Gravity-Offloading System for Large-Displacement Ground Testing of Spacecraft Mechanisms

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Abstract

Gravity offloading of deployable spacecraft mechanisms during ground testing is a long-standing problem. Deployable structures which are usually too weak to support their own weight under gravity require a means of gravity offloading as they unfurl. Conventional solutions to this problem have been helium-filled balloons or mechanical pulley/counterweight systems. These approaches, however, suffer from the deleterious effects of added inertia or friction forces. The changing form factor of the deployable structure itself and the need to track the trajectory of the center of gravity also pose a challenge to these conventional technologies. This paper presents a novel testing apparatus for high-fidelity zero-gravity simulation for special application to deployable space structures such as solar arrays, magnetometer booms, and robotic arms in class 100,000 clean room environments.

Introduction

The WAGM (Walking Anti-Gravity Machine) is an active approach to gravity offloading of space structures that deploy in three degrees of freedom. At its heart is the proven AGM (Anti-Gravity-Machine) technology [1][2] – a single degree-of-freedom gravity offloading device that supports a wide range of payload weight over several centimeters or more of vertical travel with arbitrarily low stiffness, zero static deflection, minimal added mass, freedom from spurious modes, and perhaps most importantly, zero friction. The deployable payload in the present WAGM application is single-point suspended from the AGM via a load cable. The AGM is itself mounted onto a pair of commercial off-the-shelf sealed linear belt drive tracking stages. Horizontal drag forces on the payload are minimized by an active system that actuates the linear belt drive stages such that the AGM is centered over the payload and the load cable is kept close to vertical as the payload moves under its own power. The horizontal and vertical systems work together to deliver gravity offloading for arbitrary trajectories of the payload with a total range of motion of about 2 meters (6 feet) in all three spatial directions, with capability to scale up to greater distances in each direction. In particular, one horizontal direction can have an arbitrarily long range of motion, a feature that would be useful for testing of unfolding solar arrays or extending booms.

Comparison to Conventional Gravity Offloaders

A common approach to gravity offloading deployable structures ignores the most difficult DOF (vertical) and is restricted to applications involving only translation in one or two horizontal degrees of freedom. In this approach, overhead air bearings or ball bearing dollies moving in the horizontal direction(s) carry the payload weight as it deploys [3]. Often, the payload itself must pull the dollies or air bearings along. This approach is limiting in that it not only artifically constrains the vertical degree of freedom but also imposes artificial lateral drag forces on the payload.

Buoyancy systems using floats in a water tank can deliver a large range of horizontal motion. However, in addition to logistical and cleanliness problems, they suffer from a high level of viscous damping as well as excessive vertical stiffness. Overhead helium balloons solve some of these problems but add a minimum of 16% of the payload mass, an important limitation in dynamic testing.

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Other gravity offloading approaches use support from above cable arrangements that place a simple linear spring in series with each cable. Unfortunately the very low stiffness required of the spring poses the problem of static sag. This makes suspension cable systems only practical for vertical displacements on the scale of centimeters, which is inadequate for deployment testing. The WAGM utilizes established AGM technology to deliver vertical gravity offloading with zero static sag and air spring stiffness limited only by the volume of the external volume connected to the AGM.

Figure 1: Mechanical gravity offloader

In its first application, WAGM replaced the mechanical pulley and counterweight gravity offloader shown in Figure 1. The pulley and counterweight were attached to a moving trolley which rode on a guide rail. The guide rail was attached by a hinge to the side of the spacecraft. The customer expressed dissatisfaction with the fact that the counterweight overhung the payload, the system took a long time to set up and required bolting test equipment to the side of the spacecraft, and most deleteriously, the need for the deploying payload to pull the "jib crane" around and to move the counterweight inertia compromised torque margin measurements. Torque margin of the deployment system is an important criterion to the customer as it is fundamental to on-orbit reliability. In tests on the WAGM, friction in the vertical direction at the payload end of the load cable was measured to be on the order of 0.25 – 0.35% of payload weight.[1] In the horizontal degrees of freedom, drag forces were measured to be just 0.5% of payload weight at payload speeds of 1.59 mm/s (0.0625 in/s). Moreover, interfacing to expensive flight hardware is kept to a minimum as the deploying payload under test is single point suspended from a light load cable with no other interface between the WAGM and any part of the spacecraft. The latter advantage greatly reduces setup and test time, an important factor since tests are performed with the spacecraft very close to completion and the tests on the critical schedule path.

[1] The AGM itself is completely frictionless. The measured friction is added by the 4:1 displacement amplifying mechanism described later.

Requirements and System Architecture

The WAGM was commissioned to offload the weight of a deployable robotic arm during ground testing. The requirements were:

- Minimal friction
- Minimal setup time
- Minimal interfacing to spacecraft
  - Offloading force of 355.86 N (80 lb) with an offload accuracy of ±89 mN (±0.02 lb) in x, y, z
- Insensitivity to set-up or set-up repeatability

