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On Guidance and Control for Guided Artillery Projectiles, Part 1: General Considerations

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Abstract

The problem of adding guidance, navigation and control capabiltities to spinning artillery projectiles is discussed from a fairly general perspective. Topics covered are the (limited) control authority of nose mounted control mechanisms and tradeoff conserning guidance and navigation. A brief review of relevant literature is also included and some topics for further study are suggested.
The focus of the present study is to pinpoint underlying mechanisms and properties of the problem of adding guidance and control capabilities to spinning artillery projectiles using replacement fuzes. The purpose of the study is to facilitate decision making regarding further studies of guidance methods for artillery projectiles with replacement fuzes incorporating guidance and control capabilities.

Keywords

course corrected projectile, artillery, fuze, guidance, control, navigation

Sammanfattning

Problemet med att tillföra styrning och navigeringsförmåga till snabbt roterande artilleriprojektiler diskuteras från ett allmänt perspektiv. Ämnen som behandlas är den begränsade styrförmågan som fås med nosmonterade styrdon och frågor om avvägning mellan styrning och navigering. En kort genomgång av den relevanta litteraturen på området är också inkluderad.
Fokus för studien är att identifiera underliggande mekanismer och egenskaper hos problemet med att utöka existerande spinnande artilleriprojektiler med bankorrigerande förmåga. Syftet är att möjliggöra beslut för utökade studier av metoder för styrning av artilleriprojektiler med bankorrigerande tändrör.

Nyckelord

trajektoriekorrigerad projektil, artilleri, tändrör, styrning, navigering

Contents

1 Introduction

Indirect fire refers to situations where the target cannot be seen visually by the aimer. In today's battlefield scenarios this corresponds mostly to the case where it is the range that limits the visibility of the target. Thus, modern land based indirect fire systems usually consist of various forms of field artillery, such as mortars, rockets and larger caliber artillery guns. We shall here only consider the latter, and in particular howitzers.

Howitzers are characterized by being able to fire at high elevations. This means that long range can be achieved for a given charge. To ensure stability of a (unguided) projectile throughout the flight, either fin or spin stabilization must be employed. Projectiles fired from howitzers are normally spin stabilized. The spin is induced by spiraling groves in the barrel which give the projectile a (high) spin rate about its main axis as it leaves the barrel. A well designed projectile will fly with a relatively small angle of attack and yaw angle throughout its flight. Hence (unguided) projectiles will follow an essentially ballistic flight path.

1.1 Long range indirect fire weapons

The most obvious advantage with extending the range of an indirect fire weapon is that friendly forces can be kept back until the fire has had the desired effect to incapacitate the enemy. Moreover, the extended range provides some increased safety for the personnel operating the gun. Another, sometimes overlooked, advantage with extending the range of indirect fire weapons is that it gives the commander greater flexibility in engaging targets without regrouping, hence giving him a "temporal advantage" that can be translated into being able to act quicker than the enemy can respond (Costello, 1997). However, extended range inevitably means greater dispersion, if unguided munitions are used. This results in larger number of rounds (and larger engagement times) before the fire (often a "rain of metal") has (statistically) had the desired effect.

1.2 Guided projectiles

The idea of adding guidance capabilities to conventional munitions is not new. Radio guided glide bombs were introduced by the Germans in World War II and laser-guided bombs have been used since the Vietnam war (Watts, 2007). The first mass produced guided artillery projectile was the M712 Copperhead introduced in 1972 (Watts, 2007). It was a fin stabilized, semi-active laser guided 155mm anti tank munition with a range exceeding 15km. Artillery projectiles using on-board navigation sensors are more recent. The most well-known example is perhaps the M982 Excalibur introduced in 2005 which is also a 155mm caliber round. The Excalibur has true precision guidance capabilities with a range independent circular error probable (CEP) radius of less than 10m in its latest variants (Eschel, 2011) (the maximum range is well over 20km). Both these projectiles are examples of designs that have been optimized for the task at hand, i.e. developed "from the ground up" and not based on an existing projectile or parts thereof. Since the kill radius of an ordinary 155mm fragmentation warhead is about 50m and since target location errors can also be significant (perhaps in the order of tens of meters) such an accurate and expensive projectile is often not needed however.

