Guidance and Control of a Cannon-Launched Guided Projectile

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A 155-mm cannon-launched guided projectile, called Copperhead, employing semiactive laser homing guidance, has been developed to improve artillery effectiveness against moving hard-point targets. Development of the Copperhead guidance and control configuration was motivated by the need for pinpoint accuracy and ruggedness sufficient to survive peak cannon-launch loads of 9000 *g*. Conceptual tradeoffs favored gravity-biased proportional navigation, implemented through use of a strapdown seeker with optically coupled gyro, aerodynamic tail control, and a roll position control. A unique application of a pitch/yaw gyro enabled the projectile to establish a vertical reference after launch. The configuration developed was demonstrated successfully in 8 out of 12 flight tests during its advanced development.

Introduction

THE role and capability of the U.S. Army's conventional artillery has been enhanced dramatically with the successful development of Copperhead, a cannon-launched guided projectile previously called CLGP, which employs semiactive laser homing guidance. The advanced development (AD) effort was initiated formally in February 1972 and completed in March 1975. At the conclusion of the AD program, the concept progressed to engineering development (ED). This paper addresses the design and implementation of the guidance and control (G&C) configuration for the AD Copperhead.

Conventional artillery has proven to be effective against stationary and/or area-type targets using indirect fire. Artillery fire can be adjusted readily to bear on stationary targets and to hit area targets where precise delivery is not required. However, moving targets severely aggravate the fire adjustment procedure, and hard-point targets, such as tanks, have small areas of vulnerability which require a direct hit to achieve a kill. Consequently, conventional artillery in the indirect fire mode has been relatively ineffective against these targets. With major emphasis on mobile armor in today's military community, conventional artillery must have increased kill capability against these targets.

Semiactive laser homing guidance was selected for Copperhead as the most feasible means of meeting this accuracy requirement. Related technology has been demonstrated successfully by the use of laser "smart bombs" in Vietnam. Laser ranging devices being developed for use by Army forward observers (FO) to locate targets accurately also would provide laser designation for Copperhead. The FO would use the laser ranger to establish the location of the target, estimate an engagement point, and then illuminate the target for detection by Copperhead. The Copperhead round, launched toward the estimated engagement point by supporting gun batteries located to the rear of the battle zone, then would detect and guide toward the laser energy reflected from the target. Warhead delivery accuracy then would be determined primarily by laser aiming capability.

Requirements

The two driving requirements for developing the Copperhead G&C configuration were accuracy and ruggedness. An accuracy requirement‡ was established which provided an acceptable probability of hitting a tank-type target. Given a target hit, the kill would be accomplished by a shaped-charge warhead. A representative target is the M48 tank, which is roughly 22×12×9 ft.

Ruggedness requirements were established by a 7200-*g* peak acceleration cannon-launch environment (Fig. 1) from an M109A1 155-mm self-propelled howitzer or an XM198 towed howitzer. A design requirement of 9000 *g* (axial load) was set to provide a 25% safety margin. Other major loads due to rotational accelerations, balloting, and set forward exit loads also occur during cannon launch, but the axial load proved to be the major design challenge.

Copperhead was required to develop all of its propelling energy from conventional artillery charges. This lack of an onboard propulsion system truly classified Copperhead as a projectile rather than a missile and offset the weight and cost penalties imposed by designing Copperhead to survive the cannon-launch environment.

Using muzzle velocities obtainable with conventional charges, Copperhead was required to engage moving and stationary targets at ranges between 4 and 16 km under clear weather conditions in the AD program. This was similar to the coverage envelope of conventional U.S. Army 155-mm projectiles, such as the M107 HE, in an indirect mode of fire. Physical constraints for Copperhead were established by loading and handling considerations and howitzer launch momentum. This required that weight and length be limited to 150 lb and 54 in., respectively.

The signal processor and guidance loop were required to be compatible with U.S. Army-furnished laser designators. Wavelength, pulse repetition frequency, pointing or tracking accuracy, energy output, etc., are all classified; however, the bandwidth of the pointing jitter is under 1 Hz. The standard deviation of the laser incident point relative to the desired aimpoint was approximately 20% of the accuracy requirement (i.e., 1σ spot motion $\approx$0.20 CEP required). The laser characteristics are very important to the G&C design, since spot motion, which appears as target motion to Copperhead, is the dominant error source relative to accuracy.

Guidance and Control Concept Selection

With the basic requirements established, development of a G&C configuration for Copperhead required selection from alternative design approaches in three key areas: guidance law, control mode, and seeker type. The laser smart bombs

Presented at the AIAA Guidance and Control Conference, San Diego, Calif., Aug. 16–18, 1976; submitted Sept. 1, 1976; revision received Jan. 13, 1977.

