MSC-12-8

GUIDANCE AND CONTROL DEVELOPMENTS FOR THE FIRST LIGHTWEIGHT AGM-130 MISSILE

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Abstract

The AGM-130 air-to-ground missile is a stand-off weapon with an extensive product ancestry. The GBU-15 guided bomb unit, developed in the mid-1970s was the first in this series of weapons. In the early 1980s, a rocket motor was attached to the underside of the GBU-15, resulting in the AGM-130A air-to-ground, precision-guided missile. In the early 1990s, the BLU-109/B penetrator warhead was integrated into the modular weapon system, resulting in the AGM-130C weapon. Midcourse guidance (MCG) capabilities using coupled Global Positioning System/Inertial Navigation System (GPS/INS) technology were added in 1994. Operational modes to support Horizontal Target Attack (HTA) are the most recent operational enhancement to be added to the production version of the AGM-130. An innovative "sleeved" warhead concept allows the AGM-130 modular weapon to be the delivery vehicle for warheads significantly lighter than the 2,000 pound Mk-84 or BLU-109/B. The lightweight AGM-130 can accommodate new 1,000 pound class warheads developed for specialized attack scenarios. This paper describes the guidance and control developments for the lightweight AGM-130. One demonstration flight vehicle was designed, built, and launched. This paper discusses fundamental issues representative of any development program and how they were resolved with respect to autopilot processor limitations, financial constraints, limited development time, and operational and support issues.

List of Acronyms and Symbols

DIMODS	Digital Modular Simulation
GNP	GPS Navigation Processor
HTA	Horizontal Target Attack
INS/GPS	Inertial Navigation System/Global Positioning System
IR&D	Independent Research & Development
LASP	Linear Analysis Stability Program
MCG	Midcourse Guidance
NAV	Navigation
SPO	Systems Program Office
VTA	Vertical Target Attack
I_{xx}	Roll Moment of Inertia
I_{yy}	Pitch Moment of Inertia
I_{zz}	Yaw Moment of Inertia
k_{q_0}	Adaptive Gain Based on Dynamic Pressure
k_w	Motor Inertia Adaptive Gain
$\hat{q}$	Dynamic Pressure Estimate
θ_c	Pitch Attitude Command

Background and Introduction

The AGM-130 missile is a rocket-powered, air-to-surface weapon designed for surgical strikes against fixed, high value targets. High terminal accuracy, a direct result of man-in-the-loop end game control, and a 2,000 pound warhead provide a high probability of mission success. Production versions of the 3,000 pound weapon incorporate either a Mk-84 or BLU-109/B warhead. A television guidance system or imaging infrared seeker provides target imaging capabilities in clear or adverse weather conditions.

An upgrade to the original AGM-130 modular weapon system was the development of Midcourse Guidance (MCG) navigation capabilities utilizing coupled Inertial Navigation System/Global Positioning System (INS/GPS) technologies. Seeker

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Please find enclosed one (1) copy of a manuscript I am submitting for the 1998 AIAA Missile Sciences Conference in Monterey, CA. The manuscript is titled, "Guidance and Control Developments for the First Lightweight AGM-130 Missile."

Sincerely,

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Enclosures: one (1) copy of draft manuscript
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pointing maintains the target near the center of the field-of-view to ease the Weapon System Operator's effort in target recognition and acquisition, lock-on, and aimpoint update. An INS/GPS terminal attack capability is provided in adverse weather if the target is never acquired.

A more recent enhancement to the system was the development of a Horizontal Target Attack (HTA) capability. The previous AGM-130 weapon system would fly in a level attitude at low altitudes during rocket motor burn, using a radar altimeter to determine altitude above ground. With the incorporation of the GPS system into the AGM-130, it was possible to develop altitude hold capabilities at altitudes beyond the range of the radar altimeter. The weapon can then be pitched over from these higher cruise altitudes and can acquire and attack targets with a horizontal face, impacting at steep angles. The capabilities of the BLU-109/B penetrator warhead can be exploited with this employment option.

The AGM-130 has been certified for test launch from the F-4, and employment on the F-111 and F-15E aircraft. With the recent retirement of the F-4 and F-111 aircraft from the United States Air Force inventory, the F-15E is the sole existing launch platform for the AGM-130 missile.

The AGM-130A (Mk-84 warhead) and AGM-130C (BLU-109/B warhead) have a nominal weight of 3,000 pounds. The F-16 aircraft does not currently have a weapon system with the stand-off capability of the AGM-130. However, the existing 3,000 pound AGM-130 is too heavy for carriage on the F-16 aircraft. Hence, a "lightweight" AGM-130 has been developed to provide mission capabilities comparable to those of the heavyweight AGM-130, but with a reduced weight weapon. Several 1,000 pound-class warheads have been developed in recent years. Boeing has developed a sleeved warhead concept to encapsulate a 1,000 pound-class warhead in a payload section that retains the aerodynamic characteristics of the 2,000 pound warheads. The existing guidance module, adapter section (with a few minor structural modifications), control section, data link, and rocket motor can be used to form a modular "lightweight" AGM-130. The lightweight AGM-130 weighs less than maximum weight carriage requirements for the F-16, thus providing another potential employment platform for the weapon.

