Design Tradeoffs in the Development of the Advanced Multispectral Simulation Test Acceptance Resource (AMSTAR) HWIL Facilities

Kenneth G. LeSueur
USA Test and Evaluation Command, Redstone Technical Test Center
Redstone Arsenal, AL 35898-8052

Frank J. Almendinger
Acutronic USA Inc., 640 Alpha Drive, Pittsburgh, Pennsylvania 15238

ABSTRACT

The Army's Advanced Multispectral Simulation Test Acceptance Resource (AMSTAR) is a suite of missile Hardware-In-the-Loop (HWIL) simulation / test capabilities designed to support testing from concept through production. This paper presents the design tradeoffs that were conducted in the development of the AMSTAR sensor stimulators and the flight motion simulators. The AMSTAR facility design includes systems to stimulate each of the Millimeter Wave (MMW), Infrared (IR), and Semi-Active Laser (SAL) sensors. The flight motion simulator (FMS) performance was key to the success of the simulation but required many concessions to accommodate the design considerations for the tri-mode stimulation systems.

Keywords: SIMULATION, FLIGHT MOTION, TEST, MISSILE, HARDWARE-IN-THE-LOOP, INFRA-RED, RADAR, SEMI-ACTIVE LASER

1.0 INTRODUCTION

The Advanced Multispectral Simulation, Test and Acceptance Resource (AMSTAR) is a group of missile Hardware In the Loop (HWIL) facilities developed jointly by the Redstone Technical Test Center (RTTC) and the Aviation and Missile RDEC System Simulation Development Directorate (AMRDEC SSDD) in Huntsville, AL. The AMSTAR facilities are a model of multidiscipline engineering design requirements demanding considerable analysis and systems engineering to maximize the facility performance with individual subsystems performing in less than ideal conditions.

The AMSTAR Performance bay places the missile guidance section in a closed loop simulated flight environment that supports launch to impact testing and analysis. The AMSTAR Production bay is designed to test All Up Round (AUR) missiles including the explosive components such as the rocket motor and warheads. For safety considerations, the production bay has two separate facilities separated by an earthen berm. All operators are located in the control blockhouse when live ordnance is placed in the FMS within the test chamber.

1.1 AMSTAR team – RTTC/AMRDEC/Acutronic

SSDD and RTTC combined expertise from both simulation and testing backgrounds to form a team with a unique formulation in mission and execution. Acutronic was competitively selected to supply the flight motion simulators (FMS) for both of the AMSTAR facilities. This experienced team was uniquely qualified to meet the challenging performance requirements for the state of the art multispectral HWIL simulation/test facilities.

1.2 Intended uses

The suite of AMSTAR facilities supports the complete life cycle testing of multispectral missile systems and subsystems. The intended uses include developmental performance assessments and engineering analysis, preflight tests/screening, environmental qualification testing, production acceptance testing, and stockpile reliability testing. The non-destructive testing that can be conducted within the AMSTAR facilities opens many opportunities for developers and testers to gather performance information in a repeatable environment with the ability to collect detailed data elements from the missile hardware/software and the six degree of freedom models.

2.0 PROJECTOR SYSTEMS BACKGROUND

The primary uniqueness of the AMSTAR facilities is the ability to perform real-time multi-spectral scene generation and projection into a common missile seeker aperture. To accommodate the multispectral projector system designs, many constraints and special design requirements are placed on the FMS system implementation. These tradeoffs are covered in more detail in section 4.0. The AMSTAR facilities are equipped with a dynamic Infrared (IR) scene projector, Millimeter Wave (MMW) projection, and a Semi-Active Laser (SAL) return simulator. The three projected beams are combined together and provide simultaneous in-band stimulation into a single sensor aperture.

