and the 90-90-90 motion (right).

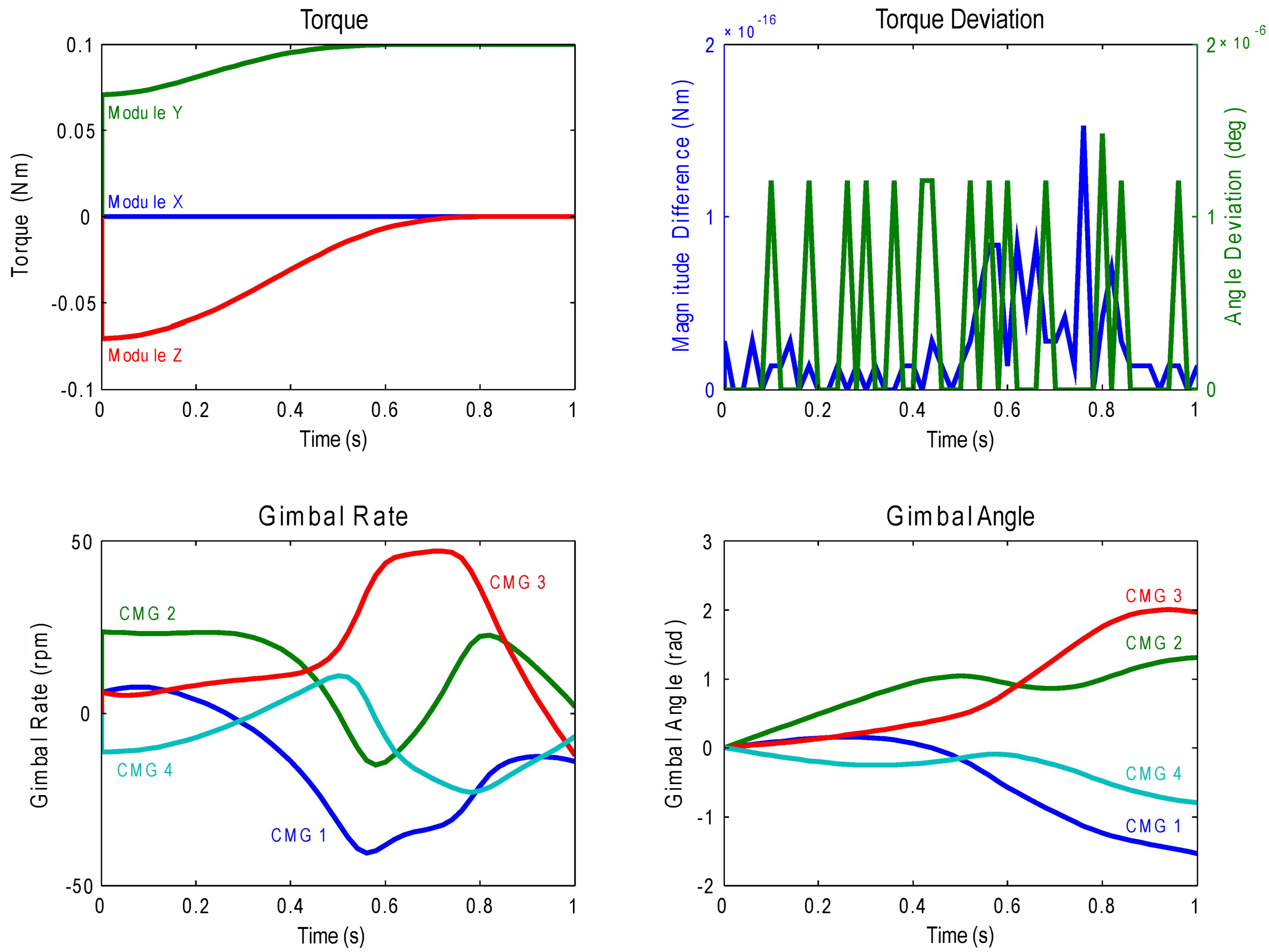

Figure 7- Results from the initial 4 CMG pyramid simulation with the 90-90-90 motion for an array with steel flywheels of radius 2 cm and height 1 cm. The torque output (upper left) does not deviate significantly from the command torque, as seen in the figure in the upper right corner (mean deviations of 2.3×10^{-17} Nm and 3.4×10^{-7} degrees). The gimbal rate (lower left) and gimbal angles (lower right) are also given.

