Dual-Mode, Reaction-Jet, Thrust-Vector Controls for Small Missiles

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This paper presents a systematic design of an all-fluidic inertial bang-bang system that operates a dual-mode, reaction-jet, thrust-vector controller for small tactical missiles. By rolling the airframe, a single-axis rate sensor, mounted along the missile axis and coplanar with a two-dimensional bang-bang controller, can provide sufficient authority to maintain line-of-sight trajectories up to 2 km with accuracies of about 1 mil (± 1 m at 1 km). One of the principal applications envisioned for such a missile would be a light, man-portable, shoulder-fired antitank weapon where range estimation for stationary targets would not be required.

Introduction

THE successful hot gas firing demonstration of a fluidic thrust-vector control (TVC) for the medium antitank weapon, Tank Breaker,[1] by McDonnell Douglas in 1981 indicates that fluidically activated flight control functions are feasible. The successful demonstration of a three-axis, fluidic laminar jet angular rate sensor (LJARS), coupled to a vortex valve reaction jet controller by Garrett[2] in November 1982, shows that all-fluidic inertial control of a missile is feasible. This marriage of fluidic inertial guidance and fluidic actuation eliminates the need for interfaces (the weak link in most sophisticated systems) between mechanical gyros and the control means, and provides for a lightweight, reliable, rugged, and cost-effective system by reduction of parts count and complexity. Weight saved in the guidance and control system can be applied to a missile warhead, resulting in a more effective, lethal, but lower-cost missile system.

The rate control guidance system that addresses the problem of keeping a small missile on a flight trajectory that approximates a gunner's line of sight (LOS) is of some considerable interest, especially for man-launched, small missile systems because it eliminates the need to estimate range on stationary targets. In 1965, Grumman[3] showed that rate control of a horizontally launched small missile, compensated for crosswind effects and gravity droop, is feasible to about 1.5 mil of accuracy. In the McDonnell Douglas roll-stabilized Tank Breaker, for example, three single-axis, two-dimensional TVC nozzles correct missile attitude along the lofted trajectory flight path to a very high degree of accuracy. To minimize complexity and parts count in a LOS system, only one rate sensor and one TVC nozzle can be used. This is achieved by rolling the airframe. In this manner, an LJARS placed with the jet axis parallel to the missile axis will sample pitch and yaw rates continuously in each quadrant of roll rotation. By locating a two-dimensional TVC nozzle at the missile base, coplanar with the LJARS, sensed error rates are converted to side thrust commands to produce moments that develop rotations about the missile center of gravity (c.g.) in opposition to those sensed. An added benefit of rolling the airframe is to remove both thrust misalignments and rate sensor null offsets. A finless airframe will reduce cost and complexity further. The viability of finless airframes was demonstrated by Rockwell[4] in the Tank Breaker program.

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In any soft-launched, line-of-sight missile system, errors developed early in the flight tend to magnify as the missile flies downrange. This is particularly true of aerodynamically induced errors such as those due to crosswinds and errors due to gravity sag. A dual-mode fluidic control system, where the sensor subassembly provides a high-deflection, low-thrust reaction jet in the absence of the main rocket jet, will maintain a preset missile attitude during the soft-launch phase. On main motor firing, the same fluidic reaction jet control system deflects the main jet to achieve the desired TVC during the boosted portion of the flight. Figure 1 illustrates this concept.

In order to compensate for gravity droop, a slightly positive angle-of-attack attitude is maintained by the rate control system so that lift and average upward component of thrust is just sufficient to balance and cancel gravity forces. Because lift is proportional to velocity squared, it is small at low velocity and high at high velocity. For this reason, a propulsion system with a regressive thrust profile is chosen. Burn is required all the way to the target in order to get continuous TVC. Such a system theoretically can hold a missile to within ± 1 m of LOS over 2 km, as reported by this author[5] in a comprehensive 5-DOF simulation.

The material presented herein consists of the design of the fluidic control system, required to control a lightweight, man-portable, shoulder-fired missile used as an antiarmor weapon.

