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High maneuverability projectile flight using low cost components

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ABSTRACT

This paper examines the problem of enhancing maneuverability of gun-launched munitions utilizing low cost technologies. Two ideas are proposed for reducing cost: (1) designing algorithms that reduce the sensor or actuator burden, and (2) performing high fidelity modeling and simulation of the entire system with realistic data input. The fundamental theory underpinning guided projectile flight systems, including nonlinear equations of motion for projectile flight, aerodynamic modeling, actuator dynamics, and measurement modeling, is outlined. Manipulation of these nonlinear models into linear system models enables airframe stability investigation and flight control design. A basic framework for low cost guidance, navigation, and control (GNC) of high maneuverability projectiles is formulated. Theory was implemented in simulation and exercised for a guided projectile system. Results support the hypothesis that algorithms can compensate for poor actuator performance and identified critical trade study parameters. Monte Carlo analysis indicated that the cost associated with measurements of a threshold accuracy rather than actuation technologies prescribes guided system performance.

1. Introduction

The acquisition opportunities for new weapons systems are increasingly limited due to budget restrictions. This environment requires a major shift in defense research toward low cost technologies. In the past, the typical research progression yielded new weapons often characterized as more complex and of higher cost. A more appropriate research emphasis is cost-effective technologies.

The focus of this study is performance improvement of guided projectiles using low cost components. Precision munitions have enjoyed some development in recent years. Feedback measurements from a laser designator have been used in guided projectiles [12,2]. GPS navigation has been utilized more recently for precision munitions [8,11,5,6]. These past efforts have all focused on indirect fire weapons mainly against stationary targets. The airframes either featured low inherent maneuverability or the nature of the feedback measurements did not permit intercepting moving targets.

This study extends past work in guided projectiles by investigating enhanced maneuverability for range extension, terminal trajectory shaping, or engaging movers. High maneuverability aircraft and missiles have been in existence for many years. Classical and modern control techniques have been applied with much success to the missile problem [1,15,14,19,20,9,18]. Cost often associated with the sensor and actuation systems; however, it is a detractor for application of aircraft and missile technology to the gun-launched environment. The land warfare community requires a high volume of available fires and the projectiles are of one-time use in contrast to manned and unmanned aircraft. Additionally, maneuver authority is often limited in the gun application due to stowing aerodynamic stabilizing and control surfaces for tube launch and reduced dynamic pressure for aerodynamic control due to the frequent absence of a rocket motor. Components must be hardened to survive the gun launch event. Finally, the performance of low cost guidance, navigation, and control (GNC) technologies (e.g., initial measurement time, measurement calibration, measurement update rates, actuator bandwidth, and processor throughput) is stressed in the dynamic ballistic environment (high Mach number, short time-of-flight, high spin rate).

In this study we propose to solve the low cost, high maneuverability projectile problem using two fundamental ideas. The first core theme is to develop algorithms which reduce the actuator or sensor burden. Cost drivers in aerospace systems are often the sensor or actuation system. We seek to understand how carefully constructed software can accommodate poor performing hardware for gun-launched munitions. The second thesis is that high fidelity multidisciplinary modeling must be developed to perform simulations which consider all aspects of the problem concurrently. Understanding the coupling between modeling of the actuator input,

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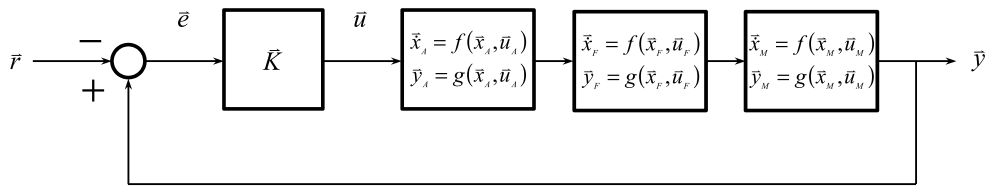

Fig. 1. Block diagram of nonlinear system dynamics with feedback control.

airframe response, and measurement output is critical to analyzing the cost-performance trades which define system requirements. Examining a portion of this problem in isolation as performed in past work does not yield cost driving technologies.

This paper is organized as follows. Nonlinear equations governing flight motion, actuator response, and measurements are derived. This paper describes these multidisciplinary nonlinear models in a comprehensive manner and formulates them for the present problem. Linearization and incorporation of flight, actuator, and measurement models into various system models which are critical to understanding guided flight behavior and underpins control design, are detailed. The overarching guidance and flight control strategy for low cost, enhanced maneuverability is sketched. The family of proportional guidance laws, which are based on the measurement models and enable interception of moving targets with minimal feedback measurements, is outlined. Flight control techniques are provided which utilize the system modeling and accommodate low cost actuation and measurement technologies. Characteristics of a high maneuverability airframe and low cost GNC system are given. Finally, linear flight control and nonlinear guidance and flight control simulation results demonstrate the implementation of the theory and efficacy of the GNC solution.