1.2.1 Modular concepts

An entirely different line of development is based on the idea of a course correcting fuze which achieves the goal of bringing down the dispersion errors significantly, while only incurring a modest extra cost.[1] A course correcting fuze is a replacement for the conventional tip mounted fuze where the replacement has various devices for navigation and control fitted, such as global positioning system (GPS) receiver and deployable drag brake, spin brake or canards. Course correcting fuzes are intended to be compatible with many existing projectiles that are kept in stock by various armed forces, so that existing ordnance can have guidance and control capabilities added in an affordable way.

An early example of this idea was proposed and studied by Regan and Smith (Regan & Smith, 1975) as a replacement for the fuze on the Mk 41 projectile, also of caliber 155mm. Their concept was based on a slowly rotating (free from the shell spin rate) canard equipped fuze for longitudinal and lateral control of the projectile's flight path. It can be regarded as a template for several later designs.

1.2.2 Sources of error

The main sources of error (dispersion) in (long range) howitzer applications are variations in wind, temperature and the variation of muzzle velocity (velocity of the projectile when it leaves the barrel) (Wennersten, 1994). Variations in projectile weight (relative to nominal, "stamped,"weight) can also be noticeable and have significant influence (Vikström, 2011). Downrange errors almost always dominate over the crossrange errors, and the region inside which 50% of the projectiles fall, centered around the nominal impact points, is most often modeled as an ellipse (with its major axis in the downrange direction). For example, a 1° error in the assumed sea level atmosphere temperature will yield a range error exceeding 50m at 25km target range and a 1m/s tailwind error will yield almost the same downrange error. Under the same conditions, an error of 1m/s in the muzzle velocity[2] will give about 25m downrange error (Wennersten, 1994). These errors are in the same order as the kill radius for a fragmentation type grenade (which is about 50m).

It should be noted, however, that the temperature and wind errors are distinctly different in character from the other errors since temperature and wind errors can never be removed by improving the performance of the gun or the projectile. The only way to remove the effects of these, often large, errors is to correct them in-flight by guidance. Therefore, there are good reasons to try to improve precision of conventional indirect fire weapons by introducing guidance and control capabilities to the projectiles.

1.2.3 Additional advantages with guidance

The number of rounds required to destroy a target with unguided rounds at ranges exceeding 20km can be in the order of 150 whereas with course correcting fuze ammunition it can be brought down to perhaps a handful,[3] given that the

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[1] The cost of a true precision guided projectile with a specially designed airframe is, in the case of Raytheon's Excalibur, currently in the range USD50000-100000 (Clark, 2010). This can be compared to the cost of less than USD10000 for a course correcting fuze such as Alliant Techsystems' PGK which can be put on an ordinary USD600 shell (Cox, 2010).

[2] If base bleed techniques for drag reduction, or rocket assisted flight is employed, this too adds to the downrange errors. However, we shell not consider these cases here.

[3] With true precision guided ammunition the number of rounds can often be kept at one, as current doctrine for Excalibur use dictates (Clark, 2010).

course correcting fuze brings down the CEP to about 50m (Cox, 2010; Clark, 2010). This reduction of number of rounds fired significantly reduces the risk of collateral damage and the burden on the logistics chain (Vikström, 2011).

1.2.4 Existing programs

A number of programs have been initiated to develop affordable precision indirect fire munitions. The prime concern for these concepts is cost-effectiveness. Instead of expensive *ab initio* developments like the Excalibur, the idea is to retrofit existing stockpile artillery projectiles with fuzes that include various guidance packages.

United Defense demonstrated in 2005 the Course Correcting Fuze (CCF), which included both drag brakes and spin brakes fixed to the airframe (no despinning) (Globalsecurity, a). The U.S. Army's XM1156 Precision Guidance Kit (PGK) program (Globalsecurity, b), with Alliant Techsystems (ATK) as prime contractor (Alliant Techsystems), explores two pairs of canards on a despun assembly.

Two European programs are the SPACIDO fuze (French Ministry of Defense, contractors: NEXTER and Junghans Microtech) and the European Correcting Fuze (ECF) (BAE Systems and Junghans Microtech). Both concepts include drag brakes only (with different implementations) (Junghans Microtech). The ECF program seems to be a successor to United Defense's CCF.

A projectile with a course correcting fuze is still spin-stabilized. As briefly discussed below, a *fin*-stabilized airframe presents somewhat different design options. Such a concept, with deployable fins at the projectile's base providing dynamic stability, is part of the Very Affordable Precision Projectile program (VAPP) run by the U.S. Army Research Laboratory (Fresconi *et al.*, 2010). This research oriented program investigates precision guidance from a broader perspective, but still with cost-effectiveness as a main requirement.