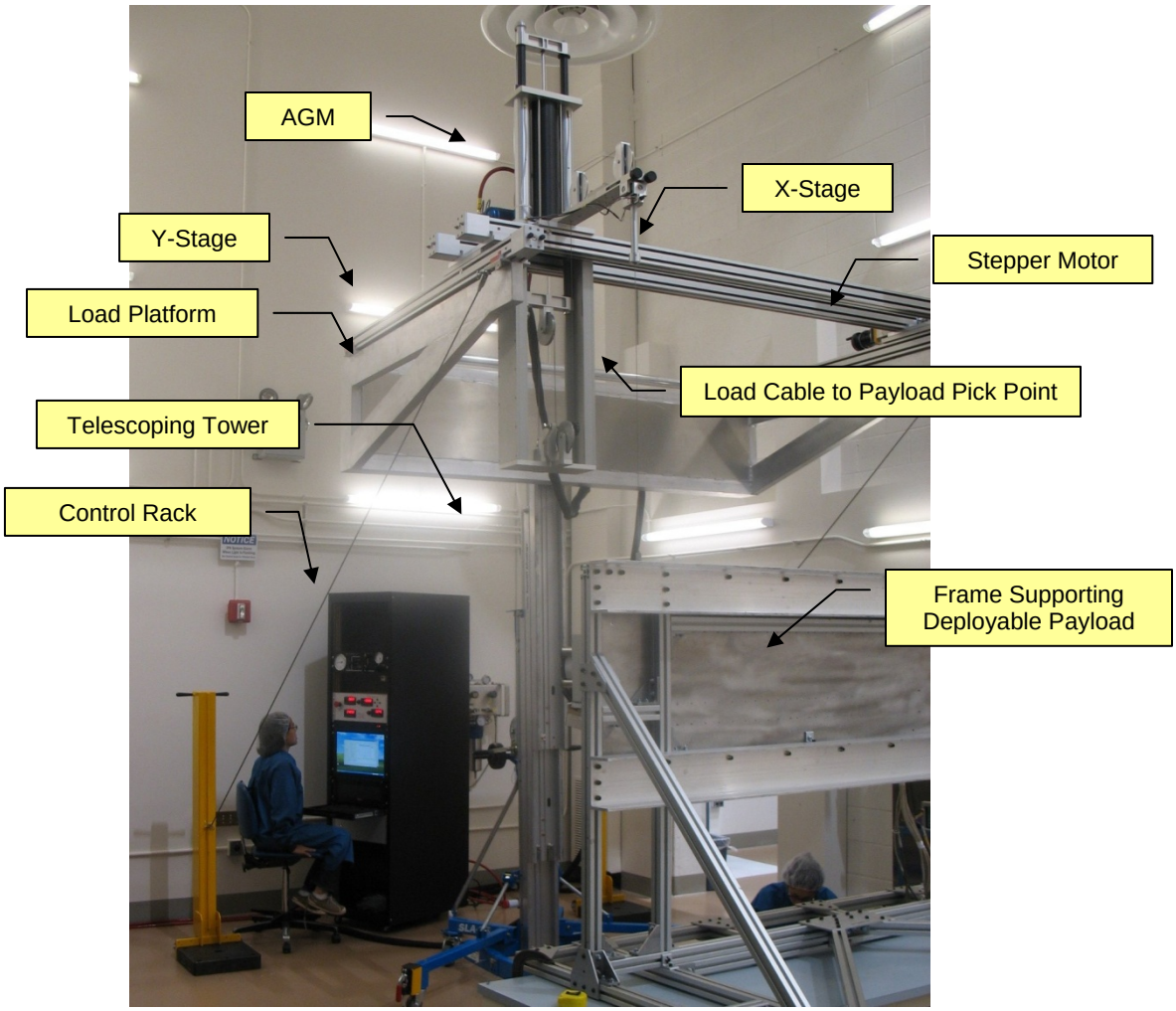

Figure 2: WAGM during acceptance testing at customer site

Figure 2 shows the WAGM during acceptance testing at the customer site. The WAGM is composed of five main subsystems.

- The gravity offloading device (AGM) that carries the weight and accommodates vertical motion of the payload.
- An X-Y stage system comprised of sealed linear belt drives that move the AGM horizontally to keep the load cable vertical during active tracking. The X-Y stages are driven by a pair of commercial off-the-shelf stepper motors.
- A COTS industrial lift whose fork has been replaced by a custom load platform onto which the X-Y stages are mounted. The industrial lift has a telescoping tower that allows for coarse adjustment of the height of the load platform. The base of the lift is equipped with casters that allow the entire assembly to be rolled into place.

- A control rack containing signal conditioning for sensors, drive electronics for the X-Y stage motors, and the control computer with its peripherals (not shown in Figure 2).
- Triangulated stiffening elements to stiffen the telescoping tower in yaw and roll (not shown in Figure 2). These will be discussed in the Lessons Learned section.

Operating Principles

At the heart of the WAGM is the proven AGM (Anti-Gravity Machine) technology. The AGM is essentially a pressure-regulated air spring. It is shown schematically in Figure 3.

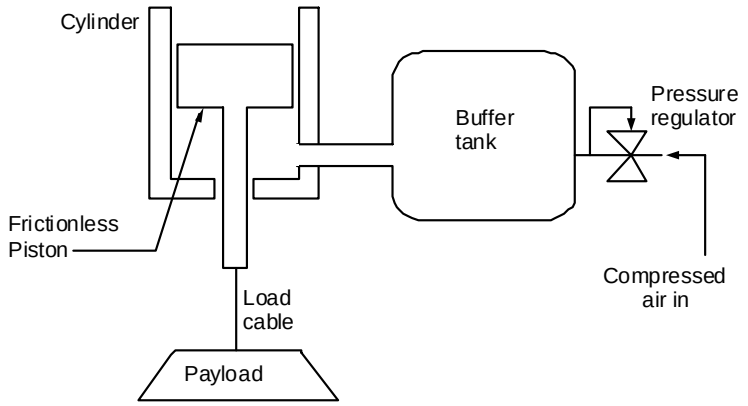

Figure 3: Operating principle of the AGM

The load is supported by force developed by an air piston that moves vertically in a closely fitted cylinder. The piston is of a special type that combines the functions of a piston and an air bearing. Air circuitry within the piston produces a very thin air film between the piston skirt and the cylinder wall, thus eliminating all friction while providing a force capacity equal to the piston area times the cylinder air pressure.