It has been found that, with this lighter AGM-130, the stand-off range of the weapon can be increased by modifying the flight profiles. Rather than using the rocket motor during a level altitude hold mode, it can be used to gain altitude (i.e., potential energy) and then can return to a glide mode, trading its potential energy for kinetic energy, thus increasing the stand-off range of the weapon.

This paper describes the development of the autopilot modifications necessary for the lightweight AGM-130. It includes discussions of: customer and system requirements, results from a linear stability analysis, the implementation of new flight profiles in the non-linear 6-DOF simulation, software requirements definition, hardware-in-the-loop (HWIL) testing, and recommendations for further study and improvements.

3-DOF Study

The heavyweight AGM-130 can fly two basic categories of missions: against a vertical target or against a horizontal target. Vertical Target Attack (VTA) missions can be launched from a wide range of altitudes and involve a descent or a short climb to low level cruise altitudes. Horizontal Target Attack (HTA) missions require a steeper flight path angle at weapon impact, necessitating a cruise altitude that is significantly higher than radar altimeter range.

Parametric trajectory shaping studies conducted with a 3-DOF missile simulation and estimated mass properties for an AGM-130 lightweight weapon indicated that a significant range increase could result from climbing steeper and longer during the thrusting portion of the fight (Reference 1). The study found that the missile's kinetic energy could be traded by climbing during the rocket motor burn to gain more potential energy (i.e., altitude), before a long glide descent to the target.

Approach

Initial discussions concerning a potential lightweight AGM-130 with the AGM-130 SPO at Eglin Air Force Base, Florida resulted in significant interest in the demonstration of such a weapon. Specific system requirements have not yet been imposed on the lightweight AGM-130, but two implicit goals have been surfaced:

- Develop a lightweight version of the AGM-130 that can be certified for employment on the F-16 aircraft.
- Extend the stand-off range of the AGM-130 through a decrease in warhead weight (from a 2,000 pound-class to 1,000 pound-class warhead) combined with trajectory shaping.

It was desired that the lightweight AGM-130 retain the aerodynamic characteristics of the heavyweight AGM-130, alleviating costly wind tunnel testing to determine the weapon's freestream aerodynamic characteristics. Accordingly, the external size and shape of the major components of the weapon have not been modified, with the exception of the warhead section. The diameter of the AGM-130A (Mk-84 warhead) is approximately 18 inches. The diameter of the AGM-130C (BLU-109/B warhead) is approximately 14 inches. The diameter of the payload "sleeve" of the lightweight AGM-130 is 16 inches. Figure 1 shows a comparison of the lightweight AGM-130 with an AGM-130A model.

