Atlas: A Novel Kinematic Architecture for Six DOF Motion Platforms

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Abstract

Conventional training simulators commonly use the hexapod configuration to provide motion cues. While widely used, studies have shown that hexapods are incapable of producing the range of motion required to achieve *high fidelity* simulation required in many applications. The Carleton University Simulator Project (CUSP), a 4$^{\text{th}}$-year capstone design project run by the Department of Mechanical and Aerospace Engineering, has investigated alternative motion platform configurations and developed a novel concept that overcomes existing limitations. This paper presents an overview of the Atlas platform: a novel six DOF motion platform architecture. Orienting is decoupled from positioning, and unlimited rotations are possible about every axis of the mechanism. The decoupling is accomplished by fixing a three DOF spherical orienting device, called the Atlas sphere, on a gantry with three linear axes. The key to the design is three omni-directional wheels in an equilateral arrangement, which impart angular motions to a sphere, thereby providing rotational actuation. The omni-wheels and their castor rollers provide virtually friction-free motion parallel to each omni-wheel rotation axis creating the possibility for unconstrained rotational motion. Since the Atlas sphere rests on these omni-wheels, there are no joints or levers constraining its motion, allowing full 360° motion about all axes. The motivation, architecture, and potential applications for this motion platform are described.

1 Introduction

Atlas is the name given to a novel six degree-of-freedom (DOF) motion platform developed in the Department of Mechanical and Aerospace Engineering at Carleton University. The platform DOF are actuated such that the orienting and positioning workspaces are decoupled. Translation is achieved using an XYZ gantry, thus the singularity-free positioning workspace is limited by the length of the gantry rails. Orienting is achieved using a spherical cockpit manipulated by three omni-wheels. The current proof-of-concept demonstrator for the Atlas spherical platform is shown in Figure 1. The orienting workspace is also singularity free [1], moreover unlimited angular displacements can be made about any axis within the workspace. This means that the orienting workspace is unbounded.

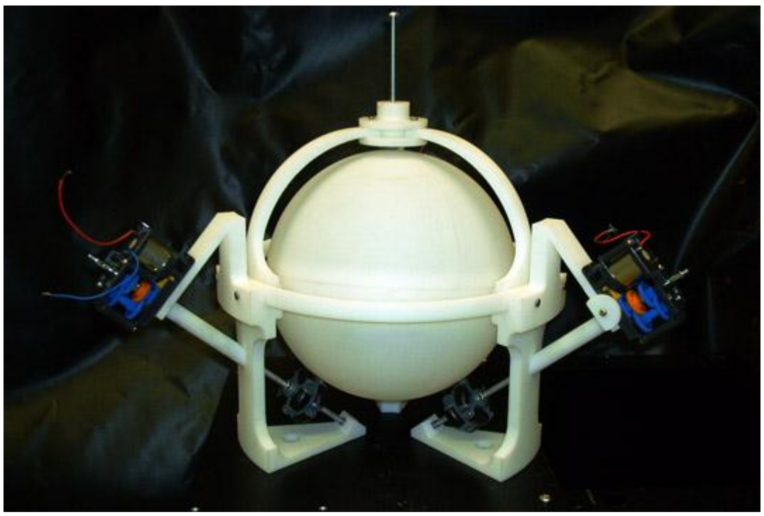

Figure 1: The Atlas proof-of-concept demonstrator.

The Atlas conceptual design was developed within the context of the Carleton University Simulator Project (CUSP), a 4^{th}-year capstone design project introduced in the 2002-2003 academic year. The decision to develop a simulation project was based on growing prevalence of simulation throughout vehicle and process design cycles and for subsequent uses ranging from simulation-based equipment acquisition through operator training. The concept of a simulator project has received strong support from the Canadian simulation community as it is projected that demand will exceed supply of recent graduates with the skill set required to integrate seamlessly in this industry over the next decade. Further, due to the strong support, significant opportunity exists for students to interact with counterparts in industry and government during their involvement with CUSP, and this interaction will further hone the important soft skills identified and highlighted by several industry panel discussions [2].