Figure 4 shows two detail views of the AGM. The piston lifts against a moving carriage (shown in red) that rides vertically on four conventional air journal bearings that completely eliminate friction between the frame and moving carriage. The volume below the piston is pressurized with air by a precision manual pressure regulator. For slow vertical motions of the piston, the pressure regulator vents air into or out of the cylinder and buffer tank to keep the pressure constant. The buffer tank assists in this function by reducing the effective stiffness of the air spring for small motions, even if they are rapid. The effective stiffness of the air spring can be reduced significantly by simply increasing the size of the external volume in the buffer tank. The tank also slows down the response of the piston pressure when the regulator set point is changed, thus making the device more tractable and easier to “dial in” to a desired pressure.

The lower end of the moving carriage connects to a cable-and-pulley motion amplifier. The amplifier allows the 45.7 cm (18 in) vertical stroke of the air cylinder to produce a 182.9 cm (72 in) vertical displacement at the end of the load cable attached to the payload. The cable-and-pulley motion amplifier is required because the piston and cylinder of the AGM require extremely close dimensional tolerances to function correctly. This limits the length of cylinder that can be fabricated and hence the working stroke of the AGM. Fortunately, the AGM has much greater force capacity than needed for the application. In general, the AGM force and stroke capabilities can be matched to the requirements of the load by using a simple displacement multiplier composed of a load cable and three pulleys. The principle is illustrated on the right in Figure 5. In the interest of minimizing friction and wear in the cable, the pulley diameter is about 80 times the diameter of the cable[2].

[2] The nominal standard for aircraft control cables is a minimum ratio of 35:1.

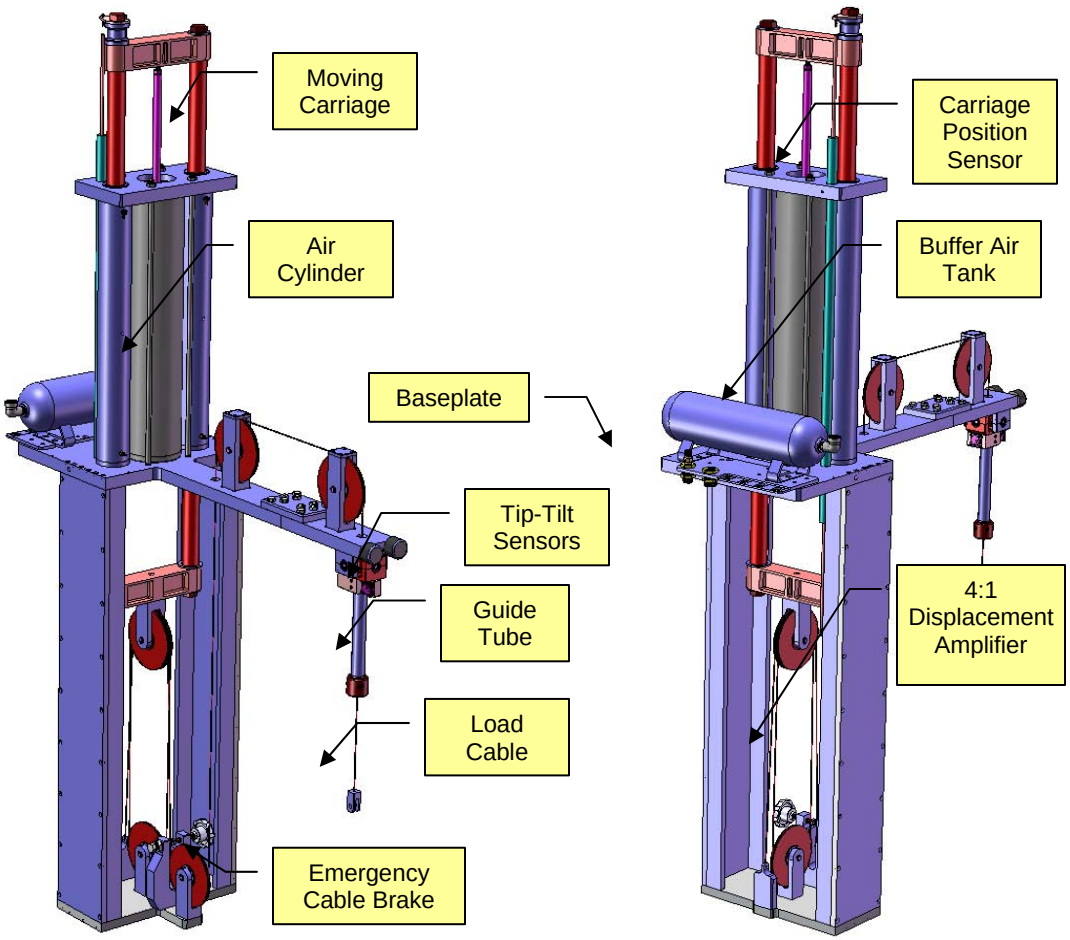

Figure 4: AGM detail

During active tracking, horizontal forces on the payload are minimized by an active system that keeps the AGM centered over the payload such that the load cable is kept very close to vertical as the payload moves. The key to doing this is a system for sensing the load cable angle relative to true vertical. This is done by routing the load cable up and over two additional pulleys and down through a guide tube as shown in Figure 6. The guide tube is part of a larger angle-sensing mechanism: the upper end of the guide tube is fixed to the lower yoke of a precision universal joint (the upper yoke of the universal joint is fixed to the baseplate of the AGM) into which are mounted two high-sensitivity, DC-coupled accelerometers (i.e. tip-tilt sensors) with their sensing axes oriented normal to the guide tube. As the payload moves horizontally the load cable departs from vertical, pulling the lower end of the guide tube with it. The DC-coupled accelerometers produce output signals proportional to the tube's deviation angle from vertical (for small angles). Using band-limiting lowpass filters in the signal conditioning, the accelerometers have a resolution noise floor of about 1 micro-g, corresponding to 1 micro-radian of angle for small angles of the guide tube around vertical. The signals from the accelerometers are gained up to a sensitivity of 200 volts/radian. The ±10 volt range at the amplifier output then corresponds to a measurement range of ±50 milliradians. The basic advantage of the sensing method is that it is unaffected by small deviations of the load platform from horizontal, as will inevitably be caused by flexing of the platform and the tower under load.