2. Theory

2.1. Problem formulation

The basic elements of a guided projectile are shown in the block diagram of Fig. 1. The nonlinear dynamics of the actuator, flight, and measurements are fed back and combined with a desired reference to yield an error. Control commands, formed by multiplying this error by a gain, influence the system dynamics to achieve the desired response.

High fidelity models of the actuator, flight, and measurements must be formulated and implemented in simulation to support the thesis of this work. These models are provided in subsequent sections.

2.2. Flight models

The flight model includes aerodynamics and flight dynamics. The reference frames and coordinate systems follow. The Earth coordinate system (subscript E) is used for the inertial frame and the body-fixed coordinate system (subscript B) is used for the body frame. These coordinate systems obey the right-hand rule and are related by the Euler angles for roll (ϕ), pitch (θ), and yaw (ψ) as shown in Fig. 2.

Applying trigonometry with the standard aerospace rotation sequence (Z–Y–X) yields the transformation matrix from quantities in body-fixed coordinates to Earth coordinates:

$$\vec{T}_{BE} = \begin{bmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi + s_\phi s_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{bmatrix} \tag{1}$$

Maneuvering projectile flight is often achieved through moveable aerodynamic surfaces. Fig. 3 shows four moveable surfaces

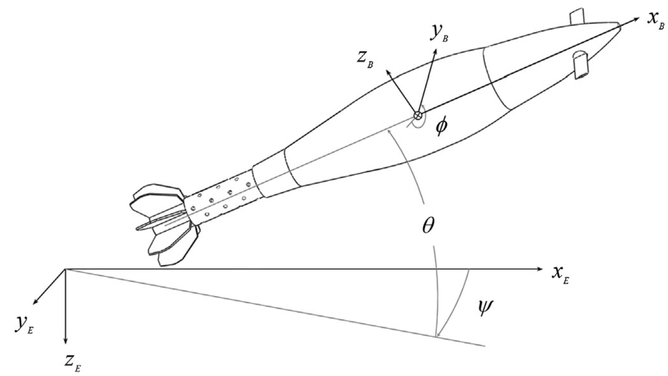

Fig. 2. Earth and body-fixed coordinate systems and Euler angles.

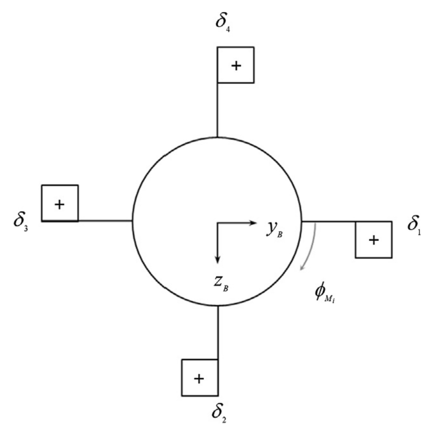

Fig. 3. Moveable aerodynamic surface numbering scheme and trailing edge deflection sign convention (viewed from projectile base).

equally distributed around the projectile; as well as the numbering scheme and sign convention associated with the trailing edge. The moveable aerodynamic surfaces are numbered starting with the surface with smallest roll angle and proceeding with increasing roll angle.

Individual moveable aerodynamic surfaces combine to yield effective roll, pitch, and yaw deflections. The drag deflections are not used in the maneuver scheme:

$$\delta_p = \frac{1}{4}(-\delta_1 - \delta_2 - \delta_3 - \delta_4)$$
$$\delta_q = \frac{1}{4}(\delta_1 - \delta_2 - \delta_3 + \delta_4)$$
$$\delta_r = \frac{1}{4}(\delta_1 + \delta_2 - \delta_3 - \delta_4)$$
$$\delta_d = \frac{1}{4}(\delta_1 - \delta_2 + \delta_3 - \delta_4) \tag{2}$$

Rigid body projectile flight states are center-of-gravity position $[\,x\ y\ z\,]^T$, attitude $[\,\phi\ \theta\ \psi\,]^T$, body translational velocity $[\,u\ v\ w\,]^T$, and body rotational velocity $[\,p\ q\ r\,]^T$. Kinematics provides the relationships between motion in the body and inertial