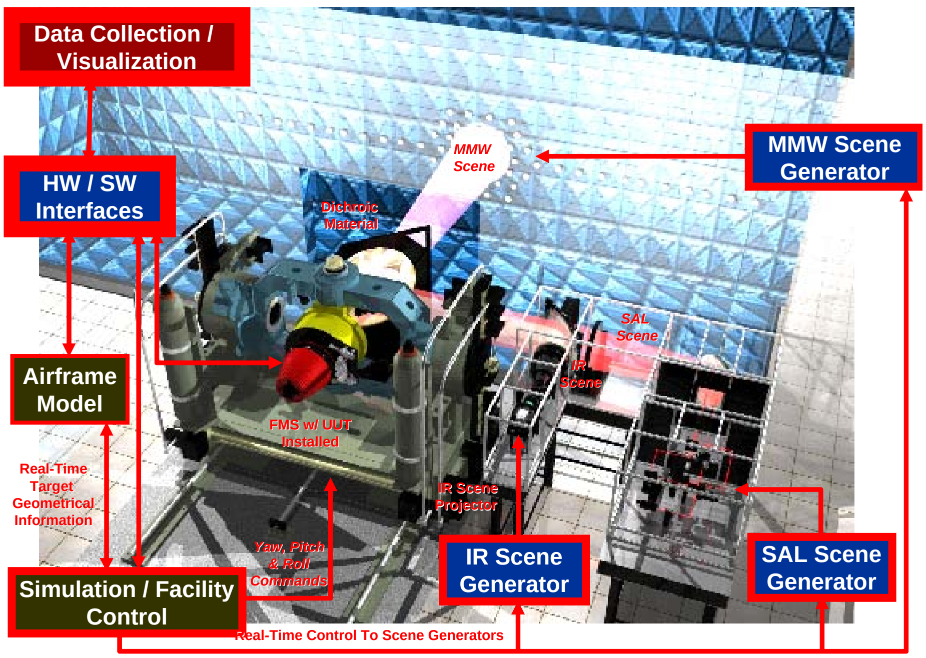

Figure 1. AMSTAR Facility Design

2.1 Infrared projection

The AMSTAR includes in-band projection systems for the mid-wave (3-5µm) IR. As seen in Figure 1, the IR and SAL projectors each have their respective collimators. The collimated output of the two projectors is passed to a beam combiner, reflecting IR and transmitting SAL. The combined image is then projected on to the dichroic mirror that reflects IR/SAL energy and transmits MMW energy into the input aperture of the UUT.

The AMSTAR incorporates a Large Format Resistor Array (LFRA) IR scene projector for providing the in-band stimulation in the IR channel. The LFRA is an array of 1024X1024 resistor elements. The IR projector is equipped with a zoom collimator that provides an exit pupil diameter of 7 inches at a standoff distance of 8.7 ft. The collimator has an adjustable focal length from 0.39m to 1.025m. [1]

2.2 Semi –active laser projection

The AMSTAR uses a three-channel Semi-Active Laser scene projector to stimulate sensors with in-band 1.064µm energy. The SAL projector system has three independent channels. Each channel has a laser, steering mirror, coarse attenuator, and fine (fast) attenuator. The steering mirrors point each of the channels at the projector screen that is placed in the focal plane of the SAL collimator. The collimator for the SAL projector is a 24-inch diameter single fused silicon lens with a focal length of 2 meters. [1]

2.3 Millimeter wave projection

The AMSTAR MMW Projection system is a Ka-Band MMW system that works by modulating the pulse train for the unit under test (UUT) with a sequence representing the target and background scene in the instantaneous FOV of the missile seeker. The MMW antenna array presents the scene to the UUT at the proper angle and polarization.

The MMW scene generation system is designed for up to four channels having independent control of the array position (amplitude & phase), attenuation, Doppler, and time delay. The system is designed to have a dynamic range of 120 dB with 0.25 dB resolution using two 60 dB attenuators. Doppler is applied using a frequency synthesizer with greater than 200 kHz BW and a step size of 0.10 Hz.

The dichroic material is a key technology used to combine the three spectrums used in AMSTAR. The dichroic properties allow it to pass Ka Band MMW with relatively little alteration while reflecting the IR and SAL scene with practically no negative effects. [1]

3.0 FLIGHT MOTION SIMULATORS

3.1 Performance specifications

The two 3-axis FMS units share basic performance requirements common to many flight simulators. In addition, a number of unique constraints (both physical and performance) were placed on them. The Performance bay simulator (Acutronic model HD-756-1) is intended for use in the hardware and software development phases of the missile guidance subsystem, whereas the Production bay (model HD-756-2) is used to test All Up Rounds (AUR). The development environment requires more stringent dynamic performance (higher velocities, accelerations, and frequency responses) than the production tests. On the other hand, the size, mass and moments of inertia for the unit under test (UUT) are several times higher for the production testing, requiring a larger FMS, higher torques, and increased stiffness. In addition, the safe handling and loading of live rounds requires special care in design, and additional safety interlocks and operational features.