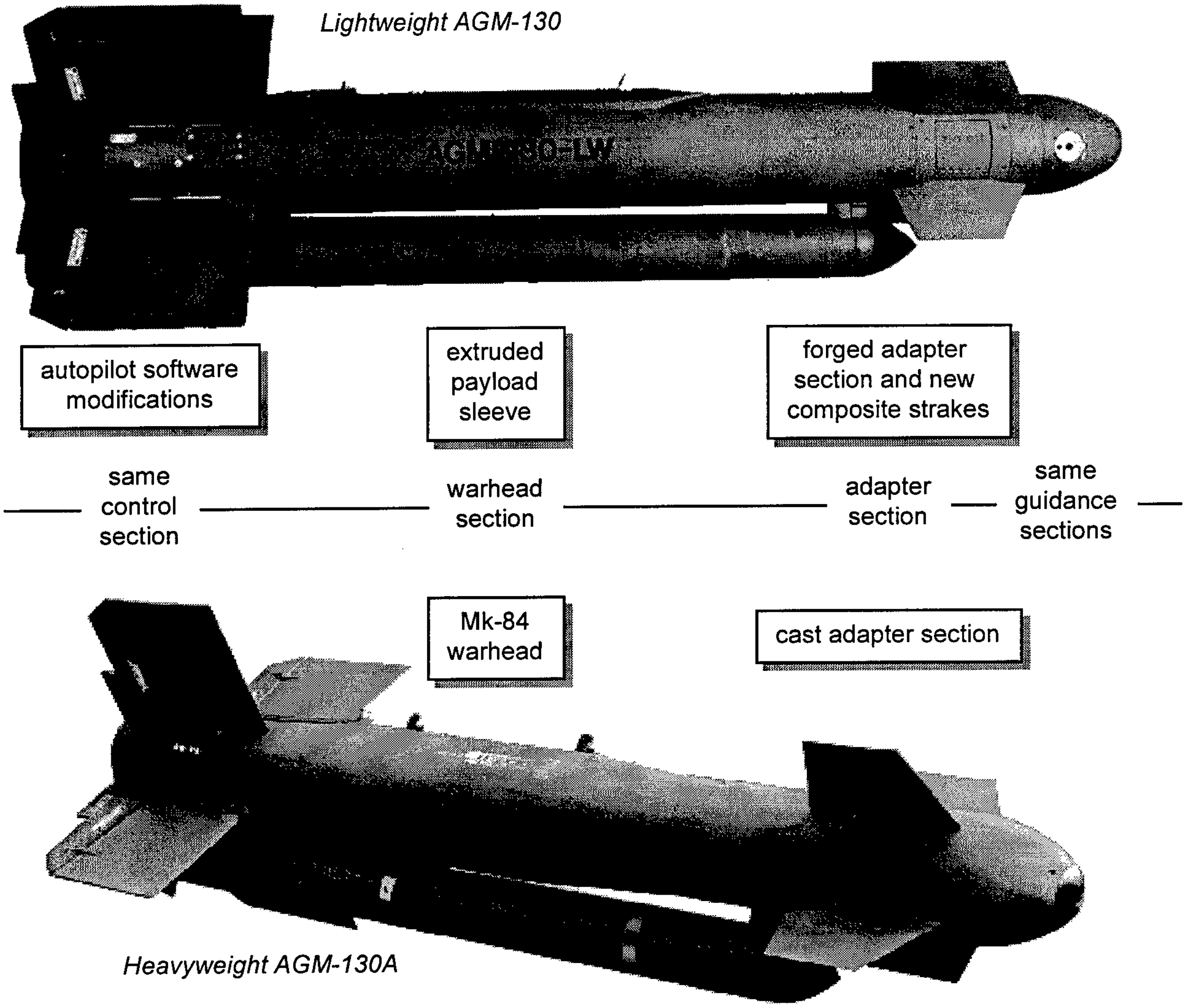

Figure 1: Lightweight AGM-130 and Heavyweight AGM-130A

The capability to do both VTA and HTA profiles was maintained in the lightweight AGM-130's autopilot. In addition, the reduction in weight allows the lightweight weapon to fly other profiles that have been designed to maximize range by trading kinetic energy for potential energy. The range extension profiles include a shallower glide slope (from high altitude launches down to the cruise altitude and after motor burnout), a steeper and longer climb during thrusting, and re-entry to the glide mode *after* motor burn. Due to the fact that the same rocket motor is used, a profile that maximizes range can result in degradation of other performance criteria, such as terminal impact velocity and/or impact angle.

The 3-DOF trajectory shaping study (Reference 1) was used to determine nominal range extension profile characteristics. Implementation of the new trajectories required modification of the 6-DOF simulation for the AGM-130. There are many ways to implement new flight profiles within the existing AGM-130 autopilot. However, overall autopilot modifications were constrained to a minimum due to processor memory allocations for available growth. In addition, it was strongly desired to retain the existing control structure and logic within the autopilot. The AGM-130 is an existing, fielded weapon system. Significant changes to the operational procedures or weapon flight characteristics would not be well received by operators. New operational modes, if implemented, would further complicate documentation, test equipment, and training/operational procedures.

The approach for the guidance and control analysis of the lightweight AGM-130 is shown in Figure 2. Sets of mass properties for the lightweight AGM-130 and pre-selected flight conditions were used with LASP (Linear Analysis Stability Program) to generate missile airframe transfer functions. These transfer functions, combined with values for estimated dynamic pressure at several flight conditions, were used in MATLAB to determine the gain and phase margins for the autopilot control loops. The margins were used to determine any necessary gain changes within the internal autopilot control structure. These gain changes, which were strictly numerical (i.e., the functionality was preserved), were then implemented in Boeing's 6-DOF nonlinear simulation, Digital Modular Simulation (DIMODS). Afterwards, all of the other necessary changes to the autopilot were coded. Deterministic performance analyses were conducted. Limited Monte Carlo testing was performed to verify the robustness of the new configuration autopilot. The embedded software requirements were generated. After the hardware version of the lightweight autopilot was programmed, it was tested with Hardware-in-the-Loop (HWIL) in Boeing's Functional Mock-Up (FMU) Laboratory.