1.3 The problem studied

The focus of the present, somewhat brief, study is to pinpoint underlying mechanisms and properties of the problem of adding guidance and control capabilities to spinning artillery projectiles using replacement fuzes. In doing this we wish to highlight such properties that may favor one or the other form of guidance (and control), depending on available navigation sensors and actuation methods. Hopefully, this will facilitate decision making regarding further studies of guidance methods for artillery projectiles with replacement fuzes incorporating guidance and control capabilities. A secondary objective is to list some of the relevant works in the field.

2 Long Range Artillery Projectile Trajectories

In Figure 2.1 a typical long range[1] flight path of a 155mm artillery shell is shown. The flight path is often divided roughly into two parts, depending on if the altitude increases or decreases. The upleg is the first part which is terminated when the summit occurs and the downleg is the remaining part. Another way to divide the flight path into parts is to divide it depending on the most significant physical characteristics of the flight condition.

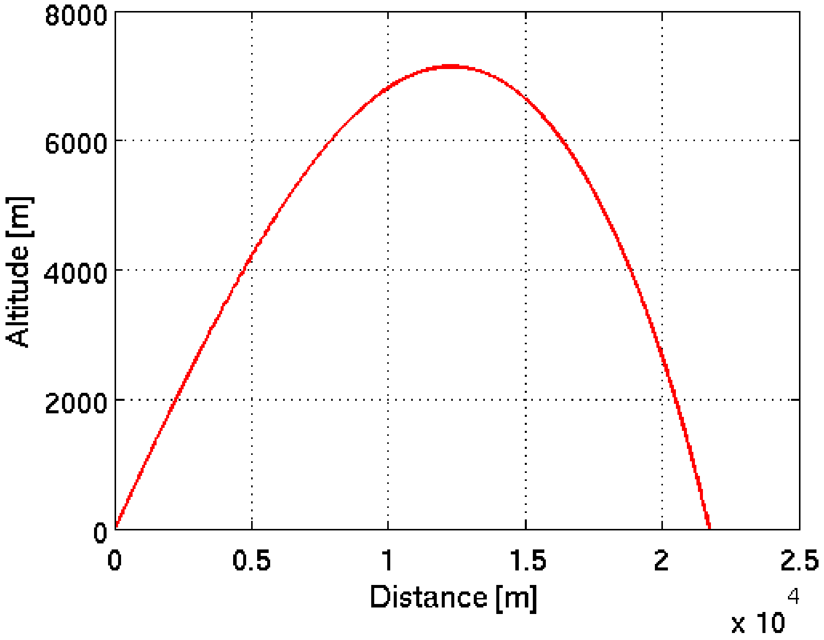

Figure 2.1: A typical maximal range flight path of a 155mm artillery projectile. The time of flight is 75s, the summit (altitude 7141m) is reached at 33.5s and the ground track length (downrange distance) is 21750m.

2.1 The supersonic phase

The muzzle velocity in the example in Fig. 2.1 is 835m/s (which is close to Mach 2.5 at sea level) and the projectile velocity is supersonic during the first third part of the flight. This part will be called the *supersonic phase*; after this the projectile travels at subsonic speed.[2]

During the supersonic phase the dynamic pressure is high and effectiveness of aerodynamic control surfaces is therefore significant. It is also the phase where small control inputs (forces, moments) will have large effects on the

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[1] We shall concentrate on flight paths that are close to maximal range, corresponding to gun elevations in the order of 45°, since these are the ones defining bounds on energy, stability and controllability.

[2] For shorter than maximal range flight paths the supersonic phase can extend all the way to impact but we don't consider such low elevation paths here.

impact point. On the other hand, since the majority of the flight path will be subsonic it is reasonable to optimize the control surfaces for subsonic operation and transonic aerodynamic effects can complicate operation of such surfaces near the end of the supersonic phase.

The supersonic phase is the part of the trajectory where the projectile is closest to the gun and where it is easiest to uplink data. Uplink data can include measurements of the actual muzzle velocity and radar measurements of the projectile position and velocity. It is also the part where any inertial navigation system (INS) can and should be initialized and where a GPS can start to acquire satellite data.

2.2 The summit phase

After the supersonic phase, when the projectile has gone through the transonic airspeed region, the change in airspeed (and hence axial acceleration) is no longer dramatic. This marks the start of the middle third part of the flight path which we shall call the *summit phase*. At the beginning of this phase the dynamic pressure and spin rate are still high which means that the projectile has both good efficiency of aerodynamic control surfaces and good gyroscopic stability. These conditions generally hold throughout the summit phase.