Reaction Wheel Array—An array of three reaction wheels was included in the analysis inspired by the results of the variable speed array simulations. The array consists of three flywheels with their spin axes aligned along one of the principle module axes. Changing the spin rate of the flywheel generates a torque aligned with the spin vector (there is no gimballing of the spin mass). Each reaction wheel controls the torque along one axis.

The simulated reaction wheel array was tested with the 90-90-90 motion to determine its feasibility. The torque output matched the commanded torque. However, the reaction wheel speeds and accelerations required to achieve these torques while compensating for the base rate effects were five orders of magnitude greater than those for the other CMG arrays.

Discussion

The most important consideration in the selection of a CMG array for use in the V2Suit is whether or not the array can generate the desired magnitude of torque in the desired direction over the course of a representative motion. The initial simulations performed in this study were designed to evaluate this capability for each array.

The results of the SGCMG array simulations show that, without considering the physical limitations of motors or gimbal restrictions on the arrays, it is possible to generate almost exactly the desired torque over the course of the two candidate arm motions. Ideally the gimbal rate command would be a smooth curve over the course of the motion without exceeding roughly 60 RPM (as seen Figure 7). However, there were several simulations in which the gimbal rate command spiked well above the maximum value deemed reasonable for these simulations (100 rpm). In these cases the arrays had encountered singularities. These simulations were conducted with an initial implementation of steering laws. More complex steering laws will be required for singularity avoidance and escape.

A key feature of the V2Suit is that the modules are wearable- as such the form factor must be as small as possible. The number of flywheels and actuators has a large impact on the final module size, and the number and size of the flywheels limits the potential torque output from the array. A larger number of smaller CMGs may be a better solution than a smaller number of larger CMGs (or vice versa) depending on torque output and form factor. Minimizing the additional hardware necessary for the array will help keep the form factor small.

The 3 scissored pairs array is commonly used and there are many readily available and reliable steering laws for this array. There is a gimbal angle limit of +/- 90 degrees for this array, meaning slip rings are unnecessary. This helps keep the overall size of the array at a minimum. This also limits the amount of time that torque can be generated in a given direction. If a pair reaches the gimbal angle limit then it must be re-set so that it can resume generating torque again. Pyramid arrays are also commonly used. Unlike the scissored pairs array, there is no need to impose gimbal limits on the pyramid array. A pyramid array would require a slip ring to allow for continuous rotation of each of the CMGs. Gimbal angle limits could also be imposed on the pyramid array to eliminate the need for a slip ring, but this would require a way to manage additional cable connected to the CMGs.

Variable speed CMG arrays are not commonly used. The steering logic is much more complicated than constant speed CMGs (as evinced by the lack of success with torque generation in these simulations). Variable speed CMGs are less efficient in terms of power than constant speed CMGs and changing the momentum of the flywheel causes different types of singularities [14]. However, some research suggests that the ability to change the speed of a CMG might be beneficial for avoiding traditional CMG singularities [16]. Each variable speed array would also require at least one slip ring.

A basic comparison of the CMG arrays, the hardware that they require, and the high level simulation results can be found in Table 1. The results of the initial round of simulations allow the candidate arrays to be narrowed down to the scissored pairs array and the two pyramid arrays due to the failures of the variable speed and reaction wheel simulations to yield successful torque output. Following the down-selection of the initial array candidates, a more detailed simulation was created in order to determine the specific parameters for the V2Suit array. Aside from the actual array architecture, the inertial properties of the flywheel will be selected, as well as the operating spin rate for the array, to generate the desired torque magnitude within reasonable gimbal limits.