The long-term objectives of the project are to develop a complete and flexible simulation facility located at Carleton University including a variety of mathematical models, a multi-functional motion platform, a general vision system, and a reconfigurable user interface all inter-operating based on high-level architecture (HLA) [3, 4]. This research and simulation facility will be used to support simulation education as well as specific research objectives motivated by industry and government. Evidence suggests that such a facility can eventually become economically self-supporting.

CUSP approaches the facility design using a two-component approach. While the full 6 DOF motion platform design advances, students and faculty gain experience in all aspects of simulation through the design and implementation of a full-scale technology demonstrator. The HLA-compliant Several Integrated Degree-of-Freedom Demonstrator (SIDFreD), illustrated in Figure 2, consists of a motion platform including 3 DOF (sway, roll, and pitch), on-board visual and auditory cuing, interfaces and mathematical models appropriate for simulating a range of vehicle types (currently a road vehicle, fixed wing aircraft, and helicopter), and a 5 level redundant safety system. This demonstrator, developed incrementally over the past 3 years, is used as a test-bed for component integration, as well as motion and graphics control software integration.

Figure 2: The SIDFreD technology demonstrator.

Practical insight gained from SIDFreD constructively impacts the full platform design. Further, much of the software architecture and dynamic modelling developed for SIDFreD will be equally applicable to Atlas.

1.1 A Little History

Vehicle simulation in various forms has been applied to all types of vehicles including fixed- and rotary-wing aircraft, surface and subsurface marine vehicles, on- and off-road ground vehicles, and rail vehicles as well as many process-related environments such as power station operation and air-traffic control. The history of vehicle simulator platforms is long, and a

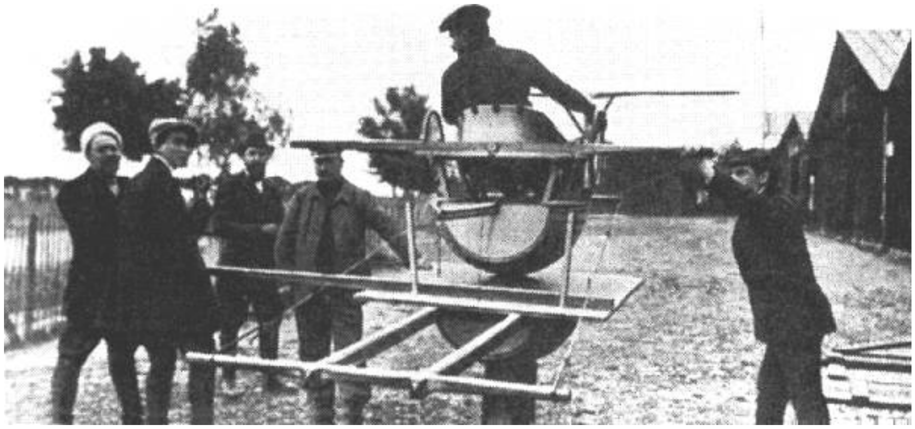

Figure 3: The Antoinette Trainer, circa 1910.

brief outline of milestones in the history of flight simulator platforms is warranted. The Antoinette Trainer was one of the first truly synthetic flight simulation motion platforms. The photograph in Figure 3 is from 1910. As can be seen, the motion platform consisted of two half-sections of a barrel mounted and moved manually to represent the pitch and roll of an aeroplane. The prospective pilot sat in the top section of this device and was required to line up a reference bar with the horizon. Note the kinematic similarity to the Atlas sphere.

The Link D2 Trainer, developed in about 1937, was based on the DC2. It was fitted with movable ailerons, rudder and elevators. The cockpit was instrumented with compass, altimeter, rate of climb indicator, airspeed indicator, turn and bank indicator, radio compass, etc. The idea was to make a totally immersive environment for *positive* training. This trainer was very suitable to demonstrate the principles of flying to the general public. The D2 evolved over the decades, and versions were still in use for pilot training in the 1960's. Figure 4 shows a Link 1-CA-1, or *Hissing Blue Box*, as it was nicknamed.

At the NASA Ames Research Center research is conducted in a unique flight simulation complex. The Vertical Motion Simulator (VMS) motion platform is the largest in the world. Housed in a ten-story building, the motion base can sustain acceleration cues for a relatively long period of time, see Figure 5. The VMS is primarily used for high-fidelity reproduction of conditions during critical phases of flight that are difficult to reproduce with visual cues alone, such as landing and takeoff.