Control System Design

A five-degree-of-freedom aerodynamic simulation of the control system, where roll was fixed, was performed by this author and was reported in a more detailed report.[5] The

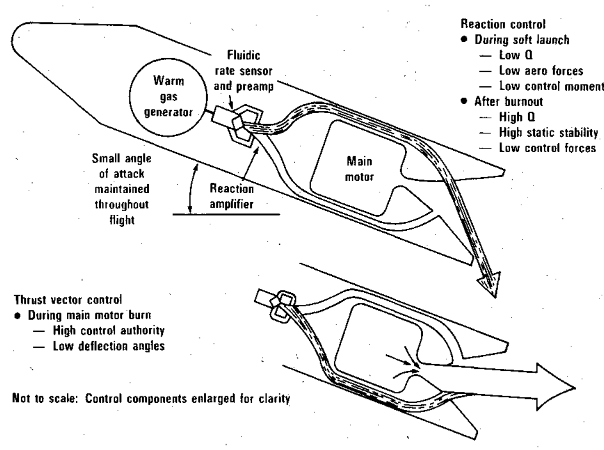

Fig. 1 Dual-mode, reaction-jet, TVC concept.

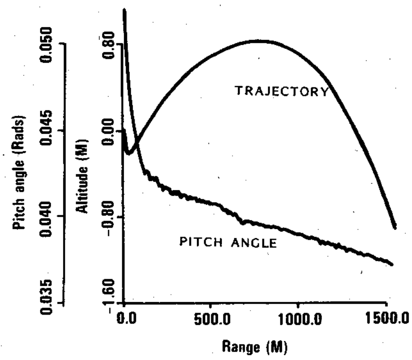

Fig. 2 Bang-bang control 5-DOF results.

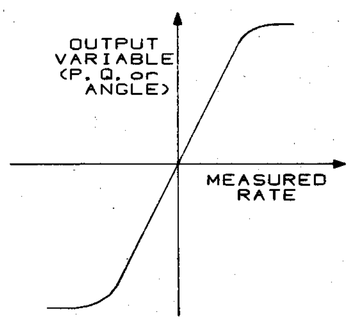

Fig. 3 Typical LJARS transfer characteristic.

significant results, however, were that a digital rate control system rolling at 20 rps with a switching threshold of 0.1 deg/s, operating in crosswinds up to 3 m/s, controlled the attitude of the missile sufficiently to keep it flying within 1 m of line of sight for well over 1 km downrange, over a range of ambient temperatures of from 0 to 40°C. Changes in propellant temperature affect the propulsive efficiency. Moreover, they require an adjustment of the initial angle of attack to compensate for this loss of efficiency.

For a case where the ambient temperature is 20°C, Fig. 2 shows the angle of attack α as a function of distance flown downrange. As can be seen, initially there is a change of α during the period when the pitch rate is less than the threshold of 0.1 deg/s. When α has decayed from 3 deg to about 2.3 deg and $\dot{\alpha}$ surpasses ± 0.1 deg/s the control system kicks in with opposing moments. Approximately each half-revolution the control system switches, the relative contributions of the pitch and yaw rates determining the duration of the dwell of the two-dimensional TVC. This corresponds to a pulse width modulation at about 20 Hz. From that point to well past 2 km, the control system keeps the decay of α to a low enough rate so that it does not fall below 2.1 deg—a variation of 0.2 deg over the entire range. The trajectory is shown in Fig. 2. One should note that the maximum excursion from LOS is less than 1 m.

The design of the fluidic controller therefore should address a system that can develop a saturated or fully switched bistable rocket exhaust at 20 Hz or more in response to signals equal to or greater than 0.1 deg/s.