Index categories: LV/M Dynamics and Control; Missile Systems.

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‡Accuracy and many other specific Copperhead and laser characteristics are classified.

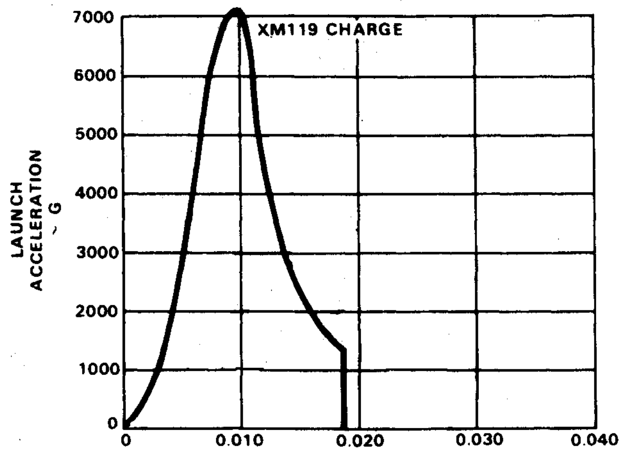


Fig. 1 Maximum launch load.

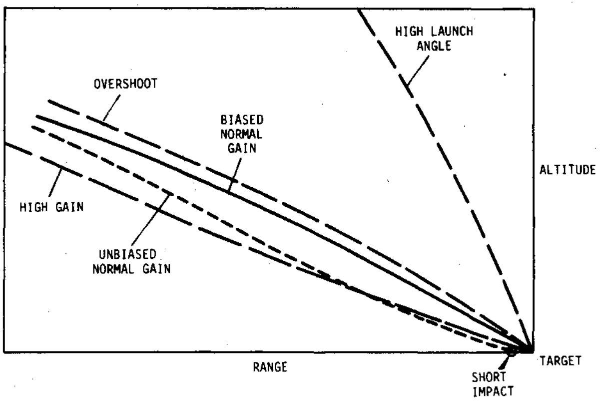


Fig. 2 PNG trajectories.

employed in Vietnam were used predominantly against stationary area targets. The guidance law used was a type of pursuit which was low in cost and effective. These weapons were able to provide a tremendous improvement in delivery accuracy relative to gravity bombs. For moving hard-point targets, however, achievable accuracy with pursuit guidance was unacceptable.

Proportional navigation guidance (PNG) is insensitive to biases such as target motion which produce constant line-of-sight (LOS) rates, and has better accuracy potential than pursuit guidance. Consequently, PNG was selected for the Copperhead application. One characteristic of PNG was of special significance to Copperhead: trajectory sag due to gravity acting on the projectile. Trajectory sag is manifested by a gradual downward droop of the trajectory, followed by a large upward correction preceding impact. For aerial targets or large surface targets, trajectory sag is of little consequence. However, for surface targets with small areas of vulnerability, trajectory sag can cause the projectile to hit the ground prior to reaching the target (Fig. 2). Since the warhead would detonate on impact, with little or no damage to the target, Copperhead had to counter the effects of trajectory sag to function effectively.

Several techniques are available to reduce or prevent sag in PNG trajectories. Sag can be reduced by increasing speed, approach angle, target overshoot, gravity bias compensation, or navigation gain. A comparison of these various techniques is shown in Table 1. The conclusion reached from this comparison is that the gravity-biased PNG technique is the preferred approach, since full trajectory selection flexibility, acquisition capability, and accuracy potential are retained. However, a disadvantage is that a means for determining "up" is required, which increases G&C cost and complexity. The concept for determining up is presented below.

Control Configuration

The use of gravity bias compensation required determination of the "up" direction so that the compensation command could be applied in the proper direction. On other gravity-compensated systems, this was accomplished by establishing the up reference prior to launch and then maintaining this reference in flight through use of a roll position sensor. Gravity bias was directed upward by controlling roll attitude to a known orientation or by resolving the gravity bias signals to compensate for roll attitude changes. Both techniques require initial reference to the up direction, and this was one area in which the cannon-launch environment strongly interacted with the selection of a control concept. No feasible technique was found to maintain the up reference during cannon-launch with axial loads over 7000 g and roll rates at muzzle exit of 5 to 20 Hz. Therefore, an approach was needed to determine the up reference after launch. Obvious techniques, such as horizon or geopotential sensors, were too operationally restrictive; i.e., time of day, type of terrain, weather disturbances, etc., would degrade performance or inhibit usage. However, a technique for determining up after launch was developed exploiting the problem source itself, gravity.