The class of *D-class full-flight simulators* imposes the highest standards of fidelity whose motion cues are generated by a motion platform, washed out to return the platform to a kinematically-neutral configuration to await the next control input from the trainee, and sustained by the visualization system. Hexapods are the typical kinematic configuration for the motion platform. While the kinematics are enormously complicated [5], there is significant industrial history and experience. Control systems have matured to become reliable, though still complicated, owing largely to the kinematics.

Figure 4: The Link 1-CA-1, circa 1950.

Figure 5: The NASE-AMES VMS facility.

A typical hexapod is shown in Figure 6. A significant kinematic limitation to this class of platform is its very limited workspace. Positions and orientations of the cockpit are manipulated by changing the lengths of the six prismatic legs. Leg interference further diminishes the reachable workspace. Typically the orienting limits are $\pm 35°, \pm 35°, \pm 50°$ in roll, pitch, and yaw, respectively. Actuation is generally achieved with hydraulics. This is the current industry standard for full flight simulator motion platforms.

1.2 Motivation

Gawron et al [6] determined, through studies addressing simulator effectiveness in training, that, based on a range of vehicle types and applications, *high-fidelity* simulation requires longitudinal, lateral, and vertical translation ranges greater than 5 m, 3 m, and 5 m re-

Figure 6: A CAE full flight simulator.

spectively; and roll, pitch, and yaw angular displacement ranges in excess of 180°. These minimums are not achieved by most existing commercial motion bases.

Recognizing the kinematic and dynamic shortcomings of the industry standard hexapod, CUSP was mandated to identify conceptual motion platform designs that would overcome the hexapod shortcomings, and have the appropriate kinematic architecture that would make the platform an appropriate motion base for as broad a range of vehicle types as possible. This has been accomplished, at least conceptually, by Atlas. It permits unlimited angular displacements about any (every) axis through the geometric centre of the sphere. Moreover, the linear displacements are limited only by the length of rails on the positioning gantry.

Given the potential for unlimited angular displacements, Atlas is ideal for a wide range of vehicle simulator motion platforms. However, it can also be used for aircraft, or satellite sensor development, design, and testing. It has additional applications in the gaming industry.

2 Atlas Platform Description

The Atlas platform is a novel conceptual design. It is essentially an inverted mouse-ball. A mouse uses two orthogonally-mounted sensors to follow the motion of the ball contact point on the plane of the mouse-pad. Whereas the Atlas sphere is driven by three omni-wheels, one is shown in Figure 7. This in turn is an adaptation of three-omni-wheeled vehicles that move in the plane [7]. Any angular displacement about any central sphere axis can be effected by linear combinations of angular displacement of the three omni-wheels. Omni-wheels have free-moving castor wheels along their periphery [8]. Because the castors are free-spinning, they allow the sphere to spin in directions perpendicular to the rotation axes of the castor wheels. The omni-wheels thereby enable a constraint-free rotational environment for the Atlas sphere allowing for 360° displacements in roll (about the X-axis), pitch (about the Y-axis), and yaw (about the Z-axis), as well as any linear combination.

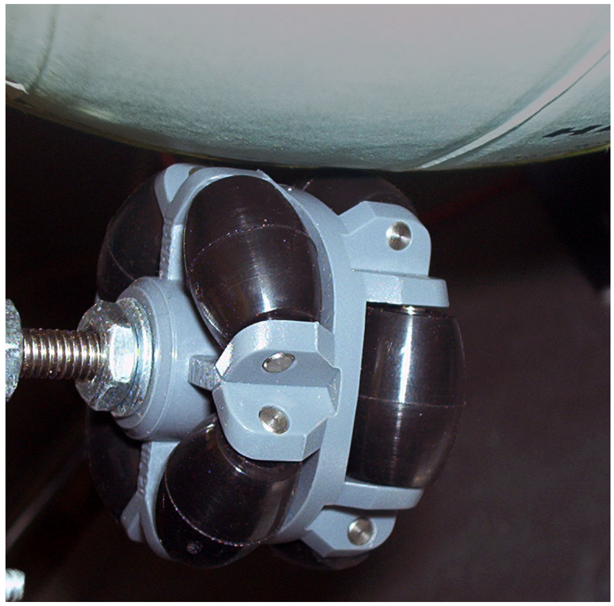

Figure 7: Detail of omni-wheel actuator.

