A Novel Flight Simulator Capable of Unbounded Rotation

R.A. Irani*, N. Schut, M.J.D. Hayes and R.G. Langlois,
*Department of Mechanical and Aerospace Engineering
Carleton University, Ottawa, Ontario, K1S 5B6
Email: *Rishad.Irani@Carleton.ca

***Abstract*—The Carleton University Simulator Project (CUSP) is developing a novel flight simulator that decouples typical translational motions from unlimited rotations about any axis. The new CUSP simulator, Atlas, consists of a sphere, housing the cockpit, and it is mounted on a motion platform. Atlas is not bound by the typical limitations in roll, pitch, and yaw of traditional flight simulators. This paper presents some of the systems involved with the novel flight simulator and the enrichment that undergraduates experience by developing the inter-relationships and communication paths between the multiple systems and elements.**

I. Introduction

The Carleton University Simulator Project (CUSP) is developing a novel full-scale flight simulator, called Atlas, that combines typical translational motions with a unique feature for the pilot – unbounded rotation decoupled from translation. A typical hexapod platform for flight simulation is limited to $\pm 23°$, $\pm 23°$, $\pm 24°$, in roll, pitch, and yaw, respectively [1]. Presented in Figure 1, the unique Atlas simulator consists of a sphere, housing the cockpit, which is mounted on a hexapod motion base. The sphere's novel unbounded rotation is achieved using 3 independent, servo-driven mecanum wheels while the motion platform provides translational motions. The result is another unique feature: 6 degree-of-freedom workspace that is singularity-free. Figure 2 shows the full-scale hardware under construction at Carleton University.

The Atlas simulator will allow one to study, train for, and ultimately prevent calamitous events caused by unusual-attitude flight. Beyond CUSP's novel design, it has also been a key educational tool for young engineers to collaborate and integrate multiple mechanical, electrical, and software systems. CUSP began in 2002 as a senior-year (final-year) design project in the Department of Mechanical and Aerospace Engineering at Carleton University and has incrementally advanced over the years. The original proof-of-concept model was the size of a basketball. The system was then scaled to a 1.4 metre diameter sphere. In 2013 the construction of Atlas began, the full-scale, 3 metre diameter prototype.

The system is transitioning from an undergraduate teaching and learning tool to a high-fidelity flight simulator for pilot training and research platform. One of the fundamental research questions which CUSP addresses is: how can one safely and precisely actuate a large sphere for unbounded rotation about any axis? The purpose of this type of actuation is to enable a new industrially-relevant flight simulator while providing multi-disciplinary engineering training for undergraduate and graduate students. The goal is to achieve a full-scale prototype which will compliment traditional flight simulators and potentially revolutionize the way pilots train and prepare for calamitous events.

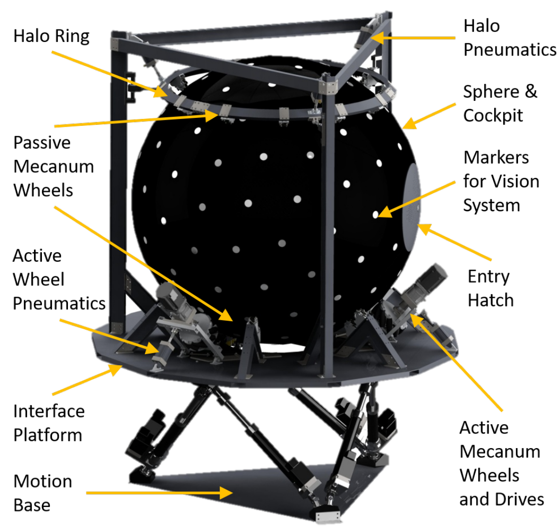

Fig. 1. Schematic of Atlas with major components labeled

The complete full-scale simulator is expected to be functional by the end of 2017 and fully operational by the end of 2018. The current paper presents some of the recent systems-level work which has taken place to date. Section II describes the educational structure and student experience, Section III provides a high-level overview of CUSP, Section IV highlights the current Command & Control architecture, Section V introduces the photogrammetry system, and Section VI provides details of the mechanical actuation and safety systems. Finally the paper concludes with the scheduled future work.

II. Educational Tool and Structure

CUSP is a multi-year project that features a multidisciplinary team, having had over 400 students from Mechanical, Aerospace, and Systems and Computer engineering as well as business programs involved over the project life. The project has involved incoming to senior year engineering students, un-

Fig. 2. Full-scale Simulator at Carleton University

dergraduate student volunteers, MASc students, PhD students, and exchange students in various capacities.