Rate Sensor Considerations

Typical laminar jet angular rate sensor (LJARS) outputs are linear up to a moderately flat saturation,[6] as shown in Fig. 3. The output is normally a differential pressure, but since the eventual differential control signal is to linearly deflect a jet through some angle (TVC), the deflected TVC angle must be linear with measured angular rate in the same fashion. This TVC angle, Ψ, may be represented functionally by an exponential function:

$$\Psi = \Psi_{\max}[1 - \exp(-K|\omega_m|)]\mathrm{sgn}(\omega_m) \qquad (1)$$

where sgn is the signum function, $\Psi_{\max}$ the maximum TVC angle, and K a gain term that determines the slope through the origin. The angular rate measured by the rolling sensor is

$$\omega_m = \dot{\alpha}\sin\omega_R t + \dot{\beta}\sin(\omega_R t + \pi/2) \qquad (2)$$

where $\dot{\alpha}$ is the pitch rate and $\dot{\beta}$ the yaw rate. The LJARS has essentially flat amplitude dynamics to well past the 90-deg phase shift point so that the phase delay can be considered as a simple lag. From a dynamic standpoint, Eq. (1) in the Laplace domain becomes

$$\Psi(s) = \Psi_{\max}[1 - \exp(-K|\omega_m|)]\mathrm{sgn}(\omega_m)\exp(-\Upsilon_d s) \qquad (3)$$

where s is the Laplace operator, and Υ_d the LJARS lag time.

The pressure transfer function, or the relationship between output differential pressure and angular rate of an LJARS is independent of size for a preferred geometry and depends only on viscosity, and is given by

$$\frac{\mathrm{d}P_{RSB}}{\mathrm{d}\omega_m} = \frac{\mu N_R X_{sp}^2 (P_r/P_s)}{57.3 c_d} \qquad (4)$$

where

P_{RSB} = blocked output differential pressure, Pa
ω_m = measured angular rate, deg/s
X_{sp} = LJARS nozzle-to-output length in nozzle widths, b_s
P_r/P_s = blocked pressure recovery normalized by supply pressure, P_s
c_d = nozzle discharge coefficient
N_R = Reynolds number = $(b_s/\mu)(2P_s/\rho)^{1/2}$
ρ = density, kg/m^3

The rate sensor frequency response must be sufficiently wide to handle any disturbances transmitted to the airframe. This requires that the bandpass be much greater than that of the airframe. In addition, the phase shift (primarily a time delay due to jet transport lag within the fluidic circuit) should not interfere with the ability of the control system to react to disturbances encountered. In order to anticipate the time-delayed signals in the rolling airframe, the rate sensor is positioned in a plane at an angle to the TVC nozzle. This angle is determined by setting the delay time Υ_d equal to the time it takes the missile to roll through that angle, so that

$$\Theta_{\text{offset}} = \Upsilon_d \omega_R \qquad (5)$$

The time delay is primarily due to the LJARS, which is four-jet transport times.[6]

$$\Upsilon_d = 4X_{sp} b_s / c_d V_s$$

where V_s is the peak velocity at the LJARS nozzle exit as obtained from the Bernoulli equation

$$V_s = (2P_s/\rho)^{1/2}$$

so that the required offset angle is

$$\Theta_{\text{offset}} = 4X_{sp} b_s \omega_R / c_d V_s \qquad (6)$$

For a typical case where $\omega_R = 20$ rps, $b_s = 0.375$ mm, $X_{sp} = 20$, $c_d = 0.6$, $\rho = 1.2059$ kg/m^3, and $P_s = 7$ Torr, the offset angle is 9 deg. For this same device, the frequency at which amplitude rolls off is well past 1000 Hz, and the 90-deg phase shift point occurs at 208 Hz. The sensitivity in air of this device [Eq. (4)] is 2.625×10^{-4} Torr/(deg/s).

Gain-Block Considerations

The conceptual bang-bang control design utilizes two supersonic switches, one for primary jet control and one for the reaction jet control. It is of interest to determine the characteristics of such bistable switches.

Hot gas tests, conducted at China Lake by Chandler Evans,[7] indicate that the cold gas mass flow required to switch a main rocket motor jet, under specifically designed conditions, may range from 0.02 to 0.001 of the motor mass flow.