2.3 The terminal phase

The *terminal phase* is the last third of the flight path. During this phase the spin rate has decreased to a level where it must be taken into account in any calculation of available control authority.[3] Indeed, the available control authority is in general limited during this phase by the gyroscopic stability properties of the projectile (Lloyd & Brown, 1979). Furthermore, it is during this phase that the likelihood of encountering jamming is the greatest, if GPS is used for navigation.

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[3] We assume that the actuators mounted at the tip of the projectile, thus giving a moment around the center of mass when used.

3 Control of Spinning Artillery Projectiles

The guidance and control problem problem for spinning projectiles where the control actuators are confined to a tip (fuze) mounted assembly has some distinct features which sets it apart from other types of missile control. First, the projectile is not designed for control and the control actuators are not placed ideally with respect to the dynamics. This means that general dynamics synthesis (i.e. "replacing" the natural open loop dynamics with a desired closed loop dynamics) is in general not possible in this case[1] and only small changes in the projectile's natural dynamics can be expected to be achievable. In particular, most often the natural (gyroscopic) stability boundaries can not be changed and the stability properties may be degraded by the addition of control mechanisms mounted on the tip. For this reason, it is in general only reasonable to assume that a tip mounted guidance and control assembly can provide *trajectory correction.*

3.1 Trajectory correction

3.1.1 Physical constraints

Severe constraints are placed on the guidance, navigation and control (GNC) and actuation components of a guided projectile. For instance, the great shock induced during gun-launch, high spin rates, compatibility and integration issues between different subparts given restrictions on size and weight etc. The maneuverability of ballistic projectiles is inherently very limited, the complexity of the maneuver system must be kept low, probably with no ability for active damping (to synthesize stable dynamics). Control authority must still be sufficient to mitigate both ballistic dispersion errors and atmospheric influence to some extent. The guidance algorithm should presumably adhere to ballistic trajectories as close as possible to avoid waste of energy and to minimize the burden on the limited control authority.

As mentioned above, a projectile may either be spin-stabilized or fin-stabilized. In the first case, the spin rate is so high (hundreds of Hz) that stabilization is achieved by "gyroscopic action." The resulting dynamics may be highly complex, showing a significant crossrange drift due to interaction between gravity, pitching moment and spin. Trajectories are sometimes prone to become dynamically unstable in their final phases. For fin-stabilized projectiles, stability is ensured by aerodynamic surfaces resulting in a center of pressure aft of the center of gravity. Spin rates are much lower (0-30 Hz) and the dynamics have more benign characteristics. Coning motion could still result from applying too large side moments (lateral control forces), but it is easier to keep the airframe dynamically stable and the design space for the maneuver system will be much larger than for spin-stabilized projectiles.

3.1.2 Control mechanisms

A conventional control mechanism is provided by movable canards mounted at the nose of the projectile. It gives course corrections in both downrange and

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[1] This can be compared to the case of an aerodynamically controlled missile where it is common that enough control authority is available to make the closed loop airframe dynamics largely independent of the operating point in the flight envelope, i.e. altitude and Mach number.

crossrange (2D). On spin-stabilized projectiles, the canard assembly must be able to roll independently to be despun into the lower spin rates appropriate for the bandwidth of the actuators. This is not necessary for fin-stabilized projectiles (given their already moderate spin rates), simplifying the construction considerably.

A bank-to-turn behavior could be implemented where a given roll angle is kept fixed for a period of time during which the canards are deflected. Alternatively, the canards could continuously follow a sinusoidal motion, producing a net control force in some given direction by regulating the phase of the sinusoid. This is the solution chosen for the fin-stabilized VAPP concept (Fresconi, 2011), (Army Research Laboratory).

The ATK's PGK is spin-stabilized with four despun canards. However, the canards are fixed and not actuated at all. One pair is canted differentially, giving a constant torque in the direction opposite of the projectile spin. The other pair is canted in the same direction, giving a constant lateral force for maneuver. By continuously adjusting a braking mechanism in the bearing between the canard assembly and the projectile, the force may be oriented and stabilized in any roll angle, thus operating in a bank-to-turn fashion (Clancy *et al.*, 2006). When no maneuver is desired, the force is averaged out by having the canard assembly spinning freely.