To undertake the development of the Atlas simulator and manage the workflow, the project was organized to resemble an industrial engineering environment. In the early developmental years of the project, the leading faculty member, ‘Project Manager’, representing the Chief Engineer role was supported by several other faculty members who represented ‘Lead Engineers’. The project was then broken into a matrix structure and each lead was responsible for a section of the matrix which could span multiple topics. In recent years, however, to focus solely on the developing and construction of the full-scale system the project has been reorganized into a common team-based organization structure but the Project Manager and Lead Engineer roles remained unchanged. Each Lead Engineer is responsible for an aspect of the simulator:

- **Sphere & Simulation** - Internal components and structure of the sphere and the user’s simulation experience;
- **Actuation & Structure** - Mechanical design and installation of the equipment;
- **Systems & Control** - Command, control and communication of the various simulator systems.

Additionally, a student representative from each team plus the Project Manager form an Integration team to coordinate the interdependencies and scheduling between the groups.

Individual students are tasked with the development of a specific aspect of the project and must go through several design gates before final acceptance and the work is adopted. The development work is discussed at the weekly individual team meetings and then once developed the work is presented to the entire CUSP team at a weekly design meeting for further refinement. Finally, the project holds two public formal design reviews: Fall and Spring, where the student’s work is scrutinized by the faculty, graduate students, and industrial subject matter experts. This structure and process has allowed for a great number of advancements while providing young engineering students with exposure to a complex multi-disciplinary system design.

III. System Overview and Development

The unique demands of Atlas have necessitated the development of several core technologies including the mechanical design of the mecanum wheels, fabrication methods, test methods, actuator control, sphere orientation sensing, sphere orientation control, and a distributed simulation architecture [2]–[7].

Currently, the three active mecanum wheels are driven by independent Kollmorgen servo motors that are connected to a National Instruments (NI) PXI controller. The Kollmorgen system provides closed-loop feedback via their own servo drives; however, due to wheel slippage and the non-deterministic nature of the rolling actuation on the sphere, another level of feedback control is required. Additionally, another closed-loop feedback system is required on the pneumatic support structure of the servo drives to ensure that active mecanum wheels are always in contact and capable of applying an appropriate amount of tractive force to the sphere. Within the NI real-time and FPGA structure, a control loop is implemented that uses the unique time-invariant Jacobian [4] to actuate the sphere while a simple state-feedback system will be used for the pneumatic servo drive supports.

To deliver the closed-loop feedback signal to the mecanum wheel actuation system, an Inertial Orientation System (IOS) provides a direct measurement of the sphere’s angular velocity. Referring to Figure 3, within the sphere, a MEMS gyroscope is connected to a cRIO real-time embedded industrial controller with a wireless transmitter to communicate the angular velocity at 256 Hz to the control structure on the Host computer. However, the IOS suffers from drift as the MEMS gyroscope has no absolute reference point. The inherent drift means that a gyroscope is not suitable as the sole feedback sensor on the sphere. Thus, the IOS information is coupled with a Visual Orientation System (VOS) to compensate for the drift [6].

The VOS consists of an optical camera that is stationary relative to the geometric centre of the sphere and unique circular barcode markers distributed over the surface of the sphere. The marker identification system was developed within LabVIEW on the 1.4 metre version of the system. The sphere’s orientation is determined by comparing the positions of at least 3 markers identified in the camera’s field of view with the known locations of the unique markers that have been stored in a database. Due to computational demand of the VOS, the system is currently only capable of operating at a discontinuous 20 Hz using an NI Vision System. Thus, a sensor fusion algorithm is employed where the VOS data is used to correct the drift from the IOS gyroscope. The fusion of the IOS and VOS uses an Unscented Kalman Filter (UKF) implemented in a C++ DLL within LabVIEW. The UKF updates a single predicted position with one or both of the positional inputs at an operating frequency of 60 Hz. Further discussion of the VOS is found in Section V. The translational motion cueing is achieved via a commercial MOOG Gough-Stewart platform.

Due to the unique design of the Atlas actuation system, wired connections for power and data (as well as ventilation) are not possible between the internal sphere cockpit and the external environment, including computing and control resources. As a result, computing within the sphere must be self-powered. Overall, computing is distributed between internal computing resources (cRIO and the on-board Windows-based computer) and external computing resources (PXI and Windows-host computer) to minimize required wireless network traffic and simulation cycle latency. The system within the sphere is powered by a 12V, 50Ah, lithium-ion battery.