Several investigators have noted that the switch times of TVC devices are on the order of milliseconds.[1,7-9] A missile TVC device has switched at well over 100 Hz, as reported by Rockwell International,[8] where tests were limited by poppet valve response. This is not inconsistent with the notion that switching occurs at close to the speed with which the fluid flows through the device. For a 3-in. distance at $M=1$, the transport time, for N_2, is approximately 0.2 ms. Two switches occur in a cycle. Therefore, a fundamental limit would exist at about 2.5 kHz.

Consider now a generic fluidic gain-block that amplifies the pressure out of the rate sensor to a given high level and then converts this into a high flow signal to control the bistable switches. In order to reduce the number of serial stages of proportional amplification, a positive-feedback high-gain stage can be implemented. Figure 4 shows the circuit schematically.

The design of the proposed circuit proceeds in a straightforward manner by considering the required flows. If one assumes that the main rocket burns at a flow rate of approximately 0.5 kg/s (see Ref. 5) and a moderately low, conservative value for flow gain of 100, then the reaction amplifier/controller must provide 0.005 kg/s (as a minimum) into essentially ambient pressure. (The control ports are located just downstream of the ideal expansion point.) Similarly, the flow required to switch the reaction amplifier is 1/100th of that required to switch the TVC flow, or 5×10^{-5} kg/s. All flows from the rate sensor up to the reaction amplifier will be at essentially ambient conditions; hence, it is fair to look at just the volumetric conditions. Thus, the volumetric flow required to switch the reaction amplifier (using air) is 4×10^{-5} m^3/s, or 2.5 liters/min. Both primary and secondary actuation devices (the TVC nozzle and the reaction device) are turbulent devices delivering high output power at relatively low signal-to-noise ratio. In order that the signal not be deteriorated in processing, it is important that the processing be done at optimum signal-to-noise ratio. For this reason, the rest of the circuit is implemented with laminar integrated circuit components.[10]

The flow amplifier consists of multiple parallel elements of a standard laminar proportional amplifier (LPA). By choosing a device with $b_s = 0.5$ mm and an aspect ratio of unity, it is noted that a single element fully deflected delivers 0.3 liters/min at a rated supply pressure of 4 Torr.[10] In order to provide 2.5 liters/min, approximately nine parallel elements are required. The standard LPA, when operated at unity pressure gain, realizes a flow gain of 13.4 (pressure gain at no flow conditions is about 10), so that only 0.1865 liters/min is required to drive the flow amplifier. The input impedance of a nine-element flow amplifier, where $\sigma = 1$, $b_s = 0.5$ mm, $P_s = 4$ Torr, $Q_s = 0.3$ liters/min/element is 1.11 Torr/(liters/min), so that at the design control flow of 0.1865 liters/min, the impressed control pressure must be 0.21 Torr.

Consider now a gain-block that converts the rate sensor output to this required 0.21 Torr when 0.1 deg/s is sensed. This corresponds to an overall rate sensitivity into the flow amplifier load of 2.1 Torr/(deg/s), so that

$$\frac{\mathrm{d}P_L}{\mathrm{d}\omega} = 2.1 \text{ Torr/(deg/s)}$$

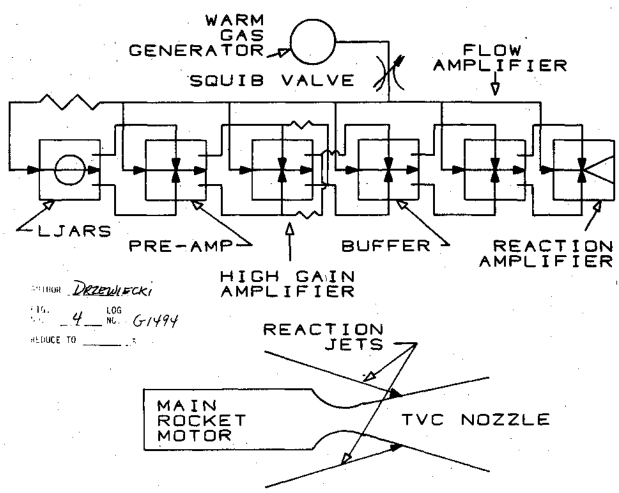

Fig. 4 Fluidic rocket controller schematic.