The two units share basic specifications, including position and rate accuracy, high-speed reflective memory (RFM) interface, and numerous safety features. Table 1 summarizes the performance requirements.

Table 1. FMS Performance Specifications

Specification		Axis	Performance Bay	Production Bay	Units
Maximum Rate		Roll	1000	600	Degrees/second
		Yaw, Pitch	600	450	
Maximum Acceleration		All	20,000	9,000	Degrees/second^2
Frequency Response		All			
	-90 degrees phase		30	15 (20 goal)	Hz
	+/- 1dB (0.5dB goal)		10	7.5	
	-5 degrees phase		10	7.5	
Position Accuracy		All	+/-0.002	+/-0.002	Degrees
Rate Accuracy		All	0.1	0.1	Percent
Rotational Freedom		Roll	+/-120	+/-120	Degrees
		Yaw	+/-45	+/-45	
		Pitch	+/-45	+/-45	
		Pitch with alternate stops	+/-35	+/-35	

3.2 Acutronic design approach

The Production bay FMS is shown in Figure 2.

Figure 2. Production bay FMS, showing integrated environmental chamber (red cylinder)

3.2.1 Mechanical design

The performance requirements, UUT sizes, and simulator size limitations are consistent with an hydraulically-actuated FMS. The power-to-weight ratio (or, more specifically, the torque-to-volume ratio) of traditional fixed-vane hydraulic actuators exceeds that of other candidate technologies, resulting in a more compact FMS. The exception is the roll axis, which can be efficiently driven with a direct-mounted permanent-magnet brushless torque ring motor. The use of the brushless roll drive reduces the complexity of the FMS by eliminating fluid joints, piping, and other hydraulic components, and results in improved dynamic performance.

The mechanical components (gimbals, bearings, shafts, base, and foundation) must be designed for maximum stiffness and minimum weight, and machined to close tolerances. The factors driving the design include maximum acceleration, frequency response, and accuracy. Because of the FMS width limitations, the clearance between rotating components becomes a major design issue.

The combination of high torque, high velocity, and high bandwidth requires careful selection of hydraulic components. The hydraulic actuators are sized to produce the torque required for the specified accelerations. The actuators selected also provide internal snubbing, which decelerates the axis near the limits of rotational freedom. The servo valves are selected to provide adequate flow capacity, and sufficient bandwidth to support inner-loop linearization of the hydraulic plant. Multiple two-stage servo valves are mounted on manifolds adjacent to each actuator. Pressure-compensated electrically driven pumps in the hydraulic power unit (HPU) provide the pressures and high flow rates required to produce maximum accelerations and rates. The use of large-cross-section piping with efficient accumulators is dictated, to minimize pressure loss and to damp pressure pulses. The HPU also incorporates many interlocks, to provide self-protection.

The roll axis design is driven by the UUT size and mass properties, as well as the requirements for a thermally insulated environmental chamber and automated UUT mounting sequence.

The handling of the AUR missiles dictates that all personnel be clear of the area whenever power is applied to equipment. Additional components are required to automatically clamp the UUT and position the FMS in load and test positions.

3.2.1 Control system design

The major electrical subsystems consist of:

1. Servo controller for 3-axis FMS
2. Programmable logic controller (PLC) for FMS translation/rotation/clamping and UUT loading
3. Roll axis brushless drive amplifier
4. HPU controls

The ACUTROL3000 precision controller is selected for its all-digital design and field-proven characteristics. A VMIC reflective memory (RFM) network provides high-speed communication with the host computer; advanced data processing algorithms allow demand and monitor vectors to be seamlessly processed between the two non-synchronized discrete time systems. Removable flash drives are required to comply with site security regulations. The controller provides transducer drive, feedback, and demodulation, servo valve drive, HPU control, commutated current commands for the roll drive, and safety interlock functions. Remote graphical user interface (GUI) software is provided, as well as a local keyboard/mouse and the integral touch-screen GUI.