Simpler mechanisms are the drag brakes and spin brakes. Each give 1D course correction only, in downrange and crossrange respectively, taken together they may give 2D. Both mechanisms act along the body x-axis of the projectile, independently of any roll angle information (no lateral control force is present). The crossrange deflection caused by the spin brakes takes place because of gyroscopic action. No despinning of the assembly is necessary. The maneuverability resulting from these mechanisms has an irreversible character by the fact that it is impossible to "undo" an overcorrection. The guidance also becomes rather inflexible, especially if the brakes are deployed only once without the possibility to retract them.

3.1.3 Implementations

When 1D-correction is employed this is done by deployment of some form of drag brake, usually in the form of control surfaces that have their "wing area" facing forward along the projectile main axis, thereby causing significant drag. Such brakes can be released by a pyrotechnic charge and even though this may potentially induce a destabilizing rocking of the projectile it is claimed that these negative effects can be controlled (Ziliani *et al.*, 2001).

The simplest way of introducing correction in the crossrange (drift) direction, i.e. to add 2D-correction capabilities, is to employ a spin brake (Pettersson *et al.*, 2007). Spin brakes consist of a set of canards that are mounted with a small angle against the wind, thereby inducing a moment on the fuze which can be more or less transferred to the projectile via a (magnetic) clutch mechanism. It is well known however, that spin brakes can only yield minor corrections in crossrange (Grignon *et al.*, 2007). In order to achieve significant crossrange correction a free spinning fuze assembly (with a slow spin rate, or even zero spin in the Earth frame) must be employed,[2] such as the classical concept proposed and analyzed in (Regan & Smith, 1975). In (Regan & Smith, 1975) the fuze

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[2] Concepts with canard control where the fuze assembly is fixed relative to the projectile body, so that the canards must oscillate with the spin frequency of the projectile, have also been considered, see e.g. the study in (Ilg, 2008) discussed below. The spin rate in this example is rather low however (approx. 20Hz), cf. the systems described in the next paragraph.

canard assembly was stabilized relative to the Earth and this concept yields a simple control formulation and efficient use of control surfaces. The limiting factor for such designs is the stability limits represented by maximum total angle of attack before gyroscopic instability occurs (Lloyd & Brown, 1979; Murphy, 1981). Concepts which combine the idea of spin brake and Earth frame stabilized canard action have also been proposed (Clancy *et al.*, 2006).

3.1.3.1 Hybrid systems

An implicit assumption in the systems described so far is that the retrofitting of the projectile with a precision guidance kit type of solution is restricted to replacing of the fuze. However, recently the performance versus economics for this approach has been questioned (Geswender & Bennet, 2008) and other solutions which require retrofitting also the end of the projectile with a fin assembly have been proposed (Fresconi *et al.*, 2010). The main advantage with tail fins is that the projectile can be made aerodynamically stable and hence aggressive control can be applied since the gyroscopic stability criterion no longer applies. When the tail fins deploy the projectile spin rate decreases dramatically down to a spin rate at which canards on a fix mounted fuze can operate (the despun roll rate of the projectile is typically in the order of 30Hz or less). More generally, there are advantages of combining spin and fin stabilization concepts since spin stabilized projectiles often offer lower drag and hence increased range. This idea was exploited in the 80's in a Swedish experimental program for naval long range course corrected projectiles (Andersson *et al.*, 1984).

3.2 The inner-outer loop guidance and control architecture

Even though there has been some progress towards the development of so called integrated guidance and control systems for missiles (Shkolnikov *et al.*, 2001; Palumbo *et al.*, 2004) the most common architecture is the classical two loop architecture (Siouris, 2004, Sec. 3.4). The two loop architecture consists of an outer (nominally slower) guidance loop which calculates acceleration commands which are then tracked by an inner (nominally faster) control loop, most often referred to as an autopilot. This paradigm is based on the assumption of a certain time scale separation between the two loops but enables, when the assumption holds, decoupled design of the guidance and control.

4 Guidance

The three main types of guidance most often considered in guided munitions contexts are trajectory shaping, trajectory prediction and trajectory following (Gagnon & Lauzon, 2008). Since trajectory shaping techniques generally are energy inefficient and are most often applicable for meeting terminal conditions (Pamadi & Ohlmeyer, 2006) (which we shall leave free, except for end point) we shall not consider trajectory shaping here.[1]

4.1 Predictive guidance

In *predictive guidance* (PG) a model of the projectile and the environment is used in each guidance update instant to compute a sequence of control actions which would yield a flight path leading to the target, given the current state (Ollerenshaw & Costello, 2005). If no errors in the model and measurements exist (and all states are measurable) this single guidance computation instant and the resulting control action is sufficient to give a flight path that takes the projectile all the way to the target. However, in reality at least a few such computations with accompanying corrections of the path are needed during the flight.