The general kinematic architecture of the Atlas simulator motion platform consists of three omni-directional wheels with each driving axes separated by 120° in the XY-plane on the sphere centre (parallel to the floor), as illustrated in Figure 1. The projection of these axes in the XY-plane form an equilateral triangle and creates equal distribution of static weight of the sphere on each omni-wheel. Each omni-wheel driving axis is sloped downward by 40°, relative to the horizontal XY-plane. As the maximum tractive force that can be imparted to the sphere surface is dependent on friction between the omni-wheels and the sphere, ability to increase the normal force at the contact points is required and is provided by an adjustable spring and bearing device seen at the top of the sphere in Figure 1.

The three omni-wheels are independently actuated with DC motors allowing for each wheel to rotate at different speeds. Each omni-wheel transfers energy through friction to the Atlas sphere and contributes to the sphere's rotational velocity. Depending on the rotational speeds of each omni-wheel (and other factors such as weight, contact surfaces, and issues still under investigation) the Atlas sphere will rotate at a certain angular velocity. The angular velocity of each of the three omni-wheels combine and contribute to the overall angular velocity of the Atlas sphere.

The centre of the Atlas sphere subassembly is positioned in space by three linearly independent translation directions on an XYZ gantry. That is, the orienting subassembly is translated by the gantry. The reachable workspace is therefore bounded only by the active length of the gantry rails. The orienting workspace is unbounded [1].

Issues that could potentially degrade the utility of the Atlas platform as a smoothly-moving orienting device are currently under investigation. The *hot topics* include the following.

1. The velocity level constraints discussed in [1] are non-integrable. Modelling the slip which induces the non-holonomic conditions is being looked into [9]. Additionally, use of rate sensors on the sphere, and shaft encoders on the three omni-wheel motors, is being pursued as a means to obtain integrable sphere and joint rates. Thus it is intended to develop a sphere state estimator, which will additionally be used for position level control.

2. The circumferential profile of the omni-wheels should be circular. It is not. Moreover, there is a gang of two free-spinning castor wheels (see Figure 7). The projection of the omni-wheel sphere contact point for one complete revolution of the omni-wheel is a pair of parallel lines. This induces a step-wise change in moment about the sphere centre. Together, these two geometric idiosyncracies may induce significant vibration of the sphere. To address these vibration concerns, work is underway to design an omni-wheel that minimizes the geometry-induced vibration. The requirements are that the circumferential profile be circular, and that the contact point range projects into the plane as a straight line.

3. As a vehicle simulator, the cockpit must fit in the interior of the sphere. Because of the unlimited rotations, the power to run the onboard instrumentation, projectors, sound effects, ventilation and air conditioning must be stored inside the sphere or transferred to the sphere. Tradeoff studies are being used to propose the most feasible alternatives to the power issue. Hydrogen fuel cells currently appear to be well suited to the application.

3 Applications

Simulator motion platforms require a high degree of repeatability for high fidelity. Moreover platform motions must be precisely timed with the graphics to avoid simulator sickness. Traditionally, hexapods have been used. This is because of the commonly held belief that they offer significantly higher payload to weight ratios than serial kinematic chains. The Atlas platform was originally designed to offer similar stiffness as hexapods, but to have a larger workspace and simplified kinematics. But, features of the design, primarily relating to the expanded range of motion, have lead to a broader range of applications than the positioning and pointing tasks assigned to hexapods. For example, hardware-in-the-loop simulation of satellite sensor packages could be performed for manoeuvres as complex as variable-axis tumbles. Basic physiological research could benefit from the large available range of motion for investigating issues such as debilitating simulator sickness. Additional applications, and sometimes associated challenges, continue to emerge as the Atlas concept is discussed.

4 Conclusions

In this paper we have described Atlas: a six DOF motion platform with decoupled positioning and orienting capabilities. The workspace is free from configurational singularities, and the orienting workspace is unbounded. This compelling attribute can be exploited to provide motion platforms for a wide range of applications. The motions of virtually any vehicle can be replicated. While the Atlas platform offers potential significant advantages in terms of range of motion, several practical technical challenges, that were identified, remain to be investigated fully and resolved.

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