Table 1- Comparison of candidate V2Suit CMG Arrays

Array	Number of Spin Masses	Number of Spin Motors	Number of Gimbal Motors	Generates Desired Torque?	Notes
3 Scissored Pairs	6	6	3	Y	Gearing to connect pairs
4 CMG Pyramid	4	4	4	Y	Slip ring or cable management
5 CMG Pyramid	5	5	5	Y	Slip ring or cable management
Variable Speed 1	16	16	4	N	Slip ring(s)
Variable Speed 2	16	16	4	N	Slip ring(s)
Reaction Wheels	3	3	0	Y	Unreasonable spin rates required

4. PARAMETERIZED CMG SIMULATION

Simulation Design

In the second round of simulation changes were made to all of the remaining arrays, including adding the dynamics from candidate motors to the model for each array. This will give an idea of how quickly the array will be able to respond to the commanded gimbal rates and estimate torque deviation as a result of this delay. Additionally, the simulations were changed to vary flywheel inertia rather than varying height, radius, and material as this would allow for various flywheel shapes to be tested.

The scissored pairs array was altered to add an additional pair in each of the module Y and Z directions. This resulted in an array with 5 scissored pairs total, one in the module X direction and 2 in the module Y and Z directions. Since the direction of the V2Suit torque is given by the cross product of the arm axis (module X axis in this case) and the direction of "down" in the module frame, there will never be a commanded perceptible torque in the module X direction. The scissored pair that controls torque in this direction will be used to counter base rate effect torques of a smaller magnitude. The Y and Z directions, in comparison, would be responsible for generating the desired perceptible torque as well as accounting for base rate effects, so the extra pair would be more useful in these directions.

In summation, the second round of simulations included 3 candidate arrays: a 5 scissored pairs array, a 4 CMG pyramid array, and a 5 CMG pyramid array. New Matlab scripts were written to allow for the simulations to be run multiple times at once with all possible combinations of the two important parameters: spin rate from 1000 to 15000 RPM, spin mass inertia from 10-8 to 10-4 kgm2. The goal of these simulations was to determine the best combination of these parameters for each candidate CMG array to generate the desired amount of torque (0.1 Nm) in the appropriate direction without exceeding a gimbal rate of 60 RPM over the course of the arm motion. The results of the simulation informed the selection of the CMG array architecture for the V2Suit module, as well as the required momentum properties for the CMG flywheel.

Simulation Results

The simulations were run with the lift arm motion. The output of the simulation was a 3 dimensional bar chart like that seen in Figure 8, which is for the 4CMG pyramid array simulation. Each bar represents a different set of parameters for the simulation, identified by the spin rates and flywheel inertias on the two lower axes. The vertical axis is the maximum gimbal rate reached by the motor during the course of the simulated arm motion. If the gimbal rate exceeded 60 RPM, the bar was cut off at 60 RPM. The best combination of parameters in this case has been defined by the smallest flywheel inertia possible spinning at the slowest rate possible such that the gimbal rate does not exceed 60 RPM during the motion. These simulations were run with a command torque magnitude of 0.1 Nm and assumed cylindrical tungsten flywheels with density 18269 kg/m^3.

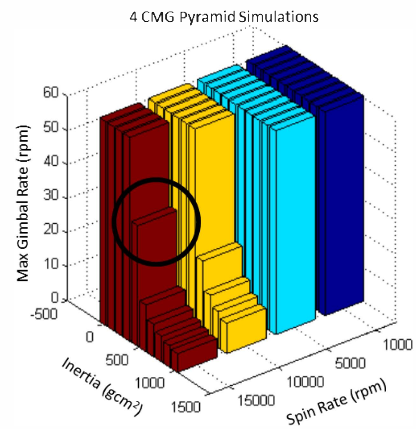

Figure 8- Results from the 4 CMG pyramid sims with motor dynamics. The ideal parameters are a spin rate of 15,000 RPM and flywheel inertia of roughly 450 gcm^2.