4.2 Trajectory and path following guidance

In *trajectory following* guidance a nominal trajectory has first been calculated from the launch point to target which, if the parameters and initial values all have their nominal values, would yield zero miss distance. Such a trajectory will be called *admissible* (since it meets the terminal condition; a trajectory which does not end at the target is thus inadmissible). The controller then aims at bringing the projectile onto the corresponding trajectory to the target. It is important to realize however, that a trajectory is (mathematically) a smooth map from a time interval to three dimensional space, i.e. it defines at each time instant not only a *position* but also a *velocity* that the projectile should have. However, bringing a projectile onto a path in space of a trajectory (a path being the image under the trajectory map of the time interval) does not necessarily mean that the projectile has the correct velocity when it arrives at a point on the path.[2] Therefore, satisfying the control objective of bringing the projectile onto the path does not necessarily mean zero miss distance.

The difference between the concepts of projectile trajectory following and projectile path following are illustrated in Figure 4.1. For this reason we shall here refer to the type of guidance which aims at placing the projectile on a given (precalculated) path to the target (without explicit consideration of the velocity) as *path following guidance* (PFG). Moreover, for controlled projectiles the concept of trajectory really becomes a family of trajectories; all those possible to realize by various modifications of the projectile dynamics through control action. (Trajectories ending at the target location are admissible.)

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[1] Guided projectiles with specially designed airframe generally have the capability to meet such terminal conditions whereas projectiles with course correcting fuzes do not, and we concentrate on the latter here.

[2] Of course, if the projectile has the correct velocity when it arrives on the path, then the point on the path is really a point on the trajectory leading to the target.

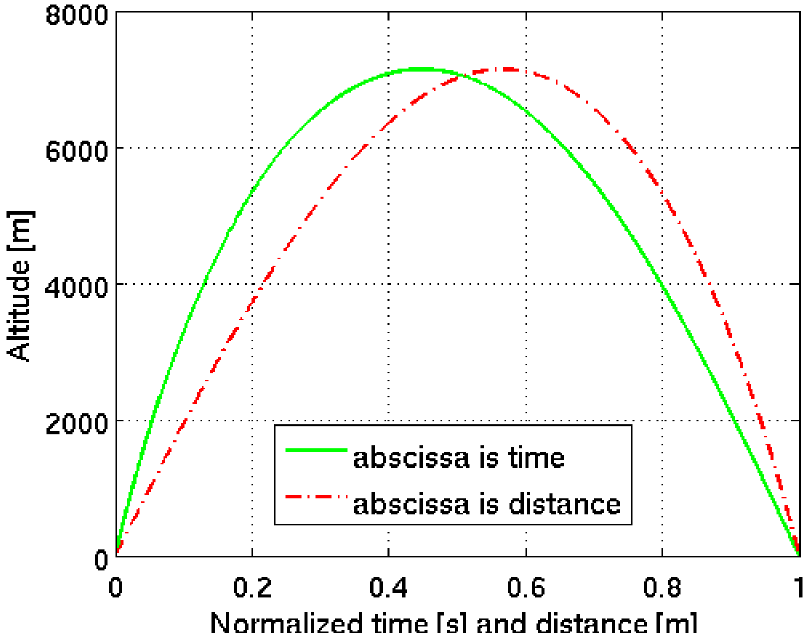

Figure 4.1: Illustration of difference between the concept of trajectory of a projectile and the path of a projectile. The difference between being at a certain altitude at a certain time versus being there at a certain downrange distance can be seen by placing a horizontal line in the figure and reading off its intersections with the two curves. If the velocity is constant the two concepts become equivalent and the two curves merge.

4.3 Properties of predictive and path following guidance

In Table 4.1 we have collected the most important and most obvious differences between predictive guidance and path following guidance.

Guidance principle properties		
Property	Predictive (PG)	Path following (PFG)
Feedback structure	no	yes
Required model fidelity	high	low
Computational complexity	high	(very) low
Updating frequency	can be low, is upwards limited by comp. time	must be high
Control effort	low	high

Table 4.1: The main properties of the two guidance principles predictive guidance and path following guidance.

In the following sections the properties listed are motivated and discussed in more detail.