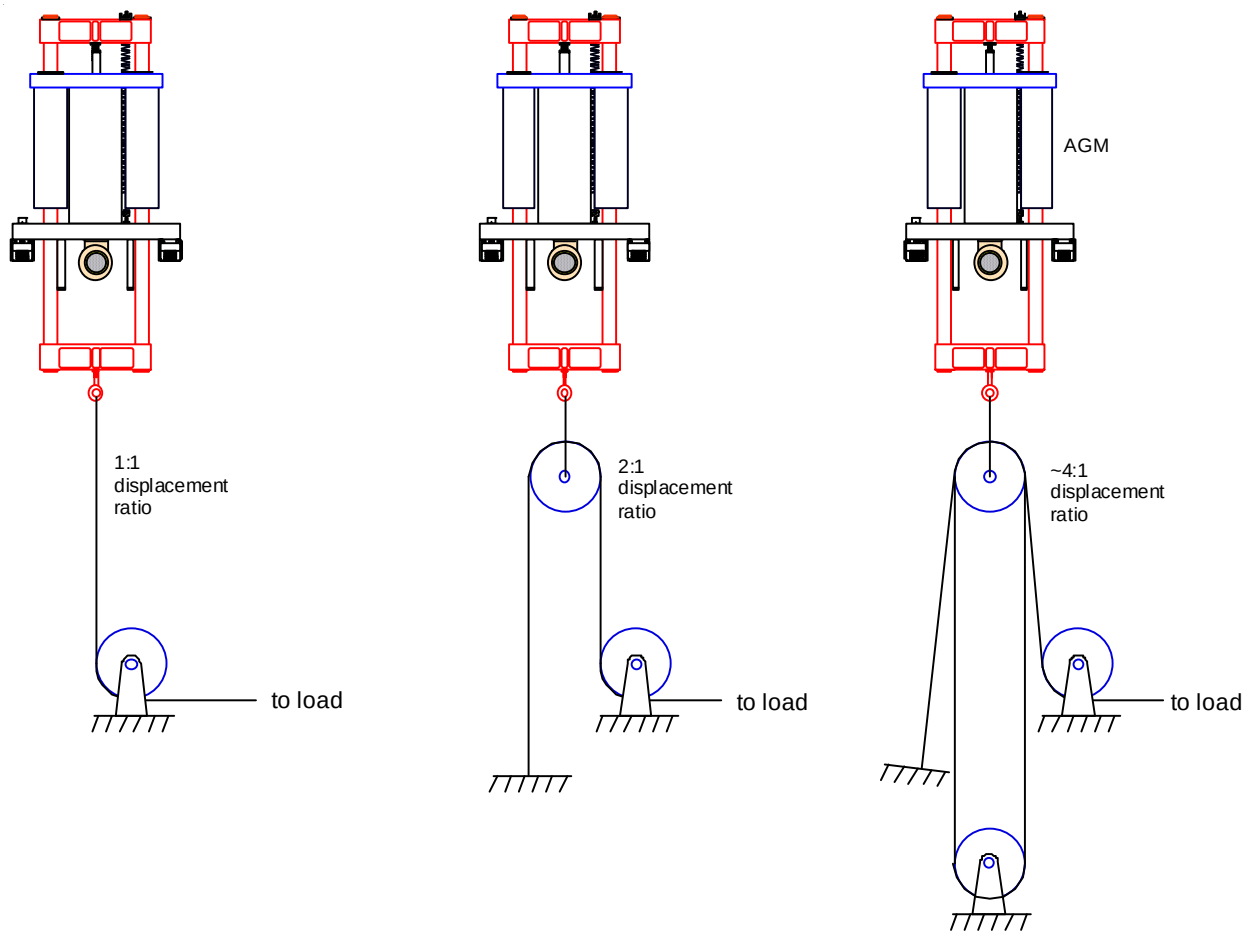

Figure 5: Cable-and-pulley displacement multipliers. The WAGM uses the 4:1 system.

The deviation angles are filtered through an analog anti-aliasing filter module before being digitized by a packaged motor controller card. Inside the motor controller card a feedback loop outputs step and direction commands to the stepper motors to position the X-Y stages such that the tip-tilt sensor is maintained directly over the payload, keeping the load cable as vertical as possible and minimizing the deviation angles. A 1-Hz low-pass digital filtering onboard the controller card is included in the feedback loop to keep the system stable and to prevent the control loop from amplifying ambient ground vibration and noise in the accelerometer signals. It is important to note that the controller only has control authority over the movement of the X-Y stages. It has no control authority over the AGM piston pressure or the AGM piston displacement. This is because the AGM is a constant force device; once the AGM cylinder pressure is set the uplift force on the payload remains essentially constant over the vertical range of motion.