The sensitivity $\mathrm{d}P_L/\mathrm{d}\omega$ may be broken down into its component gain factors so that

$$\frac{\mathrm{d}P_L}{\mathrm{d}\omega} = \frac{\mathrm{d}P_{RSB}}{\mathrm{d}\omega}\,\frac{\mathrm{d}P_c}{\mathrm{d}P_{RSB}}\,\frac{\mathrm{d}P_{oB}}{\mathrm{d}P_c}\,\frac{\mathrm{d}P_L}{\mathrm{d}P_{oB}} \tag{7}$$

where

$\frac{\mathrm{d}P_{RSB}}{\mathrm{d}\omega}$ = blocked rate sensor sensitivity

$\frac{\mathrm{d}P_c}{\mathrm{d}P_{RSB}}$ = loading factor on rate sensor into gain-block

$\frac{\mathrm{d}P_{oB}}{\mathrm{d}P_c}$ = blocked gain-block gain

$\frac{\mathrm{d}P_L}{\mathrm{d}P_{oB}}$ = loading factor for gain-block into flow amplifier

The loading factors are defined as in a simple series resistance circuit between R_o, the output resistance of the device, and R_L the load resistance,[10] so that

$$\frac{\mathrm{d}P_c}{\mathrm{d}P_{RSB}} = \frac{R_c}{(R_c + R_{oRS})} \tag{8}$$

$$\frac{\mathrm{d}P_L}{\mathrm{d}P_{oB}} = \frac{R_q}{(R_q + R_o)} \tag{9}$$

where

R_c = gain-block input resistance
R_{oRS} = LJARS output resistance
R_q = flow amplifier input resistance
R_o = gain-block output resistance

For the rate sensor described previously, the output resistance is approximately 6.22 Torr/(liters/min); the blocked sensitivity is 2.625×10^{-4} Torr/(deg/s), and the flow amplifier input resistance is 1.11 Torr/(liters/min). What remains, therefore, is to choose representative gain-block input and output impedances. The output impedance should be low enough not to be a severe mismatch with the flow amplifier, and the input should be high enough not to load down the rate sensor.

By trying to stay with standard-size, integrated circuit LPA's, one can make some judicious choices for the gain-block.[10] An LPA with $b_s = 0.25$ mm and $\sigma = 1.0$ has an input impedance of 80 Torr/(liters/min). Fifteen parallel amplifiers of the same size have an output impedance of 3.56 Torr/(liters/min).

(Note that, while it is possible to make the output and input impedances virtually any value desired, if high gain is required, more stages will be required the lower the output-to-input impedance ratio is.) With the values chosen, the required blocked gain-block gain from Eq. (7) is 3.6×10^4. This is a relatively high value of gain, but is achievable with about six stages. Reference 10 gives a simple program for determining the appropriate topology. By using the first- and last-stage information above, a six-stage gain-block of the following makeup, using the nomenclature of Ref. 10, will give a gain of roughly 10^4.

Stage 1	51005(2)
Stage 2	[2]51005(2)
Stage 3	[4]51005(2)
Stage 4	[8]51005(2)
Stage 5	[12]51005(2)
Stage 6	[15]51005(2)

This gain-block is composed solely of $\sigma = 1$ (two laminations), $b_s = 0.25$ mm elements. The first stage has one element, the second 2, the third 4, the fourth 8, the fifth 12, and the sixth 15.

The LPA nomenclature is a five-digit descriptive number, preceded by the number of parallel elements in brackets and succeeded by the number of laminations per element in parentheses. The five-digit number itself describes the elemental laminations. The first digit describes the fabrication process—5 is photochemical etching, 6 is fine blanking, and 8 is wire EDM. The next two digits are the nozzle width in mils and the last two the lamination thickness also in mils.