Conventional free-flight projectiles fly a ballistic trajectory in which curvature is produced by gravity. The velocity vector is rotated earthward in a vertical plane, and the projectile follows this motion. As the body follows the velocity vector, the direction of movement can be sensed by a pitch/yaw free gyro. Therefore, the up direction can be determined after launch and prior to the initiation of guidance maneuvers (Fig. 3). This was the technique selected for implementation by Copperhead. A detailed discussion of this vertical determination technique is presented later in the paper.

After target acquisition and guidance initiation, projectile motion generally will not continue to be in a vertical plane, and some means of storing the vertical reference is required. This could be accomplished by resolving the gravity bias into

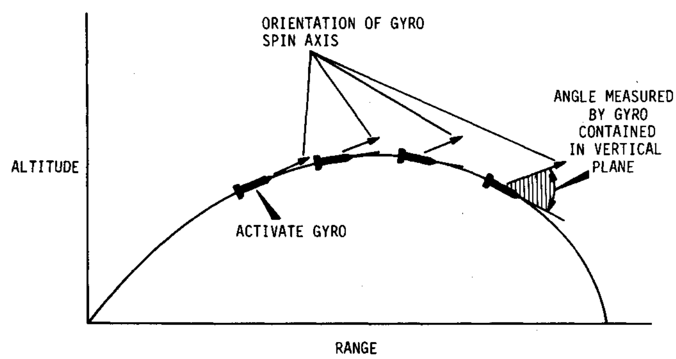


Fig. 3 Sensing vertical direction.

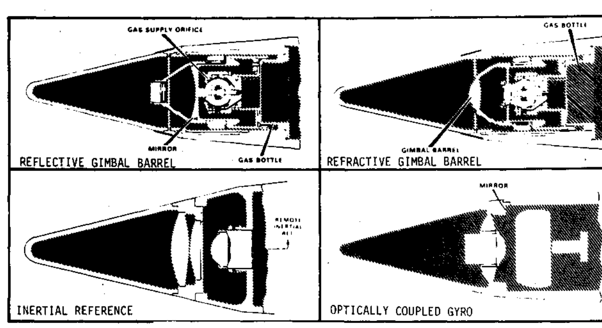


Fig. 4 Candidate Copperhead seeker concepts.

Table 1 Comparison of trajectory sag correction techniques

Techniques	Advantages	Disadvantages	Conclusion
1) Steep approach angles and/or high velocity	1) Adds no projectile complexity or cost	1) High velocity not possible at long range and implies shallow approach angle	Not compatible with operational usage
			2) Steep approach angles increase time of flight, dispersions, counter battery susceptibility, and imply low velocity
2) Increase navigation gain	1) Adds no projectile complexity or cost	1) Increases susceptibility to internal noise sources and laser spot motion	Too degrading to performance
		2) Degrades stability	
3) Overshoot target	1) Adds no projectile complexity or unit cost	1) Dispersions and target location uncertainty prevent necessary control of overshoot	Lacks reliability
		2) Limits guidance time, degrading accuracy	
4) Add compensation	1) Improves accuracy	1) Increases complexity and unit cost	Preferred approach
	2) Maintains acquisition capability		
	3) Permits full trajectory flexibility		
	4) Permits trajectory shaping		

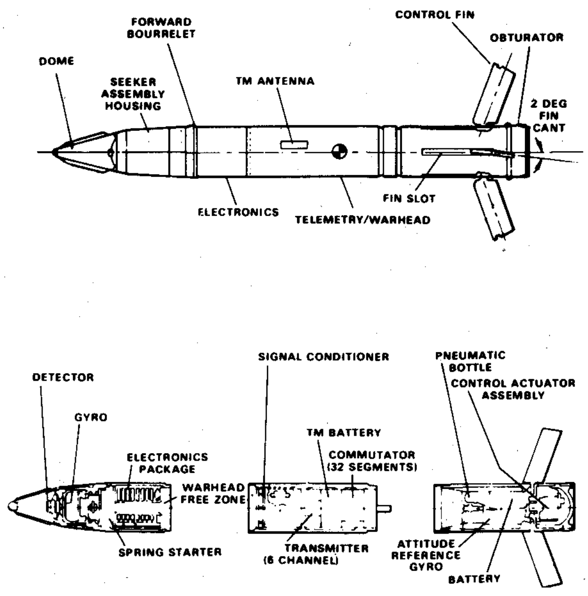
proper axes as the projectile continues free rolling or by controlling roll attitude so that gravity bias resolution is not required. Roll attitude control provides several significant benefits. It eliminates the risks of pitch/yaw/roll resonance, induced roll coupling problems, boresight error modulation, and pitch/yaw guidance cross coupling, which are associated with a free-rolling airframe. These effects tend to degrade stability and accuracy relative to a nonrolling airframe. The cost of implementing a roll control loop would be offset by the avoidance of gravity bias resolution, compensation for modulation and cross coupling, and/or the risk of performance degradation inherent in a rolling airframe. Consequently, the roll attitude control approach was selected based upon performance potential and low risk.