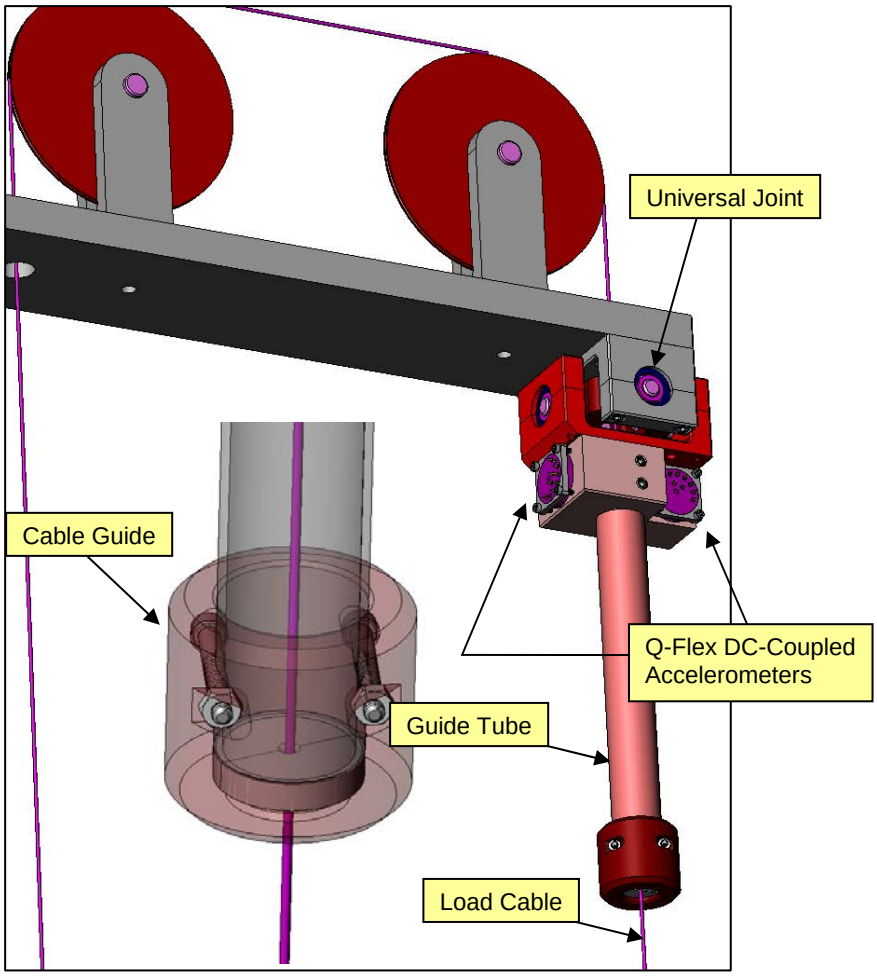

Figure 6: Q-flex DC coupled accelerometers, cable guide, and payload pick point

Figure 7 shows the control system block diagram for one translational axis. A difference in the horizontal position of the pick point relative to the AGM creates an off-vertical angle in the load cable that is sensed by the tip-tilt sensor. The analog tip-tilt sensor output is digitized and digitally low-pass filtered with a cutoff frequency of 1 Hz. Proportional gain is then applied to generate a velocity command (stepper counts/sec) that is digitally filtered and then integrated. Stepper counts are turned into engineering units and a gain is applied that accounts for the cable length variation as the pick point translates vertically. The result is the setpoint for the native position control loop running on the card. Both control loops are executed at a 2-kHz update rate.

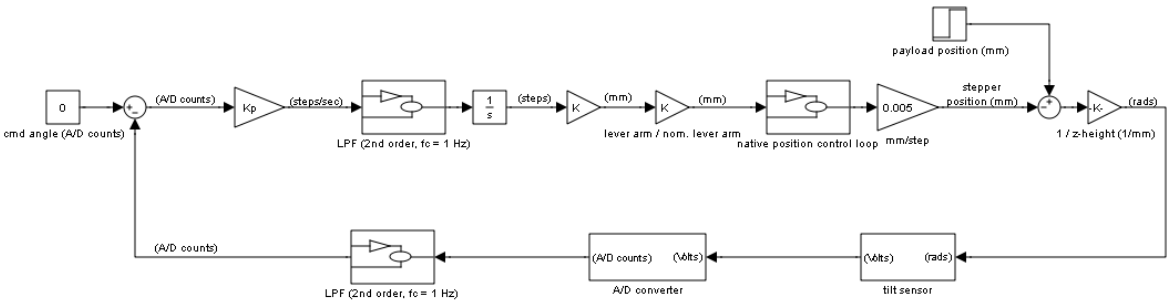

Figure 7: Control system block diagram

Test Results

Friction Tests

Figure 8 shows the WAGM set up for friction tests. Calibrated weights totaling 360.26 N (80.99 lb) were suspended from the load cable. The pressure in the AGM cylinder was adjusted to "float" the load such that the vertically moving carriage of the AGM was stationary and within its working stroke. The air

Figure 8: WAGM supporting 360.26-N (80.99-lb) payload

pressure was then increased very slowly and the pressure P_u (psig) was noted at which the load just began to move upward. The pressure was then reduced very slowly and the pressure P_d (psig) was noted at which it just begun to move downward. The friction force referred to the payload end of the load cable was then calculated according to:

$$L_f = A_p(P_u - P_d)/2N \quad (1)$$

where:

L_f = friction force in lb

A_p = piston area in in^2 (6.157 in^2 (39.72 cm^2)

N = displacement multiplier ratio of pulley system (4.0:1)

The piston pressure in psig was read from the digital panel meter of the WAGM control console (Figure 9). The pressure sensing channel had previously been calibrated against a primary pressure standard. Motion was detected via the digital readout from the carriage position sensor. A displacement change of at least 0.0508 mm (0.002 in) (twice the least-count of the meter) was taken to indicate that friction had been overcome and the carriage had moved.