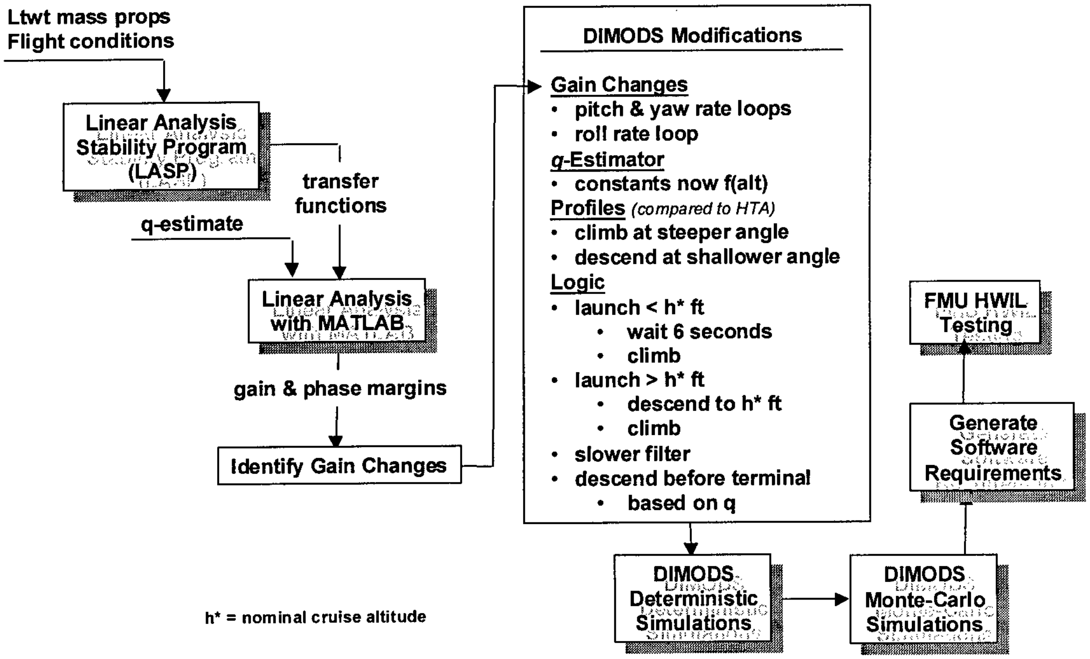

Figure 2: Lightweight AGM-130 Guidance and Control Development Process

Linear Analysis

A linear stability analysis of the lightweight AGM-130 was performed prior to modification of the autopilot software in the 6-DOF, nonlinear simulation. The linear analysis provides an indication of the stability characteristics of the system at various flight conditions. It can be used to determine changes within the autopilot that are required to prevent a flight instability condition or to indicate gain changes necessary to provide sufficient gain and phase margin.

Flight Conditions and Mass Properties

Nominal flight conditions were used in this linear analysis. Sixty-four conditions were chosen for various portions of range extension profiles (e.g., motor on/off, level flight vs. climb or descent, etc.). Low, medium, and high altitude launches were chosen for release at Mach 0.85 and 0.95. A low and medium altitude release were chosen for Mach 0.70. From the 3-DOF studies discussed in Reference 1, the Mach number, altitude, load factors, and thrust level were quantified for each of the chosen profiles. This data, presented in Table 1, was used in the linear analysis to determine the airframe transfer functions at these flight conditions. Altitudes are normalized with respect to the maximum altitude, Alt*.

Table 1: Linear Analysis Flight Conditions

number	M	Alt/Alt*	Description
1	0.85	0.125	launch, motor not burning
2	0.85	0.375	launch, motor not burning
3	0.85	0.750	launch, motor not burning
4	0.95	0.125	launch, motor not burning
5	0.95	0.500	launch, motor not burning
6	0.95	0.875	launch, motor not burning
7	0.70	0.125	launch, motor not burning
8	0.70	0.500	launch, motor not burning
9	0.65	0.150	pull-up after motor ignition
10	0.75	0.400	pull-up after motor ignition
11	0.70	0.400	pull-up after motor ignition
12	0.64	0.150	pull-up after motor ignition
13	0.72	0.400	pull-up after motor ignition
14	0.64	0.400	pull-up after motor ignition
15	0.64	0.150	pull-up after motor ignition
16	0.65	0.400	pull-up after motor ignition
17	0.74	0.250	mid climb, motor burning
18	0.85	0.525	mid climb, motor burning
19	0.78	0.500	mid climb, motor burning
20	0.72	0.250	mid climb, motor burning
21	0.82	0.500	mid climb, motor burning
22	0.74	0.450	mid climb, motor burning
23	0.74	0.250	mid climb, motor burning
24	0.77	0.525	mid climb, motor burning
25	0.83	0.375	push-over, motor burning
26	0.95	0.675	push-over, motor burning
27	0.91	0.625	push-over, motor burning
28	0.83	0.375	push-over, motor burning
29	0.94	0.650	push-over, motor burning
30	0.92	0.600	push-over, motor burning
31	0.84	0.375	push-over, motor burning
32	0.90	0.650	push-over, motor burning
33	0.72	0.375	level cruise, no motor
34	0.85	0.675	level cruise, no motor
35	0.82	0.625	level cruise, no motor
36	0.57	0.350	start glide, no motor
37	0.77	0.650	start glide, no motor
38	0.73	0.600	start glide, no motor
39	0.55	0.100	VTA terminal
40	0.55	0.150	VTA terminal
41	0.55	0.200	VTA terminal
42	0.78	0.025	HTA terminal
43	0.78	0.025	HTA terminal
44	0.78	0.025	HTA terminal
45	0.68	0.375	level cruise, no motor
46	0.88	0.650	level cruise, no motor
47	0.84	0.600	level cruise, no motor
48	0.60	0.325	start glide, no motor
49	0.70	0.625	start glide, no motor
50	0.68	0.575	start glide, no motor
51	0.53	0.100	VTA terminal
52	0.55	0.150	VTA terminal
53	0.57	0.200	VTA terminal
54	0.80	0.025	HTA terminal
55	0.80	0.025	HTA terminal
56	0.80	0.025	HTA terminal
57	0.72	0.375	level cruise, no motor
58	0.82	0.650	level cruise, no motor
59	0.60	0.350	start glide, no motor
60	0.75	0.600	start glide, no motor
61	0.50	0.100	VTA terminal
62	0.52	0.200	VTA terminal
63	0.80	0.025	HTA terminal
64	0.80	0.025	HTA terminal

The mass properties used in the linear analysis represented the latest available information at the time of the analysis. Mass properties were used for four missile configurations: body with full motor, body with motor half full, body with empty motor, body only (motor ejected case).