Referring to Figure 3, the PXI system receives the state information from the flight model and visualizer, X-Plane, and passes the information to where the data will be processed by a washout filter resulting in the appropriate motion cueing data. The resulting data are then sent to the Kollmorgan & MOOG control loops. The Windows-based host computer logs critical data via the CUSP Simple Infrastructure (CSI) that is effectively a streamlined implementation of the High Level Architecture (HLA) standard. The CSI can be used to recreate a simulation scenario or be used to emulate the hardware.

IV. Command and Control

To facilitate the development and operation of the simulator the CSI was developed to act as a distributed middleware. Using the common publish and subscribe paradigm the CSI allows for inter-communication between federates. The publish feature allows any federate to 'publish' or distribute information to the rest of the CSI. Other federates which are interested in published information can 'subscribe' to that federate's publications. The sections of the CSI were originally written in C++ and complied into Dynamic Linked Library (DLL) files. From 2004 until 2014 the CSI system was successful for several early prototypes of the simulator. Acting as the original primary controller, an embedded system running National Instruments Labview Real-time Software and an NI PCI-6713 board were used. As time passed, software components evolved and some hardware components became obsolete and were replaced or upgraded, such that not all aspects of the compiled CSI are currently operational. Out of necessity of circumventing certain hardware, students began developing sections of the closed-loop control system within the CSI system which was hosted on a Windows PC and not the real-time system. The control operations gradually migrated off the real-time systems as the computations became too great for the exisiting real-time system. The result was a non-deterministic control system which suffered from significant lag.

In January 2017, CUSP installed a new command and control hardware system supported by the National Instruments Academic Grant Program. A cRIO-9037 with 8 different IO modules now resides inside the sphere. Outside the sphere

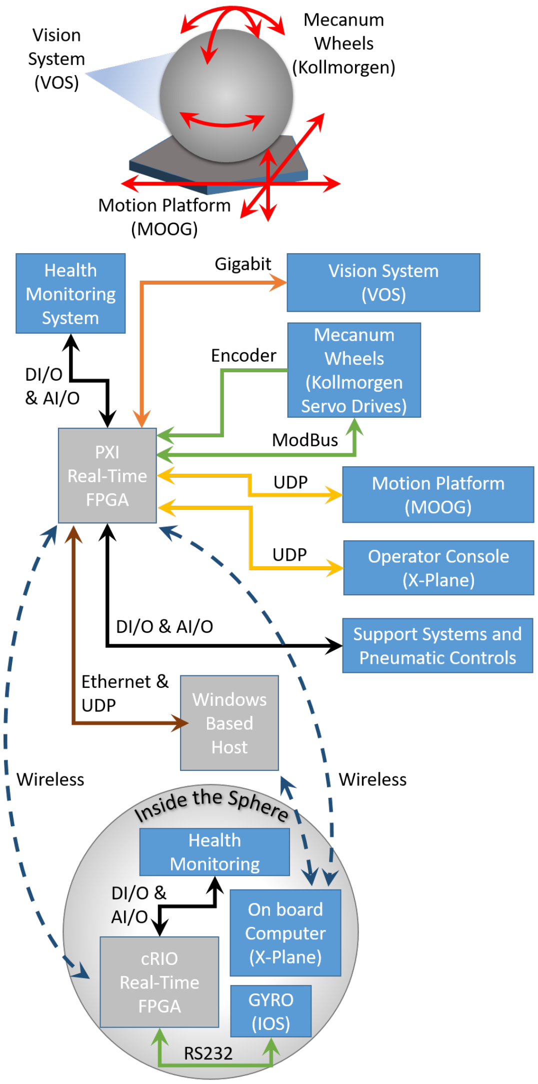

Fig. 3. Schematic of the system interaction within CUSP (Excludes emergency stops)

is a PXIe-1071 chassis with a PXIe-8840 realtime controller, a Gig-E vision card, and two expansion MXI chassis which house 10 IO modules. The hardware infrastructure currently allows for all of the control operations to be migrated and reside on the PXI system. The FPGA of the NI systems is currently configured to run in 'Scan Mode' which has allowed for the students to quickly prototype and develop key pieces of software. The CSI still exists and is used for logging and the distribution of the simulator's states and data.