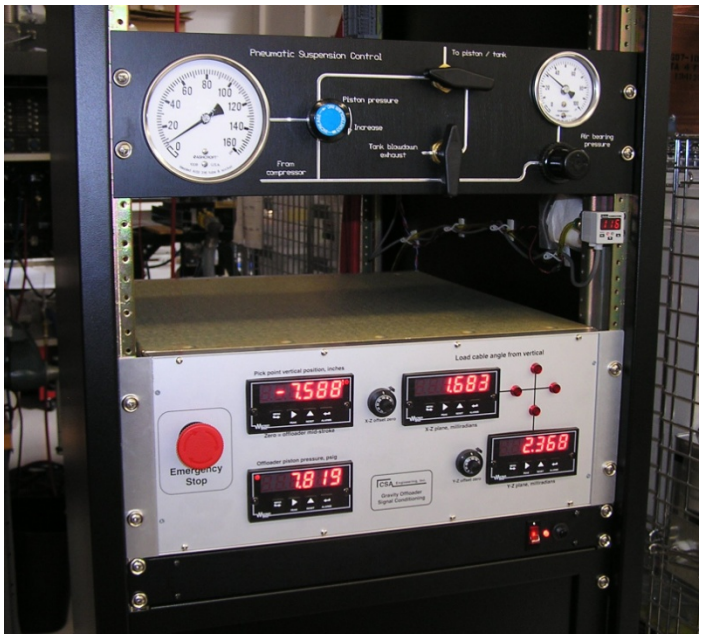

Figure 9: Piston pressure in psig (lower left) and carriage position from center in inches (upper left) on the control console. Tip-tilt sensor outputs in milliradians are displayed on the other two readouts.

The test was repeated numerous times at payloads of 360.26 N (80.99 lb) and 249.06 N (55.99 lb). Results are shown in Table 1. Each cell of the table contains two numbers. The upper number is a pressure, either P_u or P_d. The lower number is the carriage position at which the pressure was recorded, in inches from the vertical center of travel.

Table 1: Friction test results

Payload = 360.26 N (80.99 lb) Bearing pressure = 210 kPa (30.5 psig)		
Pu k Pa (psig)	Pd kPa (psig)	Friction N (lbf)
Carriage Z cm (in)	Carriage Z cm (in)	
391.23 (56.743) 18.331 (7.217)	390.48 (56.635) 18.326 (7.215)	0.369 (0.083)
390.55 (56.644) -10.419 (-4.102)	389.31 (56.464)	0.618 (0.139)
390.55 (56.644) -10.419 (-4.102)	391.01 (56.711) -10.414 (-4.1)	-0.231 (-0.052)
390.43 (56.772) -10.411 (-4.099)	390.48 (56.634) -10.416 (-4.101)	0.472 (0.106)
391.55 (56.789) -10.409 (-4.098)	390.48 (56.634) -10.416 (-4.101)	0.529 (0.119)
391.52 (56.785) -10.409 (-4.098)	389.94 (56.556) -10.416 (-4.101)	0.783 (0.176)

Payload = 360.26 N (80.99 lb) Bearing pressure = 210 kPa (30.5 psig)		
Pu kPa (psig)	Pd kPa (psig)	Friction N (lbf)
Carriage Z cm (in)	Carriage Z cm (in)	
278.71 (40.424) 0.813 (0.320)	279.48 (40.535) 0.826 (0.325)	-0.378 (-0.085)
278.62 (40.410) 0.815 (0.321)	279.49 (40.536) 0.823 (0.324)	-0.431 (-0.097)
278.62 (40.410) 0.815 (0.321)	279.50 (40.538) 0.833 (0.328)	-0.436 (-0.098)

As usual in friction testing, there is considerable scatter in the results. However, a typical value for vertical friction referred to the payload end of the load cable was 0.445 N (0.1 lb). A lower payload value resulted in less scatter but did not necessarily reduce the friction force. This is probably because a certain portion of the friction comes from cable flexing rather than bearing friction in the pulleys.

In addition to friction, the uplift force accuracy is limited by the resolution of the ultra-precision regulator. By test it was found that, with practice, the pressure could be changed in increments as small as 69 Pa (0.010 psi). This resulted in a force resolution of 69 Pa (0.01 psi) x A_p / 4 = 0.67 N (0.015 lb) due to the pressure regulator. The uplift force accuracy is the combination of the friction and the force resolution due to the pressure regulator, or $\pm$0.53 N ($\pm$0.12 lb).

Friction tests were also conducted on the AGM alone, without the 4x displacement multiplier. Figure 10 shows the AGM configured for this test. The 4x multiplier mechanism is removed, as is the lower plate that normally supports two pulleys of the multiplier. A load of 711.7 N (160 lb) is suspended directly from the lower cross-member of the AGM carriage. The piston pressure is then adjusted to an equilibrium value just sufficient to “float” the load. Piston pressure and carriage position are monitored via the digital panel meters of the control console (Figure 9). The test method then proceeds in the same way as the aforementioned friction test with the displacement amplifier. It was found that, even with the ultra-precision pressure regulator, the piston pressure could not be adjusted accurately enough to maintain a perfect equilibrium. The carriage would always rise or fall very slowly. This is typical behavior for an AGM. It indicates that friction, if there is any at all, is less than the product of the piston area and the pressure regulator resolution. For a pressure resolution of 35-69 Pa (0.005-0.010 psi) (typical for this type of ultra-precision regulator), the friction force is less than 138 mN (0.031 lb) at the offloader carriage or less than 36 mN (0.008 lb) at the payload end of the load cable when using the 4x multiplier. For practical purposes, the friction referred to the payload end of the load cable due to the AGM itself can be taken as zero.