In the bar chart, the circled bar represents the ideal set of parameters for the array. For the 4 CMG Pyramid array the ideal configuration was a flywheel of inertia roughly 450 gcm2 spinning at 15,000 RPM. For the 5 scissored pairs array the ideal configuration was a flywheel of inertia roughly 200 gcm^2 spinning at 10,000 RPM. Finally for the 5 CMG pyramid the ideal configuration was a flywheel of inertia 300 gcm^2 spinning at 15,000 RPM. While this is a useful starting point for further testing, there is no indication in this data of the performance of the simulated array in terms of accuracy of torque generation. Each simulation was run again with its ideal set of parameters for both the lift arm and 90-90-90 motions. The plots in Figure 9 show the results of the 4 CMG pyramid array simulation for the lift arm motion including the perceptible torque from the array, the deviation from the commanded torque, and gimbal rates, and the gimbal angles for each CMG in the array.

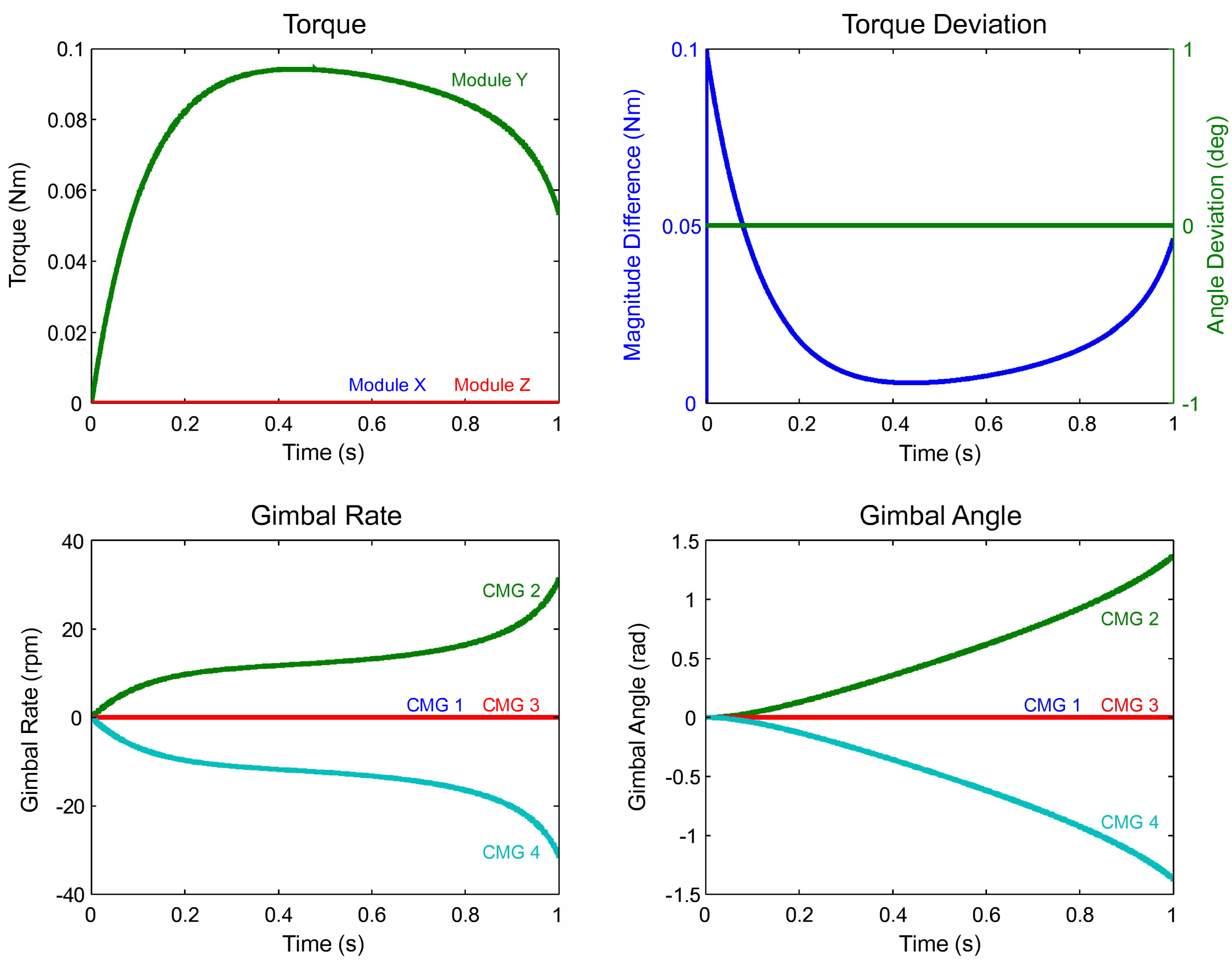

Figure 9- Results from the parameterized 4 CMG Pyramid simulation with the lift arm motion for an array with flywheels of inertia of 450 gcm^2 spinning at 15,000 RPM. The torque output (upper left) does not deviate significantly from the command torque, as seen in the figure in the upper right corner (mean deviations of 0.0201 Nm and 0 degrees). The gimbal rate (lower left) and gimbal angles (lower right) are also given.

These plots show that the simulated 4 CMG pyramid array with the motor dynamics added in is still essentially capable of generating torque in the correct direction. This holds true for the other two arrays as well. However, the amount of error between the commanded torque vector and the perceptible torque output from the array has increased from the initial simulations. The average deviations of the torque in magnitude were 0.0201 Nm for the 4 CMG pyramid array, 0.0190 Nm for the 5 scissored pairs array, and 0.0123 Nm for the 5 CMG pyramid array. There was still no significant deviation in the direction of the torque vector for these simulations. The increase in magnitude deviation is due to the fact that the gimbal rates are no longer reached instantaneously after they are commanded; this is limited by the dynamics of the gimbal motor. These simulations still used the basic pseudoinverse steering law to control the CMGs. There is potential to account for the delay caused by the motor acceleration in a more complex steering law.

Array Selection