A commercial PLC is used to control the translation, rotation, and clamping of the FMS base, as well as the UUT clamping. For the translation and rotation, it controls chopper-drive induction motors while monitoring positions. The FMS base is repeatably positioned and clamped by controlling a small HPU and activating hydraulic cylinders through solenoid valves. The UUT clamp sequence is accomplished by use of an air-over-hydraulic system, solenoid valves, and pressure switches.

The roll drive amplifier is a commercial model, matched to the characteristics of the roll torque ring motor. The motor currents are commutated by the Acutrol3000. Amplifier bandwidth is customized, and current outputs are filtered.

The HPU controls (motor soft-starters, control relays, pressure controls, switches, and sensors) are housed primarily on the HPU itself, with overall control and monitoring done by the Acutrol3000.

3.3 Measured FMS performance

Synthetic line of sight (SLOS) simulations lead to rigorous dynamic requirements for the FMS axes. Specifically, maximum velocities, accelerations, and limits on dynamic tracking error are all accentuated. In order to meet the tracking requirements, it is necessary to minimize the closed-loop phase shift and gain deviations over the low- to mid-frequency range. Refer to the frequency response specifications in table 1. The low-frequency gain and phase specifications are directly related to limits on tracking error.

In order to achieve these low-frequency requirements without excessively (and expensively) high overall loop bandwidth, the Acutrol3000 uses a flexible nested-loop scheme, with a state-space observer along with a sophisticated command processor providing a coherent set of internal position, rate, and acceleration commands.

Figure 3 illustrates the frequency response of the performance bay roll axis. The data on this plot are collected by the DataLog function in the Acutrol3000, and represent the closed-loop response to an internal programmable swept-sine generator. Note that the gain and phase up to 10 Hz are well within the specification, as well as the goal. The -90-degree phase point (specified as 30 Hz) is well over 100 Hz (about -47 degrees at 100 Hz).

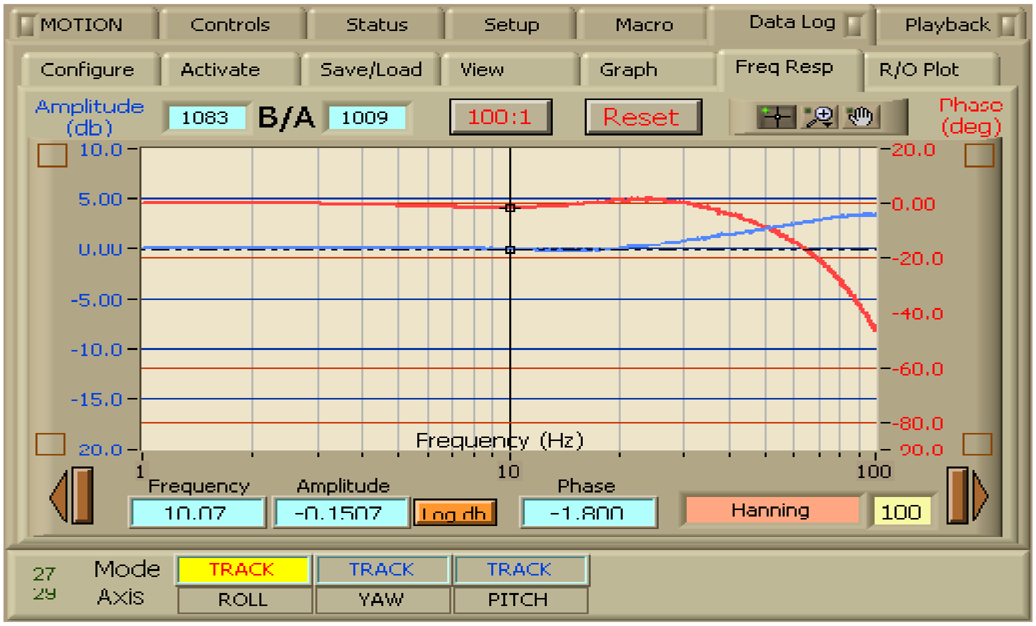

Figure 3. Performance bay roll axis position loop frequency response. Blue trace is gain (scale on left, in dB), red trace is phase (scale on right, in degrees). Cursor is at 10.07 Hz, gain is –0.1507 dB, phase is –1.80 degrees.