Airframe Transfer Functions

The LASP program uses the same aerodynamic block data as the 6-DOF simulation, DIMODS. From the aerodynamic block data, aerodynamic flight derivatives are automatically calculated and transfer functions are generated for a given flight condition (Mach number and altitude). For the lightweight

AGM-130 guidance and control analysis, LASP was used only to generate airframe transfer functions. The transfer functions were combined with models of autopilot components (software compensation, actuator, and IMU dynamics) in MATLAB to perform the stability analysis for the lightweight AGM-130.

Stability Analysis

SIMULINK models of the autopilot control loops were developed for performing the linear analysis for the AGM-130 HTA program. These same models were utilized for the linear analysis of the lightweight AGM-130 weapon system. Twelve loop configurations were investigated.

Table 2: Autopilot Control Loops Used in Linear Analysis

pitch rate loop
pitch attitude loop
pitch acceleration loop
pitch rate loop with pitch attitude loop closed
pitch rate loop with pitch acceleration loop closed
altitude hold loop
yaw rate loop
yaw attitude loop
yaw acceleration loop
yaw rate loop with yaw attitude loop closed
yaw rate loop with yaw acceleration loop closed
roll rate and attitude loop

The design objective was to retain the stability margins (both gain and phase) of the existing heavyweight weapon for as many flight conditions as could be reasonably tested during the allotted time for analysis. The specific objective was to retain at least 6 dB of gain margin and a minimum of 30° phase margin.

Each of the twelve loop structures in Table 2 was evaluated at the sixty-four flight conditions given in Table 1. In addition, three values for dynamic pressure estimates (corresponding to 50% of the actual value, the actual value, and 175% of the actual value) were used in the control loop gains that are functions of dynamic pressure. The high and low estimates were constrained to the same limits as those found in the AGM-130 autopilot.

The dynamic pressure estimator within the AGM-130 autopilot was developed for the heavyweight AGM-130. It is based on integrated axial acceleration sensed by the weapon's Inertial Measurement Unit (IMU). It was assumed that the dynamic pressure estimation errors resulting from the decreased mass and inertias of the lightweight AGM-130, relative to the heavyweight AGM-130, combined with new profiles could be of such significance that system stability could be affected. This is the reason that low, actual, and high estimates for dynamic pressure were used in the linear analysis. If the stability margins were retained with low or high estimates, the existing dynamic pressure estimator could possibly be used. The combination of three dynamic pressure estimates, times twelve loop configurations, times sixty-four flight conditions resulted in 2,304 linear analysis conditions. A MATLAB script file was written to automate the data processing.

The linear analysis results indicated that a few of the 2,304 scenarios resulted in insufficient gain or phase margins. None resulted in an instability, but some were below the gain margin goal of 6 dB, primarily with the inner (pitch and yaw) rate loops. The high dynamic pressure and low altitude flight conditions, typical of those encountered during the terminal phase of an HTA trajectory, were the most critical conditions. Based on these results, numerical changes were made to the pitch and yaw rate loop compensation gains as described in the following section. In order to minimize modifications to the autopilot software, the changes were implemented for the entire flight, as opposed to a new gain scheduling process that would only be active during the terminal phase of an HTA profile.

The form of the compensation gain in the pitch rate loop in the heavyweight AGM-130 autopilot is:

$$\alpha k_{q_0}\left(1+\beta k_w\right) \qquad (1)$$

where: α and β are constants, k_{q_0} is a function of estimated dynamic pressure, $\hat{q}$, and k_w is an adaptive gain to account for the changing inertias as the motor burns.

In order to increase the gain margin of the flight conditions where the objective 6 dB was not achieved with the existing gains in the pitch and yaw rate loops, the leading coefficients of the rate loop compensation gains were decreased by the ratio of the pitch- and yaw-plane inertias (for both the full motor and ejected motor missile configurations) of the lightweight weapon compared to those of the heavyweight weapon. In other words, the leading coefficient, α, was multiplied by the average value for:

$$\frac{I_{yy;full\_motor,lightweight}}{I_{yy;full\_motor,heavyweight}} \quad \text{and} \quad \frac{I_{yy;no\_motor,lightweight}}{I_{yy;no\_motor,heavyweight}}$$

which was less than unity. The variable term in the rate loop compensation gains, β, was multiplied by the average values of:

$$\frac{I_{yy;full\_motor,lightweight}}{I_{yy;no\_motor,lightweight}} \quad \text{and} \quad \frac{I_{yy;full\_motor,heavyweight}}{I_{yy;no\_motor,heavyweight}}$$

which was greater than unity (the ratio of the no-motor configuration to the full-motor configuration is higher for the lightweight AGM-130).