Aerodynamic control was selected for Copperhead application because reaction control systems were not considered to be competitive from a weight and risk standpoint. Tail control was selected over canard control to simplify roll control, minimize induced roll problems, and obtain the cost/weight benefits of using a single set of fins for both stabilization and control. In addition, tail control has the advantage of being located behind the warhead, avoiding a conflict between shaped charge warhead effectiveness and actuator design requirements. This conflict is produced by the need to provide a free volume forward of the warhead to allow the shaped charge penetration jet to form properly at warhead detonation. Therefore, tail control appeared superior to canard control for the Copperhead mission.

Seeker Concept

Four classes of seekers were considered (Fig. 4) for the task of detecting laser energy and providing LOS tracking data for the biased PNG scheme. The conventional seekers used in tactical missiles with optics and detector mounted on gimbals were considered too complex to harden in a low-cost, low-risk implementation. They also would need to be miniaturized to the point that the aperture would be inadequate for target detection.

Strapdown seekers proved to be an attractive optical alternative. Two basic classes were evaluated: strapdown seekers with remote inertial reference, and strapdown seekers with optically coupled gyros. Strapdown seekers with remote inertial reference need larger FOV optics to accommodate



	GUIDANCE	TELEMETRY	CONTROL	PROJECTILE TOTAL
LENGTH (IN)	21.44	16.23	18.03	54.3
WEIGHT (LB)	31.5	54.2	51.4	137.1
DIAMETER (IN)	6.00	5.96	6.00	6.0

Fig. 5 AD Copperhead configuration.

projectile body motion, thus aggravating noise, sensitivity, and optical linearity problems. The tolerance problems of isolating LOS motion from body motion were considered too great a risk for Copperhead.

For the strapdown seeker with optically coupled gyro, three ways to harden the inertial mirror were evaluated: gas bearings, fluid-floated mirror, and conventional gimbals with load transfer bearings. Although gas bearings were capable of being hardened, fabrication precision and cleanliness requirements and the complexity of deriving attitude data were considered excessive cost risks. A fluid-floated mirror was built and tested, but results indicated that it was not compatible with the tactical temperature and storage environments, and it also had the same attitude pickoff disadvantage of the gas-bearing gyro.

It was concluded that the lowest-risk, lowest-cost, and most reliable hardening approach was to use conventional gimbals with load transfer bearings and gimbal potentioneters for attitude data. This bearing is accompanied by rigid support of the gyro rotor during launch. Under cannon acceleration, the bearing deflects so that the load is transferred to the flanges of the races, thereby preventing Brinelling.

Hardware Description and Operation

The AD projectile components and subsystems were designed and cannon-qualified and then flown successfully in 8 out of 12 tests. The round consisted of three subsystems: a guidance subsystem that contained the laser seeker and guidance electronics; a telemetry subsystem that had dimensional and mass characteristics identical to the proposed Copperhead warhead; and a stabilization/control subsystem that incorporated cold-gas control actuators, a thermal battery, an attitude reference gyro (ARG), control fins, and an obturator (Fig. 5).

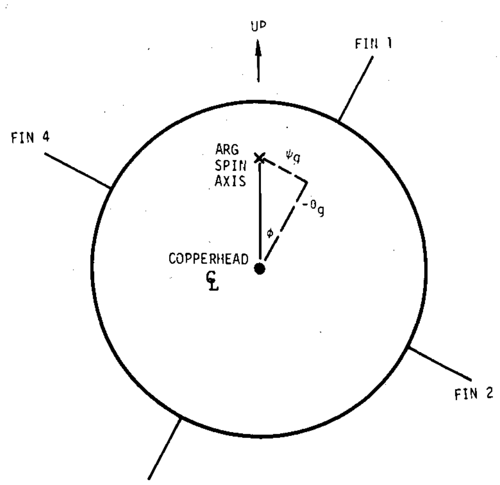


Fig. 6 Roll angle calculations using ARG.

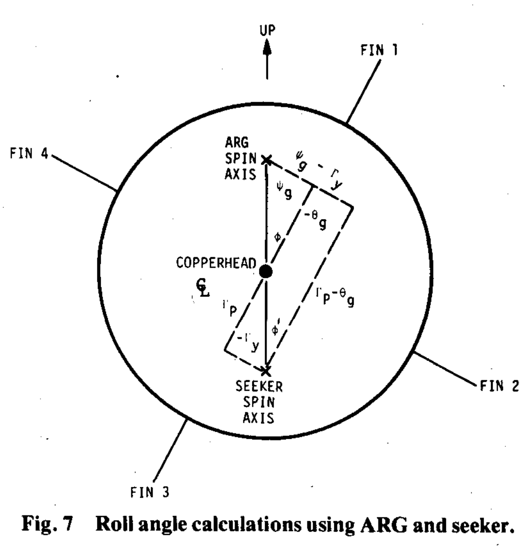


Fig. 7 Roll angle calculations using ARG and seeker.