4.3.1 Feedback structure

Predictive guidance is inherently an open loop control strategy. However, the natural way to apply PG is to use it repeatedly along a flight path, which then provides a natural feedback mechanism. This is because the actual state of the projectile (position and velocity, in a point mass model) is used to compute a new trajectory that will (if no further errors are introduced) lead to the target, regardless of possible previous deviations from a nominal trajectory. This is in contrast to path following guidance which includes a feedback mechanism by its very design; the goal of PFG is to track a given path. (Since the position is the variable tracked, this introduces a natural "integral action" into the guidance.) On the other hand, even if the projectile is brought back to the nominal path it will in general only be on a trajectory to the target if the state then coincides with the nominal state (so that the velocity error is zero). Therefore, further errors (and hence corrections to the flight path) are in this case more or less inevitable. Moreover, if navigation data is lost during some part of path following guidance the projectile must revert to predictive guidance using the last available navigation data. The two principles are thus, in principle, distinctly different (even though the may appear similar when applied for projectile guidance).

There are, however, two special cases where predictive guidance and path following guidance become (exactly) equivalent. The first one is when PFG is applied in such a "relaxed" fashion so that the first time the projectile is scheduled to arrive on the nominal path is when it arrives at the target. In this case the result is the same as if (ideal) PG had been applied along the flight. The second case of equivalence is when PFG is performed so stringently that the projectile is brought onto a path that leads to the target, and the projectile when it reaches this path has a velocity such that the state (position,velocity) is a state along an admissible trajectory.

The second case can be thought of as the inspiration for the braking strategies employed by several implementations of course correcting fuzes. If there is excess energy near the end of the flight path and proper braking (velocity brake to provide downrange correction and spin brake to provide drift correction) can be applied to bring the projectile down into a lower energy path which leads to the target the desired objective is achieved.[3]

4.3.2 Model fidelity

The required model fidelity is higher for PG since the long time effects of small modeling errors can be large; PG applied at a single instance is an open loop control technique. For PFG the opposite holds, a lower model fidelity is required and the reason is not only that it is directly based on feedback but also that the path calculation is decoupled from the path following calculation. (Indeed, calculation of the nominal trajectory is likely to be done off-line, before the projectile is fired.) The higher requirements on model fidelity in the PG case also lead to higher requirements in terms of precision for the actuators implementing the control. Another related issue is the possible loss of stability due to control action on an otherwise stable projectile (Lloyd & Brown, 1979; Murphy, 1981). To assess these effects over the flight path a precise model of the projectile dynamics is in general required and the stability issue can represent a severe restriction on the available control action and the ability to make corrections to a flight path.

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[3] However, it should be noted that if path following guidance is used up to the point where the brake is nominally applied a loss of navigation data can be catastrophic since the projectile then in general has far too high velocity to hit the target. Moreover, in order to apply braking the projectile must also in this case then revert to predictive guidance for the remainder of the flight.

4.3.2.1 Models for trajectory computation

It is well known that very accurate trajectory computation models can be obtained by a linearization technique referred to as projectile linear theory (McCoy, 1999; III & Costello, 2005). This means not only that closed form expressions for rapid computation of trajectories can be done but also that the wealth of linear control methods can be applied to the guidance problem, cf. eg. (Ollerenshaw & Costello, 2005). It is therefore reasonable to assume that trajectory computations can be done in real time[4] by an on-board computer in the trajectory correcting fuze so that predictive guidance can be applied in a iterative fashion during the flight.

4.3.3 Complexity, updating frequency and control effort

The considerations about model complexity directly translate into corresponding demands of computational complexity. Thus, the updating frequency with which a PG scheme can be updated (if used repetitively) is likely to be lower than the updating frequency in a guidance loop executing PFG. Moreover, since PFG will in general *always* result in an incorrect velocity when the projectile is brought back to the nominal trajectory (Gagnon & Lauzon, 2007), it is in general necessary with a considerably higher updating frequency in a guidance loop executing PFG (Gagnon & Lauzon, 2008).

Turning to control effort, it is clear that the set of reachable terminal points (with given bounds on the control) is larger in the beginning of the flight. Also, for a given deviation from a path leading to the target, less control effort is needed to reach points in a given (reachable) set if the deviation occurs later in the flight. Thus, control action applied early in the flight are energy efficient but prone to be affected by later errors (such as errors in the dynamic model or or in the model of the environment such as wind). Another source of error in the later part of the flight path are navigational errors induced by jamming.

Altogether this shows that there is a trade off between the potentially more efficient guidance and control formulations which aims at cancel errors early in the flight and potentially more accurate formulations which aims at waiting until the errors have accumulated later in the flight.[5]

4.3.4 Navigation considerations

4.3.4.1 Required state information

With a purely axial control mechanism, only position and velocity are needed for guidance and a GPS would suffice. With canards, the body frame attitudes are needed as well to define the orientation of the lateral control force.