Identified Gain Changes

Pitch and Yaw Rate Loops

The form of the compensation gain in the pitch rate loop in the heavyweight AGM-130 autopilot is:

$$\alpha k_{q_0}\left(1+\beta k_w\right) \qquad (2)$$

After the modifications, new values for α and β were determined such that there is now:

$$\alpha_{lw} k_{q_0}\left(1+\beta_{lw} k_w\right) \qquad (3)$$

A diagram of the adaptive gain scheduling for the pitch rate loop is given in Figure 3.

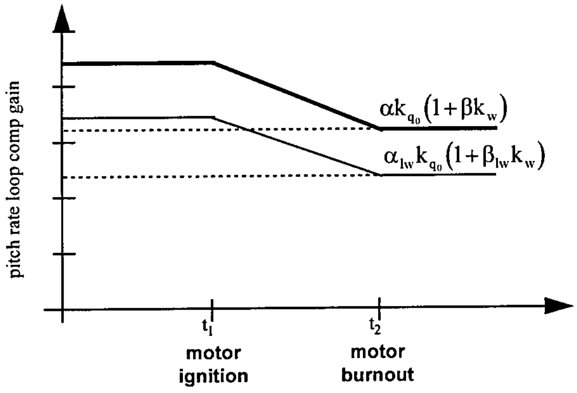

Figure 3: Pitch Rate Loop Adaptive Gain

The form of the compensation gain in the yaw rate loop in the heavyweight AGM-130 autopilot is:

$$\alpha k_{q_0}\left(1+\beta\right) \qquad \text{if } t < t_{burnout} \qquad (4$$

$$\alpha k_{q_0} \qquad \text{if } t \geq t_{burnout}$$

After the modifications, it was implemented as:

$$\begin{array}{ll} \alpha_{lw} k_{q_0}\left(1+\beta_{lw}\right) & \text{if } t < t_{burnout} \\ \alpha_{lw} k_{q_0} & \text{if } t \geq t_{burnout} \end{array} \qquad (5$$

A diagram of the adaptive gain scheduling for the yaw rate loop is given in Figure 4.

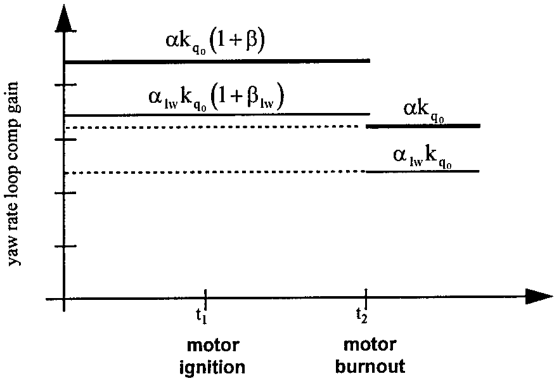

Figure 4: Yaw Rate Loop Adaptive Gain

Roll Loops

Initially, the gain changes to the pitch and yaw rate loops were made in the nonlinear simulation without making any changes to the roll loops. The gain changes, plus the necessary logic changes were coded and the system was tested. Preliminary results indicated that, for some flight conditions, the weapon would begin to oscillate about its longitudinal axis, then go unstable. The top of the climb, near the end of motor burn, at the higher altitudes was the critical flight condition. The existing dynamic pressure estimator (based on integrated axial acceleration) tended to significantly over-predict the dynamic pressure at this flight condition, often resulting in a value that would be limited to the maximum value. The higher the value for the dynamic pressure estimate, the lower the value for k_{q0}. This results in more gain margin at this flight condition in the *uncoupled* linear analysis, but the nonlinear, fully-coupled simulation revealed an instability at this flight condition.

Accordingly, in the interest of minimizing autopilot modifications for the demonstration flight vehicle, the roll rate loop compensation gain was actually *increased* to compensate for k_{q0} being too low because of the overestimate of dynamic pressure. It was believed that such a modification would be easier to implement than modifying the dynamic pressure estimator itself (which was the source of the problem). After a brief parametric study with DIMODS, the roll rate loop compensation gain was changed as follows. The form of the compensation gain in the roll rate loop in the heavyweight AGM-130 autopilot is:

$$\lambda k_{q_0}\left(1+\gamma k_w\right) \tag{6}$$

where λ and γ are constants. For the lightweight version, this becomes:

$$\lambda_{lw} k_{q_0}\left(1+\gamma_{lw} k_w\right) \tag{7}$$

It was later discovered during the Monte Carlo analyses that modification of the roll rate loop compensation gain alone was not enough to compensate for the inaccurate dynamic pressure estimate at this flight condition. The dynamic pressure estimator was also eventually modified.

Nonlinear Simulation

The autopilot software development process required modification of the nonlinear, 6-DOF simulation of the AGM-130 missile. The changes are described in the following sections.

Gain Changes

The gain changes identified through the linear analysis were implemented in the proper modules of DIMODS. Since the functional form of the rate loop compensation gains was not changed, only numerical values had to be modified.