Configuration

The projectile nose was a straked conical dome. Aft of the dome was a primary optical lens bonded to a detector assembly. The detector assembly contained other optics, a laser detector, and video preamps. The dome and primary lens attached to a coil assembly, which contained both torquing and spin-sustain coils for the seeker gyro. For launch survivability, a two-axis gimbaled gyro using load transfer bearings and a "gotcha" sleeve, which engaged the gyro rotor during launch, were housed inside the coil form assembly. These items carried the large loads incurred during cannon launch and protected the gimbal bearings from Brinnelling. The gyro rotor had a mirror surface to reflect laser energy onto the detector and incorporated a magnetic ring, which enabled the gyro to be precessed or spun when the torquing or spin coils were energized. Initial spinup for the seeker gyro was provided by a spring-starter.

The projectile electronics package consisted of eight individually potted printed circuit cards plugged into a motherboard assembly. The launch loads induced on the seeker gyro section and the electronics package were carried by a steel housing that mechanically interfaced with the telemetry or warhead subsystem. The electronics housing also incorporated a forward bourrelet, which acted as a bore rider during travel down the gun tube.

The telemetry structure was also steel and contained cutouts for a telemetry antenna and system test connectors. An external channel housed a wire harness for electrical interface with the control subsystem. All monitored Copperhead data were transmitted via IRIG channel frequencies. This subsystem had a total measurement capability of 32 data items. The telemetry transmitter was powered by a self-contained rechargeable battery.

The control housing contained four slots, which enabled fin storage inside the section. Actuator electronics, ARG, thermal battery, and a cold-gas storage bottle for the controls were mounted on the control actuator package. An aft closure contained the aft bourrelet and projectile obturator.

Operation

The operational test sequence began with activation of the telemetry subsystem prior to the anticipated launch time. Copperhead then was rammed into the gun tube, the powder charge added, the breech closed, the gun tube traversed and elevated to proper firing coordinates, and the primer added. The weapon then was ready for the fire command.

During launch, the obturator shielded the forward portion of the projectile from the hot, high-pressure gun chamber gases. In addition, the obturator partially decoupled the projectile from the gun-rifling-induced roll during launch, maintaining the exit roll rate at 20 rev/sec or less. After muzzle exit, the centrifugal force produced by the projectile roll rate caused the stabilization and control fins to deploy. Each fin had a built-in roll cant of 2°, which maintained a clockwise projectile spin. The resulting spin rate of 6 to 18 rev/sec prevented roll resonance from occurring during flight and allowed liberal tolerances in vane fabrication. These fins provided aerodynamic stability during the ballistic portion of flight and control capability during guided flight.

The launch shock activated a thermal battery, which powered a flight sequencer. The flight sequencer acted to delay full activation of the projectile until the target was within its acquisition and guidance envelope and to active components sequentially within the projectile. Sequential activation of projectile components began after the selected initial delay time had elapsed.

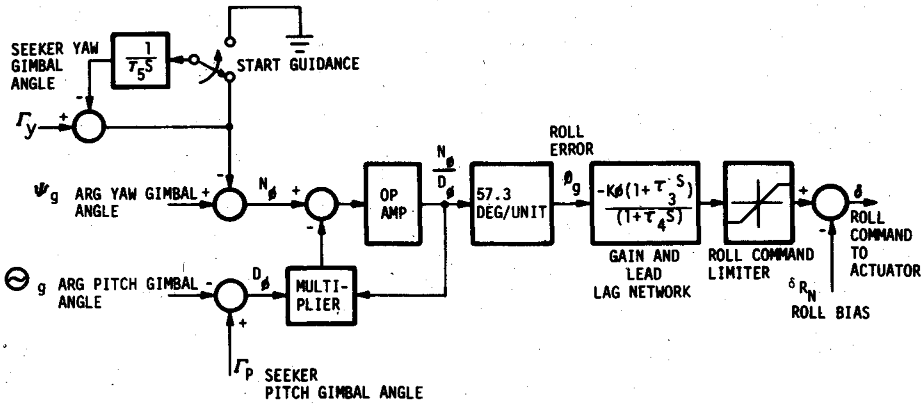


Fig. 8 Roll autopilot.