Figure 4 shows a high-level schematic of the primary control system and its interactions. The command & control system consists of the vehicle model (X-Plane) which runs within the sphere. The software determines the motion states in response to pilot inputs, disturbances, and training scenarios. The vehicle state is sent by the PXI system to a new washout filtering algorithm [3] that converts the vehicle state to the desired simulator state based on motion cueing. The estimated

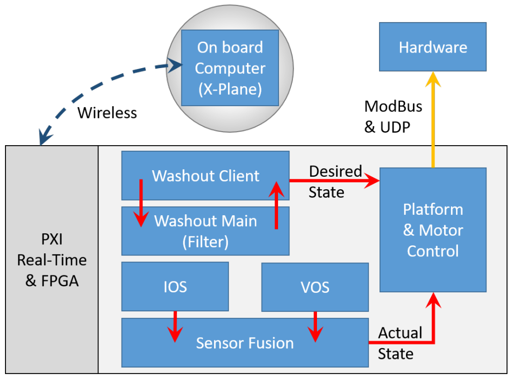

Fig. 4. Schematic of the Control system interaction

motion platform state, as determined by the UKF described earlier, is also available. The desired and actual simulator states are then sent to the motion controllers within LabVIEW which use the previously-developed Jacobian [4] to determine the individual motor rates for the three mecanum wheels and the required translational commands for the motion platform.

V. Vision System

The Visual Orientation System (VOS), as introduced in Section III, is intended to compliment the IOS by providing an absolute measurement of the sphere's angular position. A specialized motion capture system was developed for this purpose. Motion capture technology uses one or more cameras to identify and track visually distinctive features on the target object. In CUSP's application the sphere is uniform in colour so additional distinguishing features must be added without compromising the sphericity of the surface. The approach has been used in the past to measure the orientation of a golf ball in flight [8], and a previous iteration of the current design was shown to reliably measure and control the orientations of a scale model to within one degree [9].

Conceptually, the VOS uses a vision system to identify known points on the outer surface of the sphere and uses their location in the camera frame to calculate the sphere's orientation. As such, the vision system must be able to uniquely identify a number of points on the sphere's surface. To this end, circular markers are affixed to the surface, each with a unique bar code composed of concentric rings. For each marker captured in frame, the image processor simultaneously reads the identity of the marker from the bar code and finds the centre of the marker in the image frame. Using circular markers increases the speed and precision of this step. Each marker identity is then referenced to a lookup table to determine the marker's location on the sphere, and its location in space is calculated from its location in the image. As each marker has an identity and a known location but contains no directional information, the image frame must contain a minimum of two markers in order to fully define the orientation. Because of the time required for the image acquisition and processing steps, the latency and sample rate of the VOS are limited by the camera specifications and the power of the processing hardware. Visual orientation measurements are therefore combined with the higher frequency estimates provided by the IOS using an unscented Kalman filter. This combination of visual and inertial data produces an accurate measurement of angular position at high sample rates.

In addition to the sensing challenges solved by the VOS, the lack of a physical reference poses a computational problem. In a traditional actuator, the position of the output may be represented by a rotation about the axis of actuation. In the case of multiple gimbaled actuators, this approach breaks down only at gimbal lock – the mathematical singularities inherant in gimbals are masked by the physical limits of the system. As Atlas is capable of an unlimited sequence of rotations, the mathematical expression of its orientation must also be able free of singularities. As such, the output of the orientation sensing suite is expressed as an orientation quaternion, avoiding the singularities of Euler angle representations [10].

While the VOS has been successfully demonstrated on a reduced scale, there remain several obstacles to full-scale implementation. In addition to updating the software used in the proof of concept design, the selection and placement of the visual markers poses several complications. Firstly, the markers must be visibly distinguishable without impeding the actuation of the sphere, meaning that they must be ruggedly adhered and have a similar coefficient of friction to the sphere's surface. Secondly, the markers must be distributed to guarantee that two or more are present in the image frame regardless of the sphere's orientation, while minimizing the number of markers used to reduce the system complexity and image processing time. The ideal marker distribution is thus the sparsest distribution that ensures no locations are left uncovered. Unfortunately, there is no perfectly uniform spherical distribution for more than twelve points [11]. Approximations may be made by subdividing the surfaces of a platonic solid and projecting the resultant points onto the sphere's surface, but this approach allows only limited control over the number of points used. For example, subsequent subdivisions of the icosahedron produce 12, 42, 162, and 642 points with increasingly non-isotropic distributions. Figure 5 shows two distributions based on this approach. Other approaches that allow for arbitrary numbers of points include selecting points in a spherical helix as seen in Figure 6, or numerically optimizing point charges to minimize their eletrostatic potential. Further complicating the matter of marker placement is the fact that the entry hatches are not suitable for marker placement. A second camera may be added to address this issue, offset such that at least one camera is always pointed at an acceptable region of the sphere surface. The control system would then dynamically choose which camera to use, discarding the other camera's input to limit the amount of image processing required. A single camera solution might also be possible by modifying the image processing logic. Once the optimal marker locations have been determined, they must be applied and their final installed locations surveyed. The accuracy with which each marker's true location is known strongly impacts the accuracy