In general, the simulations of the CMG arrays confirm that a larger flywheel spinning faster will more readily generate 0.1 Nm of torque without exceeding the 60 RPM gimbal limit than a smaller flywheel spinning slower. The goal is still to get the smallest mass spinning at the slowest rate possible to generate this torque. Each array had a different set of ideal parameters. The results of the simulation are summarized for convenience in Table 2. Array selection will take into account torque deviation as well as other design parameters that influence the size of the array.

Table 2- Final CMG simulation results summary.

	Motion	Flywheel Inertia (gcm^2)	Flywheel Spin Rate (RPM)	Torque Deviation (Nm—deg)	# of Flywheels	# of Actuators	Notes
5 Scissored Pairs	Lift Arm	200	10,000	0.0190—0	10	15	Gearing mechanism
	90-90-90	200	10,000	0.0238—19			
5 CMG Pyramid	Lift Arm	450	15,000	0.0201—0	4	8	Slip ring/ cable management
	90-90-90	225	15,000	0.0193—7			
4 CMG Pyramid	Lift Arm	300	15,000	0.0123—0	5	10	Slip ring/ cable management
	90-90-90	125	15,000	0.0127—5			

The 5 scissored pairs array allowed for the smallest flywheel inertia and the slowest spin rate, but the mean angle deviation in the 90-90-90 simulation was significantly larger than the angle deviation for the other arrays. It is possible that this could be minimized with appropriate steering laws, but there are other disadvantages to the scissored pairs array such as the fact that it requires many more actuators and double the number of flywheels than the other two arrays. As such, this array was eliminated from consideration.

There was no significant difference in torque generation between the 4 CMG pyramid and the 5 CMG pyramid. Although the 5 CMG pyramid allows for smaller flywheels, it also requires an additional flywheel and two additional actuators. The 5 CMG pyramid was eliminated from consideration as a possible array. The 4 CMG pyramid required the largest flywheel and the fastest spin rate of the 3 candidate arrays, but also the fewest number of flywheels and actuators. It also generated the desired torque without any concerning deviations in magnitude and angle; the existing deviation will likely be reduced with the choice of appropriate steering laws for the array. When all of these factors are taken into account, the 4 CMG pyramid array becomes the best candidate for the V2Suit array due to the importance of minimizing the module size. The details of the mechanical design for the V2Suit pyramid array are presented in the following section.