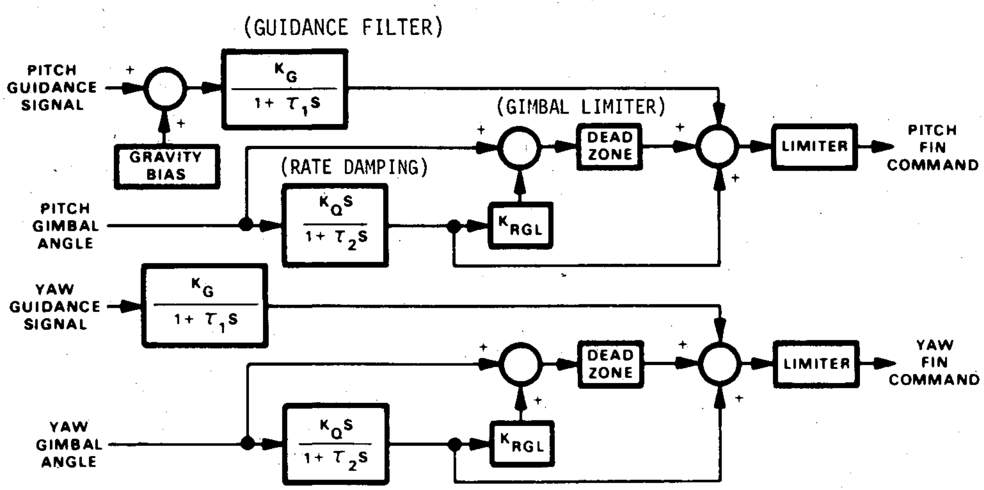


Fig. 9 Guidance autopilot.

The ARG was spun up by a spring-wound starter. The spin axis of the ARG was aligned initially with the projectile centerline. The flight sequencer waited several seconds after ARG activation to allow for development of an adequate vertical plane gimbal angle and then spun up the seeker gyro and activated the control actuators. The gimbal output signals from both gyros (seeker and ARG) were coupled to the roll autopilot, which computed roll fin commands. When the ARG yaw gimbal output was nulled, the projectile was no longer rolling and was oriented so that the projectile pitch plane was aligned with the trajectory vertical plane.

The seeker gyro, after activation, was torqued electrically to follow the body centerline. The gyro was maintained in this mode until target acquisition was achieved. The laser energy, reflected by the target, was sensed by the laser seeker mounted in the forward end of the missile. The seeker was an optically coupled system using body-fixed optics and detector and an electrically torqued seeker gyro that coupled to the optics by means of a mirror located on the gyro rotor. Laser energy entered through a conical dome and then passed through a primary lens onto the gyro mirror. The mirror reflected the energy through a secondary lens, which converged the energy on the laser detector. After target acquisition, tracking was begun and the gyro was torqued toward the incoming laser return. The guidance electronics computed torquing commands that were proportional to the angle between the LOS and the perpendicular to the gyro mirror surface. After the seeker was aligned with the target, guidance was initiated by coupling pitch and yaw commands to the actuators. The autopilot used derivatives of the seeker gyro gimbal signals to enhance body damping, and those commands were summed with guidance commands during guided flight. Gravity bias was added to the pitch guidance command to compensate for trajectory sag.

Vertical Reference and Roll Control Technique

A vertical reference for measurement of projectile roll angle was established by use of a two-axis, pitch-yaw ARG. The ARG had its spin axis initially aligned along the centerline of the projectile. The gyro was activated at a preselected point on the trajectory prior to reaching the anticipated target-acquisition point. As gravity caused the trajectory and projectile to pitch over, an angle developed between the spin axis of the gyro and the centerline of the projectile (Fig. 3). The angle developed was confined to the vertical plane of the trajectory. This angle, between the ARG spin axis and the projectile centerline, was sensed electrically by potentiometers mounted on each gimbal axis of the ARG.

The Copperhead airframe was rolled deliberately during ballistic flight at two to four times the pitch/yaw natural frequency of the body to prevent pitch/yaw/roll resonance coupling and to reduce free-flight trajectory dispersions. The roll rate was stopped by generating a roll vane command tending to null the yaw gimbal output of the ARG. This technique forced the projectile to stop rolling at an orientation having zero yaw gimbal output, which, in turn, meant that the vertical plane angle between the ARG spin axis and projectile centerline was sensed solely by the pitch gimbal potentiometer. With establishment of the proper signal polarities by the roll autopilot, the designated projectile pitch-up direction was aligned with the earth-up direction. With this known projectile orientation established, a fixed-gravity bias signal was added to the pitch guidance command.

The principle of the roll loop operation is illustrated further by Fig. 6, which depicts the output of the ARG in a vectorial representation at some instant of time. Note that roll error (ϕ) using Napier's formula for a right spherical triangle can be expressed as

$$\phi = \tan^{-1}(\tan\psi g/\sin\theta g) \quad (1)$$

Making small angle approximations for ϕ, ψg, and θg, the roll error (ϕ) can be approximated as

$$\phi \approx -(\psi g/\theta g) \quad (2)$$

Also, any projectile yawing motion would produce a ψg and hence an indicated roll position error. This undesirable condition was corrected by using the seeker gyro to decouple body yawing motion from the roll loop (Fig. 7).