Dynamic Pressure Estimator

As stated previously, the over-estimation of the dynamic pressure during the top of the climb portion of the trajectory resulted in a "roll unstable" flight condition during some of the Monte Carlo error analysis runs. Fixing the problem by increasing the roll rate loop compensation gain was not enough to prevent the instability in all Monte Carlo situations. Hence, the dynamic pressure estimator was modified to fix the source of the roll instability problem.

Data from the GPS/INS Navigation Processor (GNP) was used to increase the fidelity of the estimates of dynamic pressure. The structure of the q-estimator was preserved with the exception of the inclusion of the GNP data in the calculations. There were several parts of the dynamic pressure estimation sequence that were affected by these changes, both during the glide phase and the thrust phase.

The dynamic pressure estimation during glide and thrust phases was modified. The following sections provide descriptions of how the dynamic pressure estimation was implemented in the demonstration lightweight AGM-130 flight test vehicle.

During the glide phase, the altitude above ground is now used in the estimation. It was also necessary to update the velocity estimation during glide with GNP data. Gains that were previously constants are now functions of altitude. The portion of the dynamic pressure estimation dedicated to the rocket-motor-burning portion of the mission was also modified. GPS/INS data was used to improve the estimate.

Flight Profiles

In order to allow the AGM-130 to fly the new range extension profiles, several other modifications were made. The following sections describe the major modifications necessary to fly the new profiles.

Glide Slope

The heavyweight AGM-130 maintains control through a pitch leveling circuit during glide portions of flights. For the lightweight AGM-130, a shallower pitch angle is commanded to increase the glide distance. The pitch leveling circuit still functions to maintain weapon control during the glide portions of the flight.

Motor Events

For launches below a nominal cruise altitude, h*, the range extension profiles follow the same procedures as those of an HTA-type profile where the launch altitude is below the designated cruise altitude. After a brief safe separation period, the system will enter the altitude hold mode, ignite the motor, and climb to the cruise altitude. For launches above h* feet, the range extension profiles required a minor change to the logic that allows the weapon to descend to h* feet before ignition of the rocket motor. After launch, the missile will enter the glide mode, then descend to h* feet before entering the altitude hold mode and igniting the rocket motor for climb.

Rate of Climb

The maximum rate of climb for the AGM-130 heavyweight weapon is limited. In order for the lightweight weapon to climb significantly steeper, the maximum positive rate of climb was increased 55%.

Limiting the maximum rate of climb was chosen as the method to control the climb flight path angle during thrusting. An alternate approach, commanding the flight path angle during climb, was also investigated and implemented in DIMODS. This approach provided no benefits over the existing implementation and was not used in order to minimize autopilot modifications.

Cruise Altitude Determination

In the existing heavyweight AGM-130 weapon, the cruise altitude is input in the targeting screen in the F-15E cockpit. The cruise altitude for a range extension profile is calculated internally by the autopilot based on the height above ground at launch. An alternate approach, but not yet implemented, would be to calculate the cruise altitude based on height above ground *and* velocity at launch. This minor modification would make the system more robust to launches at lower velocities by commanding proportionately lower cruise altitudes and would take advantage of launches at higher Mach numbers by commanding proportionately higher cruise altitudes. The current implementation (as developed for the demonstration launch) determines the cruise altitude only as a function of altitude.

Logic

It was necessary to enable the lightweight AGM-130 to return to the glide mode after the rocket motor has terminated and been ejected. Since most of the missile's kinetic energy was used to gain potential energy (i.e., altitude), the missile can not hold a level cruise altitude for more than a few seconds after the rocket motor is ejected. In order to maintain controllability of the weapon, it was determined that the missile should enter the glide mode as soon the dynamic pressure reaches a minimum threshold for steady, controlled flight. There is a logical switch that must be true in order for the missile to enter the glide mode. The new logic for that switch in the lightweight AGM-130 autopilot will also allow the weapon to re-enter the glide mode after the motor burn. The formulation will allow the missile to return to pitch attitude control when all three of the following are true:

1. the missile has been under GNP altitude control,
2. the dynamic pressure estimate is less than a minimum threshold, and
3. the rocket motor has separated from the weapon

The logic does not interfere with the current implementation of the missile's terminal mode.

Summary

All of the lightweight modifications in DIMODS were coded with an initiation flag. If the flag is set to zero, no changes occur. If the flag is set to 1, then only the pitch, yaw, and roll rate loop compensation gains are changed (this option is intended to allow the lightweight weapon to fly any existing VTA or HTA mission). If the flag is 2, all modifications are active. The embedded software was coded similarly. For the demonstration flight vehicle, the flag was hard-coded to a 2. For a future tactical version of this weapon, it is envisioned that a new seeker menu item would allow the Weapon System Operator to select the proper option for the designated mission.

Upon completion of the implementation in DIMODS, the next step in the evolution of the autopilot software for the lightweight AGM-130 was the embedded software development and testing. The embedded software requirements were defined for the hardware autopilot and the changes were coded.

HWIL Testing

After the embedded software was coded, it was tested in the Functional Mock-Up (FMU) laboratory. This hardware autopilot version was downloaded into the emulator and tested. A TV seeker, a targeting screen, strip chart recorders, a real-time computer, and the three-axis-table were used for the hardware-in-the-loop (HWIL) testing.