Figure 4 shows the same type of plot for the production bay pitch axis. The plot is more typical of a hydraulic axis – not as flat as the brushless roll axis. Note, however, that the gain and phase up to 7.5 Hz are well within the specification, as well as the goal. The -90-degree phase point (specified as 15 Hz, with a goal of 20 Hz) exceeds 30 Hz (better than -80 degrees at 30 Hz).

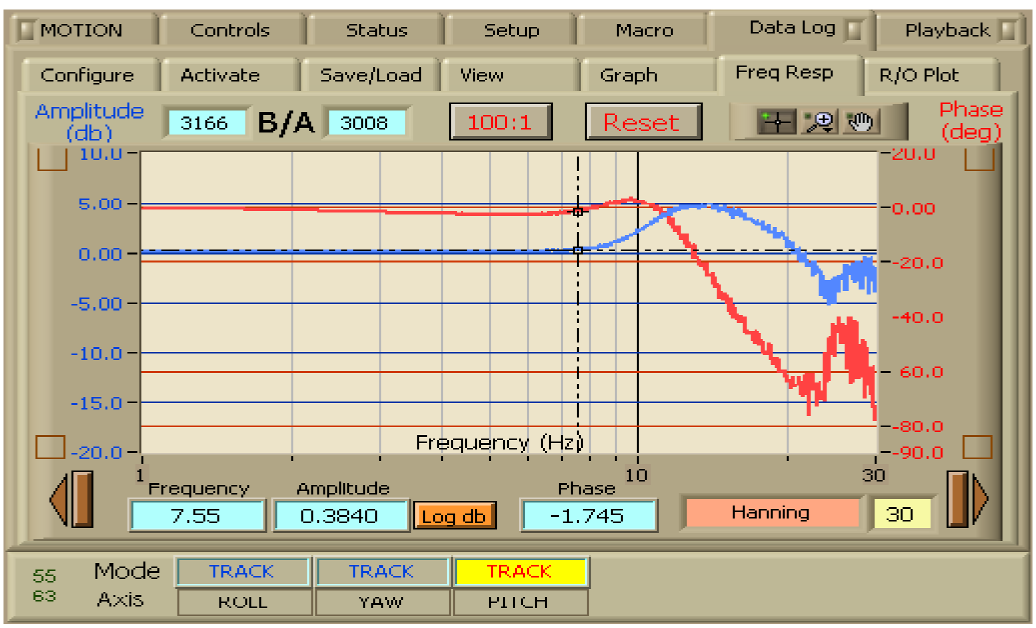

Figure 4. Production bay pitch axis position loop frequency response. Blue trace is gain (scale on left, in dB), red trace is phase (scale on right, in degrees). Cursor is at 7.55 Hz, gain is +0.384 dB, phase is –1.745 degrees.

4.0 DESIGN TRADEOFFS

The extreme performance requirements of the AMSTAR facilities demanded an in-depth tradeoff analysis to accomplish the primary system goals in a conflicting multidiscipline engineering environment. Below are some of the most challenging performance considerations and the approach taken by the AMSTAR design team.

4.1 FMS width versus optical path length

As seen in figure 1, the width of the FMS has a direct impact on the optical path length of the IR and SAL systems. Increases in the optical path length cause the optical element diameter to increase to cover the required Field Of View (FOV) in each projection band. The cost of the optical elements increases considerably as the size of the element increases. As the elements approach 36 inches and above, producing and coating of the optical elements comes into question. The probability of successful yield is decreased as the size increases and suppliers are reluctant to commit to delivery dates. The cost and problematic production of large optical elements were serious issues that drove several FMS design parameters.

The FMS pitch actuator design, the placement of piping, accumulators, and valves were just a few of the design considerations that were made to limit the FMS width. One of the design trades that was considered to reduce the optical path length was to place the optical subsystems in a vertical mounting arrangement. This approach would reduce the path length, but it was determined that the complexity of vertically mounting the large optical elements, along with maintenance and calibration considerations, outweighed the cost and complexity of the longer path length. Thus, the approach was not taken.

A design constraint was placed on the FMS that would keep the front of the FMS pitch gimbal and trunnions clear of any hydraulic piping and accumulators, electrical wiring, and other support equipment. This design consideration was needed to aid the mounting of anechoic and radar absorbing material needed to keep down the MMW reflections and other interference.