In order to reduce the number of stages required and to increase gain, the gain of an amplifier stage can be increased by using positive feedback, without introduction of hysteresis. If the single-stage gain is high enough, only buffer stages will be needed. The dc, small-signal differential representation of an LPA with positive feedback, Fig. 5a, is essentially the H-network of resistors shown in Fig. 5b.

By summing the flows at the ΔP_o and ΔP_c nodes and noting that $\Delta P_B = G \Delta P_c$, and by doing the nontrivial elimination of ΔP_c, one obtains the transfer function between ΔP_o and ΔP_i as:

$$\Delta P_o / \Delta P_i = (G + R_o/R_f) / \left[(1 + R_i/R_d + R_i/R_f) \times (1 + R_o/R_L + R_o/R_f) - (G + R_o/R_f)(R_i/R_f) \right] \quad (10)$$

For certain values of R_f and R_i, the denominator may approach zero, whence the gain becomes infinite. (One may notice that lowering R_f increases feedback signal, but simultaneously loads down the LPA, thus reducing overall gain.) If one chooses to use the eight-element fourth stage for positive feedback with the 15-element stage as a load, the following values for resistances can be used to find a value for R_f for infinite gain:

$$R_o = 6.67 \text{ Torr/(liters/min)}$$

$$R_d = 10 \text{ Torr/(liters/min)}$$

$$R_i = 15 \text{ Torr/(liters/min)}$$

$$R_L = 6.67 \text{ Torr/(liters/min)}$$

With $G = 10$ (a nominal value for blocked gain), a feedback resistance of $R_f = 17.7$ Torr/(liters/min) will provide essentially digital operation without hysteresis. By backing off slightly [e.g., to 18 Torr/(liters/min)], the in-stage gain would be only 111.4, but over 20 times more than the stage it replaces. Since the gain depends only on ratios of laminar resistances, which will not change with temperature, then quite precise values can be maintained without loss of gain (provided G remains roughly constant).

If one now assumes that there will always be sufficient gain to eliminate three stages, then a three-stage device should be sufficient to drive the nine-element, double-size, flow amplifier. Figure 4, therefore, was a good representation of the total system implementation.

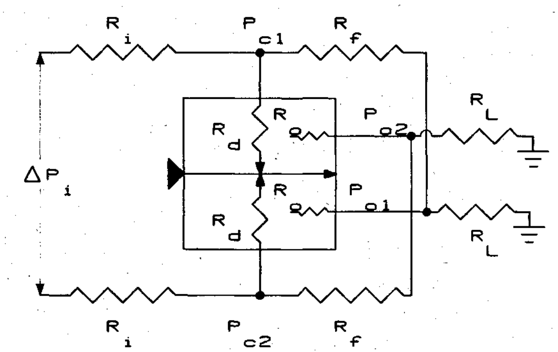

Fig. 5a Positive feedback around an LPA.

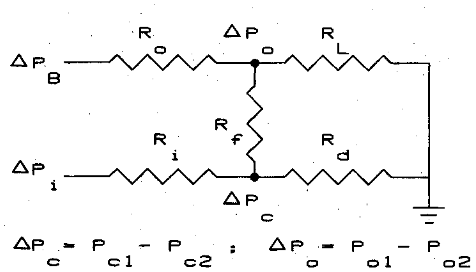

Fig. 5b Positive feedback resistor bridge equivalent circuit.

Implementation

The performance data shown in Fig. 2 corresponds to a missile that is 1 m long and 81 mm in diameter. These values may, of course, be changed at will. For example, the Grumman flight tests[3] were performed on 6-in.-diam, 136-in.-long airframes and showed similar 1 mil accuracy.

Spinup to 20 rps is achieved by canted soft-launch motors that are in-launcher tube burning.

Figure 6 shows a schematic of the man-portable missile system. The canted soft-launch nozzles are shown on either side of the TVC nozzle.