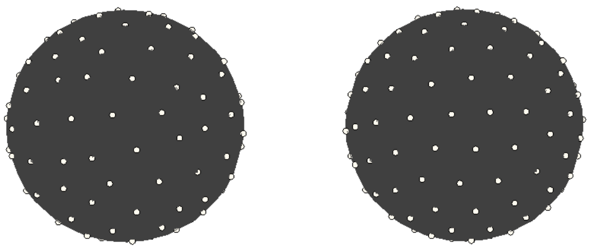

Fig. 5. Two geometric distributions of fewer than 2^7 markers. Left: Dodecahedron, subdivided twice (110 points). Right: Icosahedron and then subdivided once (122 points).

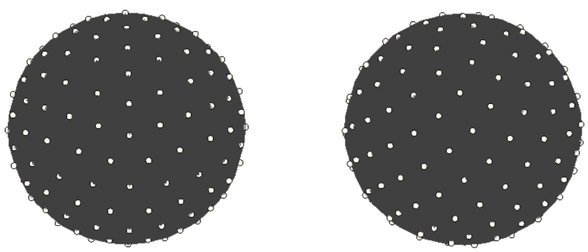

Fig. 6. Comparison of point selection approaches. Left: 162 points developed by projecting three successive subdivisions of the icosahedron. Right: 162 points placed in a spherical helix pattern.

of the system as a whole; thus, an Optotrak [12], a high-precision commercial optical tracking device, will be used to survey the markers.

VI. Mechanical Systems

A. Linear Motions - MOOG Platform

A MOOG MB-EP-6DOF 2800KG Gough-Stewart hexapod provides the linear-translational motions for the simulator. The rotational features of the hexapod have been disabled (hard coded to zero) so that the Kollmorgan servo drives exclusively control the orientation of the sphere. The motion envelope of the platform is ± 46 cm surge, ± 46 cm sway, ± 39 cm heave. The maximum accelerations are ± 0.65 g in surge and sway and ± 0.90 g in heave.

B. Rotational Motions - Kollmorgan Servo Drives

To orient the sphere, the three active mecanum wheels are driven by individual AKM AKM64L-ANCNC-00 Kollmorgan motors and a 60:1 Apex dynamics AF180-060-S2-P2 gear box.

The mecanum wheels were developed in-house as no commercially-available wheels could be found to meet the requirements of the full-scale simulator. The urethane roller material and finish allows for a contact patch of approximately 16 cm^2 which allows for a maximum pressure on the sphere to be below 7 MPa. The actuation system was initially designed assuming a minimum coefficient of friction between the mecanum wheel castors and sphere of 0.6. Subsequent experimental validation confirmed a static coefficient of 0.64 and a dynamic coefficient of 0.57. Since by design the castors will be rolling with the exception of minimal scrubbing due to relative castor rotation about an axis perpendicular to the sphere surface, sufficient frictional capacity is anticipated.

The mechanical system constraining and actuating the six-DOF motion of the sphere comprises a dynamic system that is redundantly supported. As such, and given that the contact forces between the sphere and the actuation system are important for both structural design and control, a dynamic model is being developed. Figure 7 shows a schematic representation of the model and development. Contact points are modelled as linear directed elements characterized by stiffness and damping coefficient. These coefficients have been determined by a combination of experimentation using a Mechanical Testing System and finite element analysis. As an example, the spring constant of mecanum wheel castor rollers was found to be 1551.2 ± 29.0 N/m and the associated damping coefficient was found to be highly frequency dependent and ranging between 100 Ns/m at 3 Hz to 2200 Ns/m at 1 Hz. The model continues to develop with the inclusion of angular motions anticipated to be the next significant iteration of the model.

A continuous time model of the Kollmorgan and actuator drives was also identified to be,

$$C_{RPM}(s) = \frac{9.93s + 0.008}{s^2 + 9.57s} R_{SetPoint}(s) \tag{1}$$

which will also be useful for the development of the dynamic model.