4.2 FMS pitch rotation versus dichroic mirror size and placement

The placement of the Dichroic beam combiner in front of the missile seeker is constrained by three different aspects of the HWIL system. First, the MMW considerations would ideally place the dichroic beam combiner very close to the seeker head and have a large diameter to keep the edge of the dichroic element at a large angle away from the seeker FOV centerline. In consideration of the IR and SAL projectors, a dichroic combiner that is close to the seeker keeps the optical path to a minimum which reduces optical element size, complexity, and cost. The performance aspect that keeps this panacea from occurring is the pitch axis of the FMS, which would impact a large dichroic element placed too close to the missile seeker.

During the design of the AMSTAR systems, this topic was given considerable examination and experimentation. There is a desire to keep the FMS pitch axis angular rotation as large as possible to maximize the different types of missile flight scenarios that can be simulated, and to support testing of weapon systems that would not require a dichroic combiner and thus not need to limit rotation. MMW tests were performed on glass blanks that simulated the effects of the edges of the dichroic material on the MMW signal return. This data was used to help determine an optimum tradeoff between the three conflicting design parameters: optical path length, FMS pitch axis rotation, and potential MMW interference with the dichroic material edges.

It was determined to keep the FMS pitch axis travel at +/- 45 degrees to accommodate future needs, and to add removable stop blocks to limit the rotation to +/- 35 degrees for applications needing the dichroic beam combiner. The dichroic beam combiner was set at a diameter of 40 inches and was placed as close to the missile seeker as possible, keeping it slightly outside the impact zone with the FMS pitch axis. The optic elements (IR/SAL beam combiner, IR collimator, and SAL beam combiner) were sized accordingly, given the dichroic placement and the FMS width.

4.3 FMS performance versus integrated environmental conditioning chamber

The AMSTAR facilities are required to support testing of missile systems while exposed to maximum temperature extremes. It was desired to have the FMS meet the demanding rotational acceleration, velocity and position specifications with the added weight and volume of an integrated environmental conditioning chamber. The missile systems intended for use in AMSTAR have a -65 to +160 degrees Fahrenheit performance requirement. The extreme conditions of the -65 degrees dictated the amount of insulation required to prevent condensation on the external skin of the environmental chamber. Because the environmental chamber is mounted in (and rotates with) the innermost roll axis, the added inertia ripples through the requirements for all three axes. It was critical to meet the chamber specifications without adding undue volume and weight which would result in added difficulty in meeting the other performance specifications.

Another difficult performance aspect of the environmental chamber was having adequate conditioned air flow around the entire missile guidance section needed to keep the temperature differential to a minimum. By having a large air space around the missile and using a large supply hose size, the backpressure on the environmental conditioning system is reduced and the target temperature is easier to achieve. The downside to this approach is added weight and volume of the larger environmental chamber and the weight of the large hoses attached to the chamber, directly impacting the size of the FMS motors, gimbals, valves, etc. Initial efforts utilized a traditional closed loop environmental conditioning system that has a supply and return line running to the Unit Under Test (UUT). The final technique for the performance bay FMS utilizes a single pass system that eliminates the return line. This reduces the inertial load on the FMS and through the increased supply hose diameter, the environmental conditioner fan back pressure is reduced. The challenging performance in this approach is transferred to the environmental conditioning unit, requiring it to convert ambient air to the desired temperature extreme in a single pass.