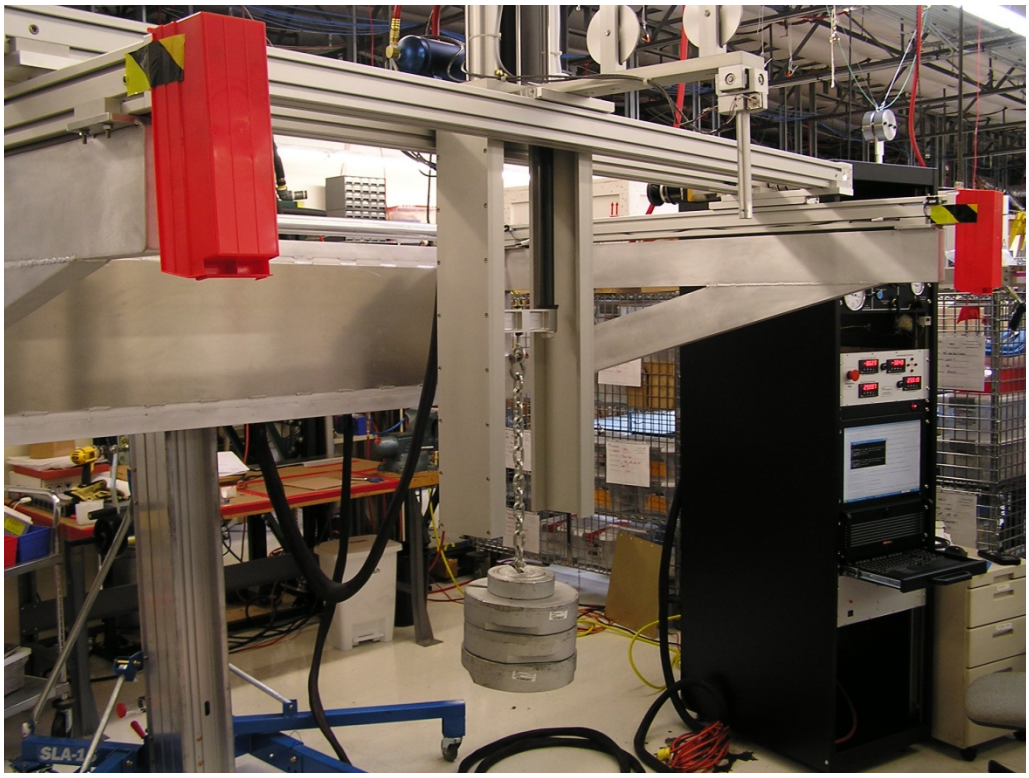

Figure 10: Friction test of AGM alone, without 4x displacement multiplier

Proof Load Testing

Figure 11 shows the WAGM set up for proof load testing. The goal was to demonstrate that the WAGM could support a load of 711.7 N (160 lb) at the payload end of the load cable without sustaining visible damage and retain all functionality. There was no requirement for the AGM to float the proof load nor was there a requirement for the X-Y stages to be moving while supporting the proof load.

For the test, the XY stages were both positioned at their outermost locations. That is, the Y stage was positioned as far as possible from the tower and the X stage was positioned at either travel limit. The AGM was depressurized and the supply pressure to the air bearings was set to its normal value of 206.842 x 10^3 Pa (30 psig). The tower was extended high enough so that a weight pan could be hung from the payload end of the load cable without the pan touching the floor. At least 711.7 N (160 lb) of weights were placed on the weight pan and the entire system was examined for signs of distress. The weights were left in place for a minimum of five minutes and then removed.

Figure 11 shows the WAGM with 716.1 N (160.99 lb) of certified weights hung from the payload end of the load cable. The XY stage was at one outboard “corner” of its range of motion, per the test requirement. No damage was visible or otherwise apparent during or following the proof load test, nor was any effect on performance detected during the remaining tests.

Figure 11: WAGM undergoing proof load test

X-Y Tracking Accuracy

The customer requested that the offload force resolution be less than 89 mN (0.02 lb) in all three spatial directions. Friction tests and review of the pressure regulator resolution showed that 534 mN (0.12 lb) of vertical force resolution was possible. In the horizontal degrees of freedom this requirement is a function of the payload weight and the angular tracking error when the payload is moving at constant velocity. For a maximum payload weight of 355.8 N (80 lb) and a maximum payload speed of 1.59 mm/s (0.0625 in/s)

this translated into less than 0.25 milliradian allowable steady state angular deviation of the cable guide tube, an aggressive goal to be sure.

CSA conducted a so-called 'box test' to determine the steady state angular tracking error at the maximum payload speed. A box test exercises the robotic arm through its entire range of motion in all three spatial directions. Prior to start, a dummy weight was hung from the load cable and the tip tilt sensors were zeroed. The WAGM custom software generates a log of pressure, position, and angle at a 2-Hz sampling frequency. This sampling frequency is sufficient because as mentioned previously the tip-tilt sensor signals are fed through anti-alias filters before digitization by the controller card, whereupon the signals are then further digitally low-pass filtered onboard the controller card at a cutoff frequency of 1 Hz. The data logged over the entire box test trajectory were plotted against time in order to determine the steady state x-y tracking accuracy as a function of robot arm speed.

The upper panel of Figure 12 shows both the raw signals of X-Z angle and Y-Z angle taken directly from the WAGM software log, as well as the signals post-processed in MATLAB with zero phase shifting digital filtering at 1 Hz for better visualization of the mean underlying angular errors. The lower panel of Figure 12 shows the trajectory of the payload in all three coordinate directions. The Z-trajectory in the lower panel reflects the length of the load cable from the universal joint to the pick point on the payload. Figure 12 shows that the steady state angular tracking error is a function of the payload speed. This is because the feedback control loop utilizes only proportional control (see Figure 7). Integral control was not utilized because it was found that the integral gain required to have any significant effect within the deployment time made the system unstable.