5. CMG Array Mechanical Design

The major design goal for the V2suit module is to minimize the overall size of the module so that the form factor will ultimately be wearable and unobtrusive. Again, the exact design specifications to make the module 'wearable' have yet to be defined. Further investigation into the effect of various sizes of appendages attached to a person's limbs on their ability to move and perform tasks unencumbered is necessary to define this specification. This research attempts to design a CMG array with the parameters defined by the simulation analysis in an as-small-as-possible form factor using a combination of custom and off-the-shelf components. The main challenge is packaging the CMG array and associated electronics, cables, and assembly hardware into a functional and minimally sized module. Additional design considerations for the module include safety and comfort for the wearer. In this iteration of the design the assumption is that the V2Suit will be operated tethered to a wall outlet.

Based on these design considerations, a final V2Suit module design was formulated to create a prototype module. The module was built using a combination of off the shelf and custom machined components. It will be used to test the basic control and steering laws for the CMG array as well as measure the torque output from the CMG array.

The selection of the 4 CMG pyramid array structure is a key factor that will determine the overall design of the V2Suit module. The 4 CMG pyramid array utilizes the fewest number of CMGs of any of the candidate arrays, which is beneficial from a size minimization standpoint. The module needs to contain 4 CMG assemblies and the associated circuitry and electronics to control them as well as an IMU. The design is broken down into a few sub-assemblies and categories: the spin assembly, the gimbal assembly, cable management, and the overall module assembly.

Spin Assembly Design

The V2Suit CMG spin assembly consists of a spinning mass, a spin motor, an enclosure to surround the spinning mass, and other associated bearings and assembly hardware. All parts were designed with the goal of minimizing the volume of the assembly as well as the total volume of the sweep generated by revolving the assembly one full time around the gimbal axis. The gimbal sweep is a key driver of module size. The cylindrical shape for the enclosure and the design of the spinning mass help to minimize the gimbal sweep.

The inertia of the spin mass for the CMG within the 4 CMG pyramid array was specified at 450 gcm^2 in the simulations. The design for the spin mass should achieve an inertia as close to this as possible in order to generate the desired torque. For perspective, a stainless steel cylindrical flywheel would need to be 2 cm in radius and 2cm in height to have this inertia. Using a more dense material or a shape other than a regular cylinder could yield the same inertia in a smaller form factor. Ultimately for the V2Suit spin mass a cup shape was chosen which fits around the spin motor. The cup shape allows for a high ratio of the inertia of the spin mass to the total volume of the mass/motor combination. The mass is made of a high-density tungsten alloy. The inertia about the spin axis is approximately 364 gcm^2, slightly smaller than the desired inertia. The possible torque output of an array with flywheels of this size, shown in Figure 10, indicates that this inertia is more than capable of generating the desired 0.1 Nm of output torque given appropriate steering laws.

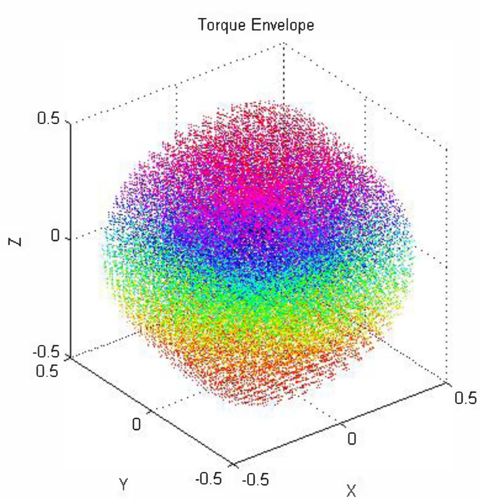

Figure 10- Possible Torque output of a 4 CMG pyramid array with a flywheel inertia of 363 gcm2 assuming a maximum gimbal rate of 30 RPM.