Since body yaw motions were sensed equally by the ARG and seeker gimbal pickoffs, body yaw motion was decoupled from the roll calculation simply by using the difference of the two gimbal angle signals. To maintain the proper gain, the pitch difference also was employed, yielding

$$\phi \approx \phi' = -(\psi g - \Gamma y)/(\theta g - \Gamma p) \quad (3)$$

The roll angle calculation defined by Eq. (3) had one problem in that yaw motion of the seeker also would produce apparent roll error. The only significant yaw motion of the seeker was found to be the relatively slow initial alignment with the LOS. Decoupling of this motion was accomplished by high-pass filtering the yaw seeker gimbal angle input to the roll calculation until the start of guidance.

The high-pass filter circuit, which decoupled seeker yaw motion prior to the start of guidance, also was used to store the yaw gimbal angle present at guidance initiation. Roll calculations were referenced to yaw variations about this angle for the duration of flight, thereby preventing a vertical reference shift at the start of guidance.

The roll angle calculation defined by Eq. (3) has two stable null conditions lying 180° apart. This ambiguity was resolved through the implementation of the roll angle calculation. The division operation was performed by an operational amplifier (op amp) and multiplier (Fig. 8). If the body was upside down from the desired orientation, the polarity of the gimbal angles produced positive feedback to the op amp, thus driving it to saturation. The net result was that any time the roll error exceeded 90° a maximum roll command would drive it toward the desired zero error.

The roll position loop was stabilized using a first-order lead-lag network. A roll command bias was added to neutralize the mechanical roll vane bias and permit symmetrical roll control capability. Roll commands were coupled to the two yaw control fins only. This approach enables the pitch fins to use a common actuator, thus reducing actuator cost.

The resulting roll loop consistently demonstrated the ability to establish roll control within 1 sec of activation at initial roll rates up to 10 rev/sec. Simulation and tests indicated that roll errors at impact due to gyro drifts, projectile out-of-plane maneuvers, and noise were generally under 30°. Roll error was an important consideration, since it resulted in the gravity

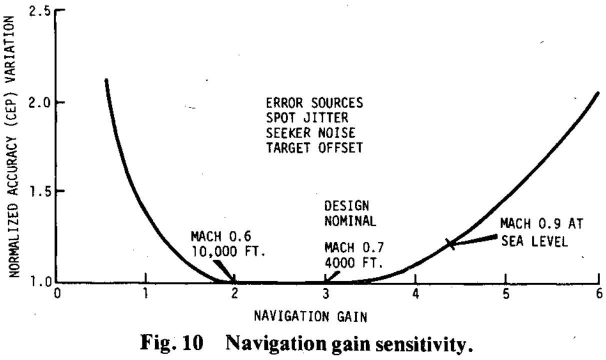


Fig. 10 Navigation gain sensitivity.

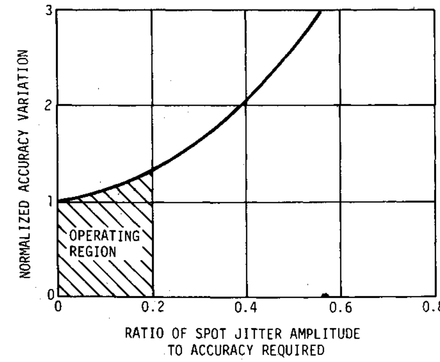


Fig. 11 Spot jitter sensitivity.

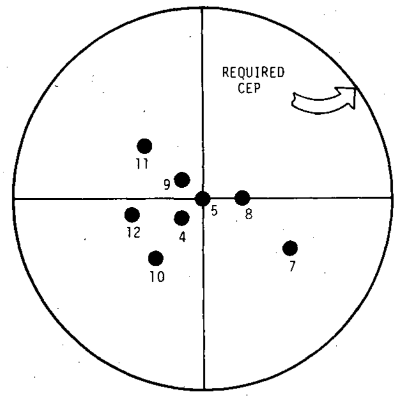


Fig. 12 Copperhead G&C performance during advanced development.

bias compensation being misdirected. The preceding roll loop performance proved more than adequate to meet roll control requirements during the AD flight demonstration program.

Guidance Loop Design

Proportional navigation guidance was implemented in Copperhead using the seeker track mode torque commands to measure the LOS angular rate (Fig. 9). As the seeker gyro was driven to track the target, the torque commands were proportional to the gyro precession rate, which approximated the LOS angular rate. Steering commands then were proportional to the torque commands. Gravity bias compensation to correct for trajectory sag was added directly to the steering command in the pitch channel.