C. Restraint

To ensure that the mecanum wheels are in contact with the sphere, two sets of passive mecanum wheels are used to constrain the sphere relative to the motion base. As indicated in Figure 1, one set of passive wheels is located at the bottom of the sphere with the active mecanum wheels and the other passive set is located above the sphere on a halo ring.

A pneumatic system brings the halo ring and the active wheels into contact with the sphere. The pneumatics are regulated to ensure that the active wheels always remain in contact with the sphere to provide tractive effort. The command and control system monitors the line pressures to ensure safe operating conditions.

D. Interface Platform

Referring to Figure 1, the structure which mounts to the flying frame of the MOOG platform and supports mechanical infrastructure and rotational actuators is known as the 'Interface Platform'. It is a steel web structure and has been instrumented with 48 strain gages to validate the structural FEA model which will be a focus in upcoming work. Moreover, using the validated FEA model, a selection of the stain gages will be integrated into the command and control system as a safety feature to warn the operators/technicians of potential over-stress or otherwise dangerous structural conditions.

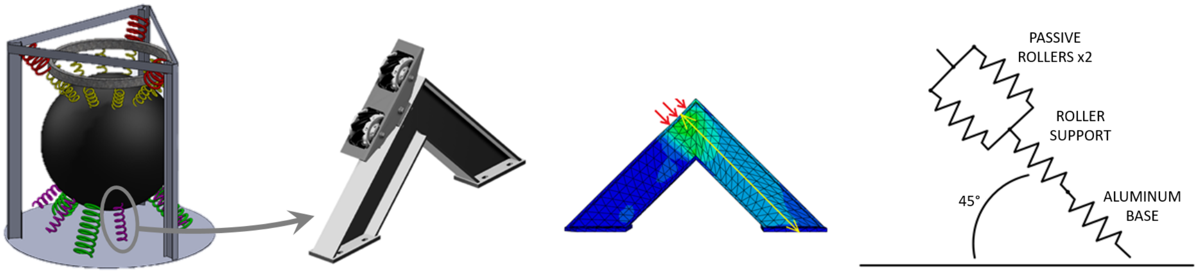

Fig. 7. Dynamic model elements: Schematic representation of the overall model (left), lower passive wheel assembly solid model (middle left), lower passive wheel support structure FEA model (middle right), dynamic representation of the lower passive wheel sitffness model (right).

E. Safety Systems and Monitoring

This year a Master Safety Program was begun to analyze and monitor all of the systems which are both critical and non-critical to the Atlas simulator. Running within the LabVIEW Real-Time Controllers, the VI will oversee a number of other sub-VIs which monitor and/or control the pneumatics, limit switches, and environmental sensors, as well as any other system which are classified to require systematic monitoring.

The Master Safety Program monitors the status and the duration of the error before shutdown. If a fault is found by the master safety program, the program will act based on the fault category which includes Red, Yellow and Blue E-stop states.

Red E-Stop: Equivalent of a category 0 stop, to remove power from the actuation systems to create an uncontrolled stop.

Yellow E-Stop: Equivalent of a category 2 stop, which halts the system while holding it under power. This is a controlled stop since the system is still under the command of the computers but held static in the current orientation. As it is a controlled stop, there is the option to adjust the sphere and motion platform into a known orientation.

Blue E-Stop: An extension of the category 2 stop, as it is a controlled stop which returns the system to the home position. The home position will allow for the pilot or technicians to enter or exit the sphere easily. The condition may be over-ridden at any point by a Red or Yellow stop should the need arise.

Due to the lack of a physical connection from inside the sphere to the external systems, the emergency stop system must also be wireless and powered independently. Moreover, the systems should be compliant with the CAN/CSA-Z267 Safety Code for Amusement Rides and Devices and/or CAN/CSA-Z432 Safeguarding of Machinery. The implementation of the E-Stop and Master Safety Program is ongoing and will need to be completed prior to commissioning.

VII. Conclusion and Future Work

This paper presented an overview of some of the systems involved with a novel six-DOF motion platform with decoupled positioning and orienting capabilities, known as Atlas. The systems presented were developed and primarily implemented by undergraduate students over the past 4 years. The student's education has been enriched by the exposure to a multi-disciplinary project that emulates an industrial environment and structure.

This paper also presents the current inter-relationships and communication paths between the multiple systems and elements.

It is anticipated that the overall system will be functional and under control for all 6 degrees-of-freedom by the end of 2018. The upgraded vision system will be implemented and tested through 2017 and 2018. The Master Safety Program will be deployed in late 2017 and refined through 2018 until the final commissioning.

Acknowledgment

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