The fluidic circuit needs to be powered by some clean fluid source capable of providing sufficient flow for the reaction switch, the fluidic controller circuit, and the rate sensor. By summing all the flows and computing the total required mass

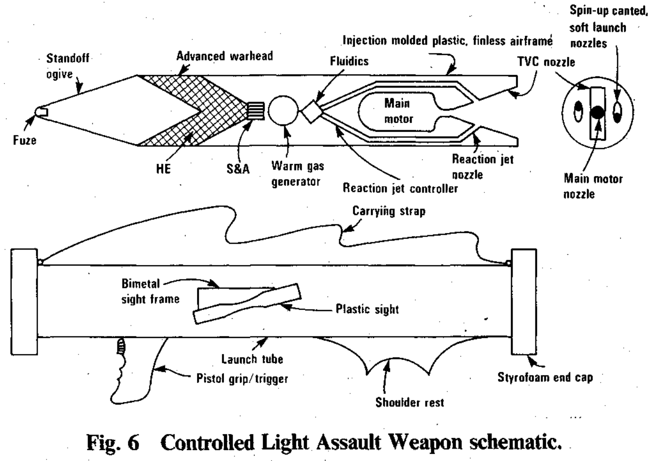

Fig. 6 Controlled Light Assault Weapon schematic.

for a 3-s time of flight it is found that 0.0156 kg of gas (air) is needed. For an 81-mm-diam missile, a 76.2-mm (3-in.) diam spherical bottle would need to be pressurized to about 10 MPa (1500 psi) to contain twice that much mass. This is a reasonable size and pressure.

Alternatively, a clean-burning, warm gas generator could be used, the advantage here being that no pressurized containers are necessary so that system shelf-life and reliability would be much greater for lack of leaks and high-pressure plumbing. Operation under such conditions has been demonstrated recently by Garrett[11] on a roll stabilization system, using vortex valve reaction jets and an LJARS.

A preliminary study of the manufacturing costs of such a missile, conducted by this author,[5] indicates that the cost of the entire missile, including warhead, airframe, inertial control system, and propulsion system can be comparable or even less than conventional light assault weapons.

Summary and Conclusions

This study has demonstrated the feasibility of developing a small, soft-launched, inertially guided, low-cost, line-of-sight missile. By inertially stabilizing the attitude with a single-axis fluidic rate sensor in a rolling airframe, with fluidic reaction jet and thrust-vector control, the missile flies within 1 m of line of sight. This eliminates the need to estimate range of stationary targets.

A state-of-the-art implementation of the fluidic controller has been developed using standard off-the-shelf integrated circuit components.

The concept of a low-cost, inertially stabilized missile is applicable to other missiles and rockets. Fluidically stabilized missiles may be platforms for low-cost, strapped-down staring seekers that improve accuracy by providing a terminal homing capability that guides them to a target. For example, an imaging IR focal plane array with a field of view of 2 deg, strapped down, can identify and home-in on targets at 2 km. These seekers, without gimbals or moving parts, would require only a single electrofluidic interface to control the system. By increasing the motor size longer ranges can be readily accommodated.

By using the basic airframe, an air-launched version that eliminates launch transients and downwash errors could be used as a highly accurate 2.75-in. rocket replacement. With modular changes to the warhead, area targets could be engaged, as well as low-performance aircraft targets. In this manner, costly homing missiles could be reserved to attack high value, point targets, and these less costly rockets could perform other precision missions.

One of the more interesting spinoff applications of this technology would be improvement of the accuracy of artillery rockets. Controlling a rocket accurately to a straight-line, upward trajectory, followed by a ballistic trajectory from a precise point some distance away from the launcher, would result in an apparent lengthening of the launch tube to, say, 500 m, and would eliminate launch transients from affecting the probable circular error, CEP. In light of recent, very successful Assault Breaker tests,[12] we know that terminally guided submunitions, that need to search only a limited area, are very potent. By delivering a rocket to a tight basket and thereupon dispensing munitions, lethality can be virtually assured, with low technical risk.

Acknowledgments

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