A first-order lag filter was used to attenuate disturbances due to seeker noise and laser spot motion (jitter). Seeker noise results from background noise and optical/mechanical irregularities in the seeker gyro/mirror. Spot jitter is spatial motion of the target spot resulting from designator tracking errors and beam direction fluctuations.

Most projectile and missile airframes exhibit aerodynamic damping ratios that are generally under 0.10. For Copperhead, the damping ratio was approximately 0.03 during the guided portion of the flight regime. To provide adequate airframe response and still limit the magnitude of overshoot, a first-order rate damping loop was incorporated which increased the effective damping ratio to about 0.7. Body rate was approximated by differentiating the output signal of the seeker pitch and yaw gimbal potentiometers and then smoothing with a first-order filter.

A dead-zone circuit called a "gimbal limiter" enabled Copperhead to use its maneuver capabilities fully and fly at large angles of attack without exceeding the mechanical gimbal limits of the seeker gyro. As long as the seeker gyro gimbal angle did not exceed 40% of its maximum range, the limiter was inactive. When the gimbal angle exceeded this

Table 2 Copperhead performance against M48 tank

MGP no.	Test date	Range, m	Target speed, mph	g force	Comment
4	8/9/74	7712	0	3218	First success
5	9/4/74	7712	10	3178	First moving target hit
7	11/4/74	12,164	0	7185	Maximum g
8	12/13/74	4000	0	1639	Minimum range
9	1/27/75	4000	20	1588	Maximum speed target
10	4/3/76	16,000	0	7185	Maximum range
11	10/3/75	7712	0	3296	RPV designator
12	2/26/76	7712	8	—	Helicopter designator night shot

break point, a vane command was computed proportional to the gimbal angle excess which acted to reduce body attitude and keep the seeker gyro from hitting its gimbal stops and tumbling. The rate damping loop also was coupled to the gimbal limiter to improve stability.

When all guidance commands were combined, the pitch command consisted of LOS error, gravity bias compensation, rate damping, and gimbal limiter components. The yaw command was similar in makeup, with the exception of the gravity bias compensation. Roll commands were added to yaw commands within the control actuator electronics.

To implement the guidance and roll commands from the autopilot, a cold-gas control actuation system was used. The actuators used a carrier frequency to time-dwell-modulate solenoid valves, which then operated a differential area piston. Vane position feedback was used to adjust the time-dwell-modulation duty cycle to produce the desired vane response. The actuators were similar to those used on TOW and HOBO.

During the AD demonstration, it was necessary to fly trajectories at 4-, 8-, 12-, and 16-km ranges. Although these tests spanned a significant range of launch conditions (muzzle velocity and quadrant elevation), the flight conditions (Mach number and dynamic pressure) were sufficiently limited not to require any gain variations in roll or guidance loop except for gravity bias. Gravity bias was varied as a function of range and preselected prior to flight.

Guidance gain was established to provide a near-optimum navigation ratio throughout the flight regime (Fig. 10). With gravity bias, the gain could be kept low enough to prevent oversensitivity to spot jitter and seeker noise. Of these two major error sources, spot jitter had the larger impact on accuracy. However, within the anticipated range of designator performance, accuracy for the developed design was not degraded seriously (Fig. 11). Spot-jitter amplitude is directly proportional to target range from the designator and also is affected by target motion. Hence the biased PNG guidance autopilot offered consistent performance over the anticipated flight-test conditions.

Results

A total of 12 AD rounds were tested to: 1) evaluate and substantiate the survivability of the projectile in the cannon-launch environment, and 2) test the performance capabilities of the guidance and control configuration. Eight of the last nine rounds proved successful by surviving the cannon-launch environment, establishing roll control, acquiring the target, and homing in to achieve a *direct hit* against laser-designated tanks. Of the four rounds that failed, one was a no-test, two were cannon-induced failures, and one was an autopilot-produced failure. Each failure was prevented from recurring by appropriate design modifications. Performance of the guidance and control loop was outstanding. *Every* round that did not experience a failure prior to the start of guidance was able to achieve a direct hit on the target. Accuracy of Copperhead proved to be far superior to the basic Army requirement, as illustrated in Fig. 12 and summarized in Table 2.

Stationary and/or moving tank targets were engaged successfully at required minimum to maximum ranges; three different types of laser designation (ground-located, remotely piloted vehicle, and helicopter-mounted) were shown to be compatible with the Copperhead mission; and survivability was demonstrated at minimum to maximum launch accelerations. Thus, all of the basic requirements of accuracy, ruggedness, laser designator compatibility, and range capability were met during the development effort.