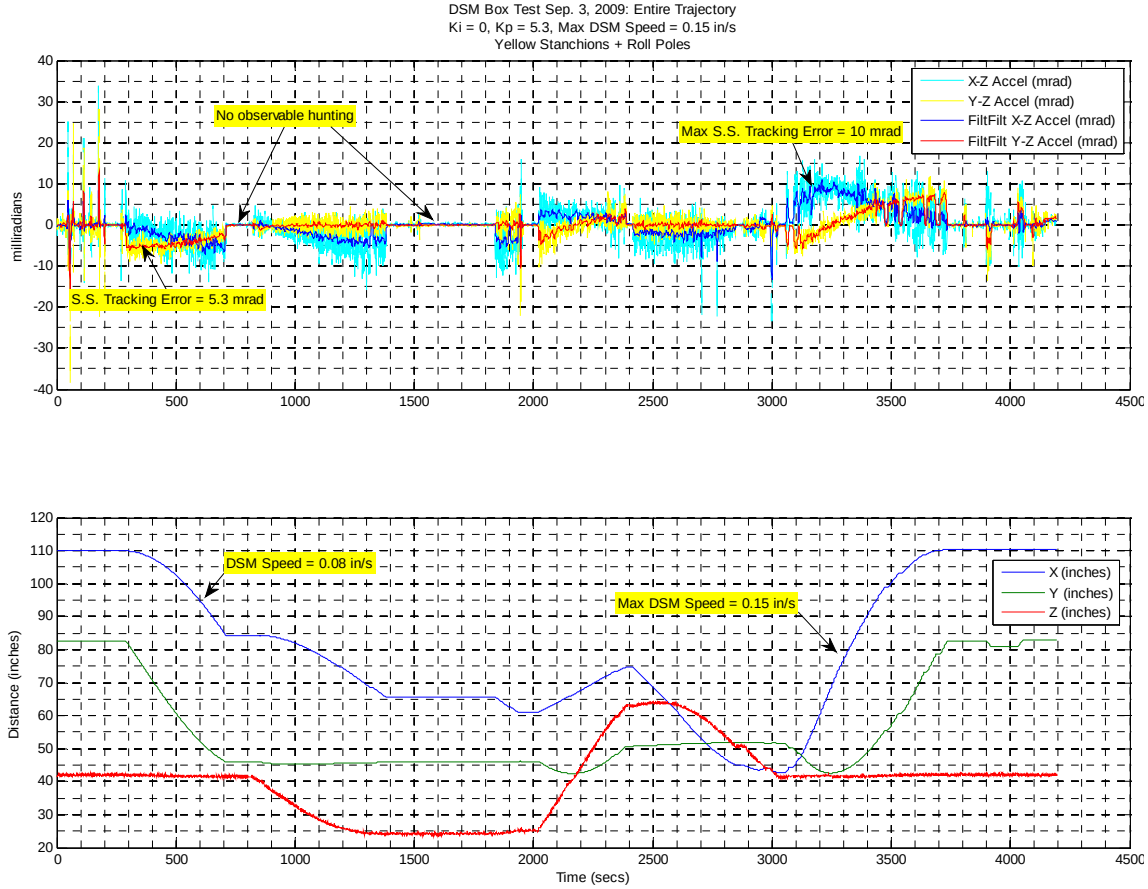

Figure 12: Angular tracking error vs. payload speed during a box test

Figure 12 shows that at a payload speed of 3.81 mm/s (0.15 in/s) the steady state tracking error approached 10 milliradians. Close to the contractual maximum payload speed of 1.6 mm/s (0.0625 in/s) the steady state tracking error was around 5 milliradians. For a maximum payload weight of 355.8 N (80 lb), this corresponds to a lateral drag force of just 1.779 N (0.4 lb).

Lessons Learned

Free play in the stages of the COTS telescoping tower presented some significant challenges during development. Free play around the vertical axis of the telescoping tower produced a yaw mode that interacted unfavorably with the horizontal active tracking system. Free play in the roll direction gave rise to a sudden shift of the load platform as the AGM traversed over center in the X-direction.

To mitigate the control engagement of the yaw mode two anchor stanchions and a set of guy cables were added to stiffen the tower in yaw. To eliminate load platform shifting two telescoping poles were installed beneath the tines of the load platform to stiffen the tower in roll. The customer deemed the set-up repeatability of these stiffening elements insufficient however, and so another stiffening solution was devised that lent itself to greater repeatability of setup.

Figure 13: Pair of triangulated roll poles to stiffen telescoping tower of industrial lift

The solution implemented was a pair of telescoping tubes that triangulate the structure (Figure 13). The telescoping tubing retracts and extends automatically with the raising and lowering of the load platform.

The two sections of each tube are clamped together once the load platform is at the desired height. The setup is straightforward and repeatable with the use of a torque wrench to pre-load the triangulating members.

Refashioning COTS equipment for use in an application for which it was not originally intended should be approached with caution. Such use often depends on characteristics of the COTS equipment that are not usually important (free play of the tower in yaw and roll) and may therefore not be well controlled in design and manufacture. This is the risk that comes with the cost savings motivating the use of COTS equipment. In hindsight, the problems with the tower could have been solved at the design stage by simply using two towers, one lifting at each rear corner of the load platform. More attention to tower stiffness could potentially allow the X-Y control system to be stable at higher gains and possibly with integral gain, thus giving higher tracking accuracy.

Conclusions

WAGM is the first proven three-DOF gravity offloading system of its kind to deliver high fidelity zero-gravity simulation over large displacements with very low set-up time. Its very simple interface to the payload suggests that it could be used for zero-g simulation with a wide variety of deployable structures and other uses as well. Potential applications of WAGM include:

- Ground testing of deployable spacecraft structures
- Pick and placement of heavy, sensitive equipment (e.g., during spacecraft installation)
- Gravity offloading of human subjects for injury rehabilitation or to study the effects of zero-gravity conditions on the musculoskeletal system

With its improvements over existing technologies in zero-gravity simulation fidelity, set-up time, and extended range of motion, it is easy to envision many applications for WAGM at significant cost savings to the user in terms of set-up time, testing time, and accurate system validation.

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