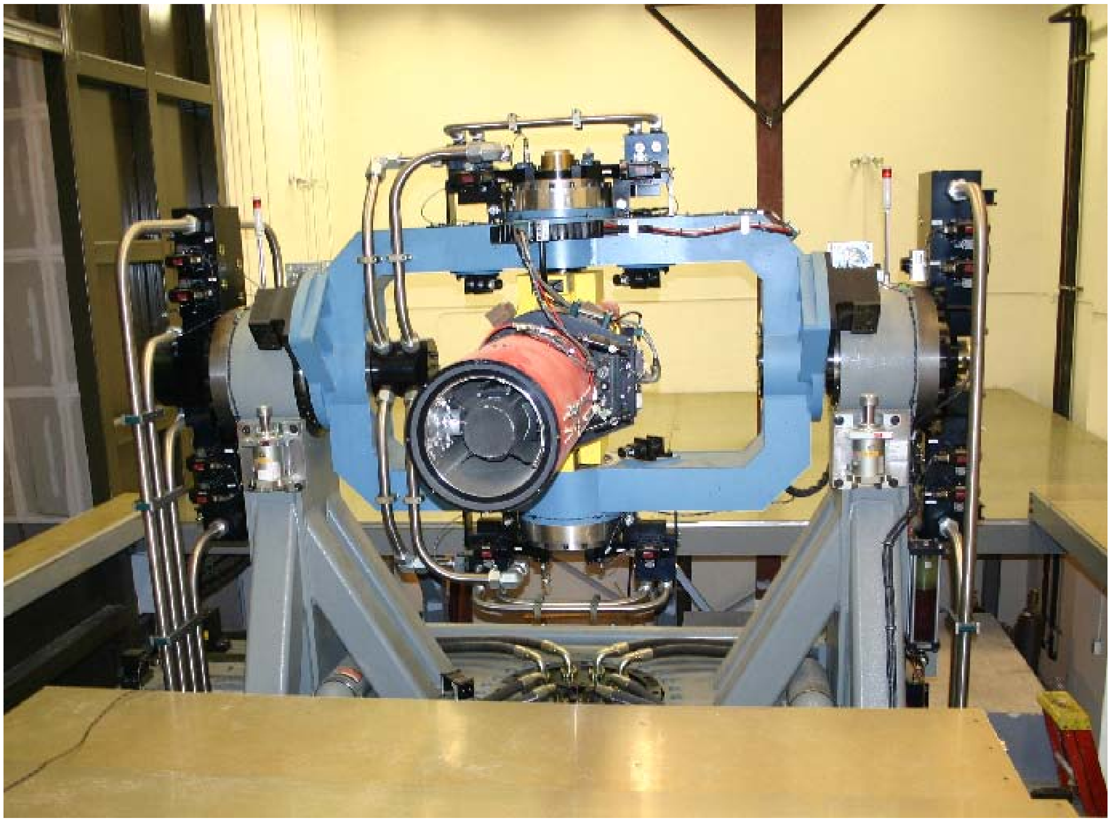

Figure 5. Rear view of production bay FMS, environmental chamber with inert missile installed. FMS base translated from test position and rotated to UUT loading position.

4.4 FMS performance versus loading/maintenance considerations

Because the AMSTAR facilities are intended to support production testing it was necessary to design the FMS and its environmental chamber to facilitate easy loading and unloading of the test items. In the case of the production bay FMS, the floor to missile position was critical because the missiles are greater than 100 pounds and are typically hand loaded. The FMS was required to move away from the anechoic chamber (test position) and rotate 90 degrees to support the rear loading of the missile. Reference figure 5 above, where the missile is shown mounted inside the integrated environmental chamber on the FMS.

For safety reasons, personnel are required to vacate to the control facility after a missile is loaded, but before power is applied to equipment in the vicinity of the AUR missiles. This restriction led to the design of a remotely controlled, automated sequence involving UUT clamping, FMS rotation, translation to test position, FMS base alignment, and clamping. The operation is monitored at a remote GUI. The reverse procedure is performed before personnel enter the area to unload the missile.

5.0 CONCLUSIONS

All of the performance and cost tradeoffs performed during the design phase of the AMSTAR facilities provide a capability that maximizes the performance of the facility within the cost and schedule constraints. Performance concessions were required on each of the subsystems to settle conflicting requirements with other subsystems. The FMS was a central subsystem that had to accommodate design demands from many other elements while maintaining its own demanding level of performance. Time will tell if the correct design/performance/cost compromises were made in the AMSTAR facilities. For now, the AMSTAR is the highest fidelity multispectral system of its kind and is currently performing acceptably in each of the critical categories.

6.0 REFERENCES

[1] K. LeSueur, M. Lowry, J. Morris, “Development and Integration of the Army’s Advanced Multispectral Simulation Test Acceptance Resource (AMSTAR) HWIL Facilities”, Proceedings of SPIE (2005), presented at Defense and Security Symposium, 28 March-1Apr 2005.

[2] Louis A. DeMore, Paul Mackin, Michael Swamp, Roger Rusterholtz, “Improvements in Flight Table Dynamic Transparency for Hardware-in-the-Loop Facilities”, Proceedings of SPIE Vol. 4027 (2000), presented at Aerosense 2000, 24-26 April 2000.