Cable Management

As mentioned previously, there must be limits imposed on the gimballing of the CMGs in the pyramid array to eliminate the need for a slip ring. A limit of ± 2 revolutions was imposed on the gimbal angle for each CMG, meaning there needs to be enough cable available running to the spin motor to account for this range and a means of managing the cable as the CMG gimbals.

The concept for a cable management system for the V2Suit CMG array involves two spools per CMG. At a gimbal angle of 0, all of the free cable will be wound around a spool adjacent to the CMG. As the CMG gimbals in one direction, this spool is unwound and the cable winds around a spool surrounding the spin assembly to keep it out of the way. When the CMG is gimbaled the other direction, a constant force spring in the adjacent spool will retract the newly free cable.

Gimbal Assembly

The spin assembly is canted so that the gimbal axis is at an angle of 35.27 degrees relative to the base of the module, making it perpendicular to the face of an imaginary pyramid with an elevation angle of 54.73 degrees [15]. The gimbal assembly has two supports for the spin assembly and the gimbal motor. The entire assembly can be seen in Figure 11.

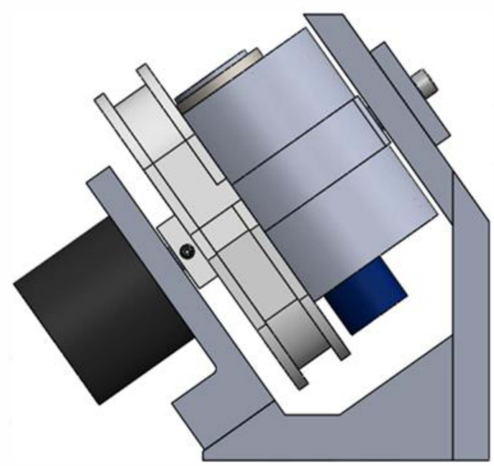

Figure 11- The gimbal assembly consists of the spin assembly attached to the gimbal motor. The spin assembly is supported on either end. A cable management spool surrounds the spin assembly.

Complete Module Design

The V2Suit module will need to contain the 4 CMGs in the array as well as the cable management spools for each CMG. Additionally the module will ultimately contain an IMU and assorted electronics for controlling the CMG motors. For the brassboard unit, the motor electronics will be located elsewhere. A basic layout for the V2Suit module can be seen in Figure 12. The module has a 6 in. square footprint and is 3.5 in. tall.

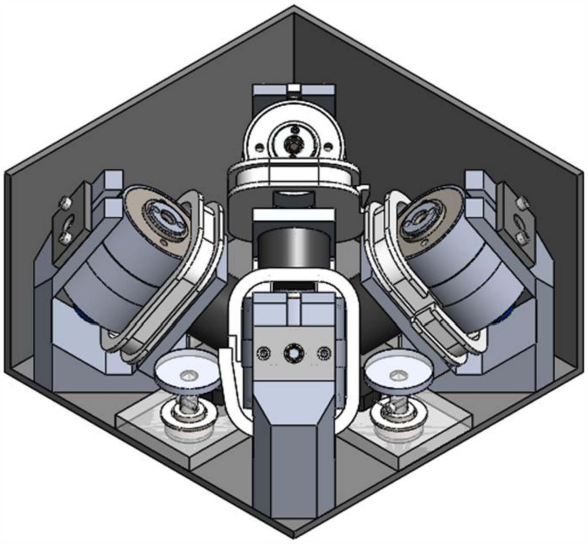

Figure 12- V2Suit module layout; each CMG fits into the corner of a 6”x6”x3.5” module.

An IMU can be located in the center of the module. It is possible that in future iterations the motor electronics would be located along the walls of the module or on a raised platform in the center of the module above the IMU. The spools for cable management for each CMG can be seen in the space adjacent to the CMGs. Orienting the CMGs into the module’s corners rather than having them aligned with the module axes allows the overall size of the module to be smaller. The gimbal sweep was taken into account in this design and dictated the relative positions of the CMGs.

V2Suit CMG Array Prototype

The mechanical design for the CMG array was used to construct a prototype module, which can be seen in Figure 13. This prototype is currently being used to develop and test steering laws to generate torque for the V2Suit system.