Objectives

There were two major objectives of the HWIL testing for the lightweight AGM-130. The first was to verify that the functionality of all previously released versions of the autopilot was fully retained. The modifications made during the Midcourse Guidance (MCG) and Horizontal Target Acquisition (HTA) programs were left completely intact in the autopilot to retain the capabilities of the existing heavyweight AGM-130 weapon system. The second objective was to verify the functionality of the modifications made exclusively for the lightweight weapon.

Approach

Limited regression (i.e., confidence) testing of previous missions was conducted in the FMU. Five

(5) HTA missions and four (4) MCG missions were selected. These nine missions were chosen because they provided the opportunity to test several of the most important features of those programs (i.e., launching above the cruise altitude, launching below cruise altitude, use of the GNP, launching in the manual mode, use of heading changes and altitude decrements, high and low Mach number releases, high and low altitude releases, GNP auto terminal, math model seeker terminal, etc.). The range extension profiles were tested for the lightweight weapon only, but both VTA and HTA flight profiles were tested for heavyweight and lightweight weapons with the same version of the autopilot software.

HWIL Results

Five versions of software loads were required to get to the final version of the software that was launched in the demonstration flight vehicle. Two minor problems were encountered in the first two loads: a calculation for pitch attitude was coded incorrectly and one statement within the dynamic pressure estimator routine incorrectly used the altitude from the GNP. After 10 FMU runs, the first successful range extension profile for the lightweight AGM-130 was flown in the FMU. All subsequent runs were used for experimentation to determine the characteristics and robustness of the software interfaced with the hardware. The other loads incorporated changes desired as the demonstration objectives were determined (such as specific modifications for the data link and the zero fin preset for launch from the F-16).

Summary

A 3-DOF simulation was used to initially determine that range extension through trajectory shaping was possible for a lightweight version of the AGM-130. Before those trajectories could be implemented in the nonlinear, 6-DOF simulation, a linear stability analysis was performed with MATLAB and SIMULINK. The linear analysis indicated that gain changes would be necessary to preserve satisfactory stability margins for some flight conditions.

In order to minimize changes to autopilot software, the gain changes were implemented in the autopilot software for the lightweight AGM-130 for all missions and flight conditions, not just the critical flight conditions. To minimize modifications to the autopilot software, no new autopilot control loops were developed for the lightweight AGM-130. The trajectory shaping was implemented using the existing altitude hold loop. The autopilot now calculates the missile's cruise altitude based on release conditions and can climb at a steeper angle than is permitted with the heavyweight vehicle. After the rocket motor burnout, the lightweight weapon returns to pitch attitude loop control if flying a range extension profile, before entering the terminal mode.

The 6-DOF simulation of the range extension profiles was used to generate software requirements for the embedded software. After the embedded software was developed in JOVIAL, it was tested in the Functional Mock-Up Laboratory. More than 140 runs were completed in the FMU to establish confidence that the autopilot modifications did not inadvertently affect any of the capabilities of the existing heavyweight weapon and to test the new range extension modifications. After the final JOVIAL load was developed and tested in the emulator, it was loaded into the hardware autopilot, which was also tested in the FMU, and was later installed in the demonstration flight vehicle.

Flight Test Results

LTWT-01 (Mission number 6382) was launched on 11 Oct 1997 at 14:54:00Z (9:54:00 CDT) over test range B-70 at Eglin Air Force Base, Florida. The demonstration lightweight missile was launched at 476 KTAS, from an altitude of 13,350 ft.

Mission 6382 used four aircraft, plus a refueling tanker. An F-16 (#441) was the release aircraft. An F-15E (#188) was a test control aircraft. A second F-16 (#469) was the terminal control aircraft. A third F-16 (#188) was the chase (photography) aircraft.

The LTWT-01 weapon showed very benign transient motion during separation from the F-16. Upon release, the weapon rolled 1.5° lugs outboard, then recovered. The weapon yawed 0.5° nose outboard, then 0.5° nose inboard, then settled at 0°. The weapon pitched down slightly more than 3° during separation.

The propulsion interlock timer occurred 6.239 seconds after first motion, enabling roll leveling, rocket motor functions, and midcourse functions. Since the missile altitude was below the calculated cruise altitude, the missile began a climb to the desired GPS altitude. The flight path angle during the climb was approximately 15 - 17 degrees, or twice that of the heavyweight weapon.

After nominal motor ignition and burn-out events, motor separation was commanded. Coincident with this command, a failure of the fin actuation system (unrelated to the AGM-130 lightweight configuration autopilot software changes) caused fin 3 to deflect fully (trailing edge up), causing the weapon to roll and a loss of control.

With the exception of the actuator subsystem failure, the demonstration lightweight AGM-130 flight vehicle performed as intended. Based on post-flight data analysis, the modifications to the autopilot that allow the AGM-130 to fly range extension profiles were all fully functional.

References

1. Energy Management Approach for AGM-130 Range Extension, Rockwell Report C96-238, 31 October 1996.