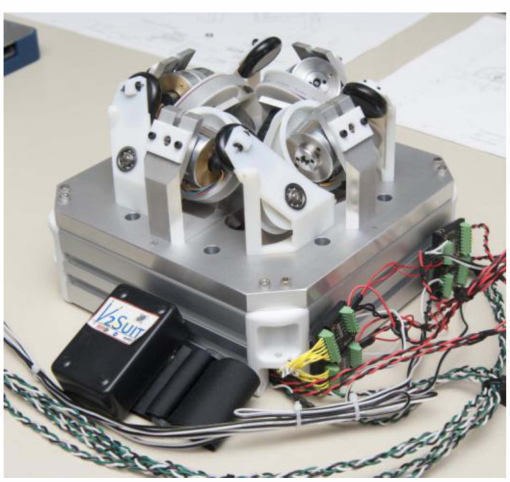

Figure 13- Completed V2Suit CMG array prototype

6. CONCLUSION

The V2Suit aims to utilize CMGs to generate torques in a body-worn system to act as a countermeasure for sensorimotor adaptation and musculoskeletal deconditioning during long-duration spaceflight [4]. The smallest commercially available CMG arrays are used for satellite stabilization and are not sufficiently small for a body-worn application. This work developed a smaller form factor CMG unit still capable of generating adequate torque to be used in further research for the V2Suit.

Based on the results of the analysis and detailed CMG simulation, a 4 CMG pyramid array has been designed for use inside the V2Suit module. The goal behind the mechanical design was to arrive at a functional CMG unit that would take up a minimum amount of volume. This design ultimately has a 6 inch square footprint and a height of 3.5 inches. This result is larger than is ideally desirable for a body-worn module. This prototype achieves a ‘holdable’ form factor. Future design iteration, research, and improvements in areas such as motor technology will enable further reduction of the module size to a wearable form factor. Smaller gimbal and spin motors would reduce the overall module size. Additionally, the cable management system takes up a large amount of space. Eliminating the need for excess cable with a very small slip ring (something not currently available commercially) would reduce the module size.

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Biography

Rebecca A. Vasquez *is a Member of the Technical Staff in the Delivery Systems group at The Charles Stark Draper Laboratory, Inc. She holds an S.M. (’14) and an S.B. (’12) in Mechanical Engineering from the Massachusetts Institute of Technology.*

Mitchell L. Hansberry *is a Senior Member of the Technical Staff in the Delivery Systems group at the Charles Stark Draper Laboratory, Inc. He has been a mechanical design engineer for 30 years.*

Akil J. Middleton *is a Member of the Technical Staff in the GNC Mission Design Group at Draper Laboratory. He has worked on modeling and control of planetary vehicles, as well as guidance and navigation algorithms for guided parafoils. Akil holds both a B.S. and S.M. in Aeronautics and Astronautics from MIT.*

Kevin R. Duda *is a Senior Member of the Technical Staff in the Human-Centered Engineering Group at The Charles Stark Draper Laboratory, Inc. He is currently a Fellow of the NASA Innovative Advanced Concepts (NIAC). Dr. Duda is also actively involved in AIAA as the Vice Chair of the Life Sciences and Systems Technical Committee. He is an instrument and seaplane rated private pilot and holds a B.S. in Aerospace Engineering from Embry-Riddle Aeronautical University and a M.S. and Ph.D. in Aeronautics and Astronautics from MIT.*

Dava J. Newman *is a Professor in the Department of Aeronautics and Astronautics and Engineering Systems at MIT and affiliate faculty in the Harvard-MIT Health Sciences and Technology Program. She is also a MacVicar Faculty Fellow; Director of the Technology and Policy Program at MIT; and Director of the MIT–Portugal Program. Dr. Newman specializes in investigating human performance across the spectrum of gravity. She is an expert in the areas of extravehicular activity (EVA), human movement, physics-based modeling, biomechanics, energetics and human-robotic cooperation. She has an active research program in advanced EVA including advanced space suit design, and biomedical devices, especially to enhance locomotion implementing wearable sensors.*