This information could be provided by an integrated GPS/INS system. Such navigation systems are routinely employed in many missiles and precision weapon systems. They are available today as commercial-off-the-shelf components, e.g. the IGS-2XX series of deeply integrated MEMS and SAAM GPS receivers, gun-hardened and anti-jam capable, from Integrated Guidance Systems LLC (Honeywell/Rockwell Collins) (Integrated Guidance Systems).

However, this may not be a viable solution given the demands for cost-effectiveness and low complexity. Apart from elevated cost, there are other reasons as well for avoiding the INS.

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[4] Moreover, these computations may be supported by table lookup of certain quantities.

[5] This can be explicitly taken into account in PG by e.g. time dependent weighting matrices in an LQ based formulation of predictive control.

First, the target location error (TLE) is a critical parameter for the effectiveness of any precision guidance concept. It may not be on par with the very low CEP (< 5 m) specified for the IGS unit, making the cost for the latter unjustified.

There are also known observability issues concerning the estimation and in-flight calibration of inertial measurement unit (IMU) bias and drift errors that may be of concern for unboosted ballistic projectiles with low maneuverability (Ohlmeyer & Pepitone, 1998).

The IMU is not needed for feedback purposes in the control system. The fact that the airframe should be dynamically stable from the beginning together with modest requirements on the speed of response to guidance, makes it possible to do without an acceleration and angular rate feedback control.

4.3.4.2 Navigation without INS

We briefly review some steps taken to reduce the reliance on INS.

In a standard integrated GPS/INS system, the IMU signals are used as input to the process model: accelerometer signals drive the navigation equations and integrated gyro signals give the attitudes.

For the ballistic projectiles in question, both spin- and fin-stabilized, the total angle of attack is usually small (at least for non-excessive quadrant elevations). There are analytical approximations for the quasi steady-state value of the relative orientation of the body frame x-axis with respect to the velocity vector, referred to as the “yaw of repose” (McCoy, 1999). Used as corrections to the flight path angles, one gets the body system pitch and yaw angles directly from the velocity vector. With pitch and yaw discarded from the state vector, the dimensionality of the process model is reduced by two. Only roll angle remains to be measured by some means.

This reduction of the number of navigation states should also be reflected in the impact point prediction by the guidance system. The small angle of attack makes a “modified point mass model” (McCoy, 1999) (3 DOF dynamics + expression for the yaw of repose) sufficiently accurate for trajectory prediction. This equalizes the information handled by the GNC system.

A solution along these lines is given in the context of naval gun-launched projectiles by (Ohlmeyer & Fraysse, 2002), using an accelerometer-only IMU concept. The outputs from an array of six accelerometers are not only driving the navigation equations, but also providing measurements of the roll rate and roll acceleration. A three-axis magnetometer is also used in addition to a GPS receiver to provide measurement inputs to the Kalman filter based on the “gyro-less” INS.

A further simplification of this concept is presented in (Pamadi & Ohlmeyer, 2004). A standalone GPS receiver gives position and velocity (i.e. unaided, without using the accelerometer data). Roll rate and roll angle are measured by an accelerometer array aided by magnetometer measurements to remove bias errors. This corresponds to an almost “uncoupled” mode of operation.

Much effort has been spent on methods for estimating the roll angle for a spinning projectile, also referred to as “upfinding” (Kreichauf & Lindquist, 2006), (Lucia, 1995). To save costs, space and power consumption, it would be much preferred if the upfinding capability could be included in the GPS receiver. All navigation functions would then be performed by one sensor only. The U.S. Army Research Laboratory (ARL) is currently investigating implementations and algorithms for GPS based upfinding (Ilg *et al.*, 2011). Another example, with more technical details, is given in the patent application (Velde *et al.*, 2010).

Both ATK's PGK and ARL's VAPP concepts use standalone SAAM GPS receivers including roll angle determination (Fresconi *et al.*, 2010). The ECF rely on GPS C/A receiver only (Junghans Microtech), having no need for roll information. The SPACIDO projectile have no navigation system at all, instead the trajectory corrections are based on measurements from a muzzle velocity radar.

A drawback with expelling the INS is the loss of aiding functionality and robustness, which was the rationale for the GPS/INS marriage from the beginning. GPS is very vulnerable to jamming and this becomes one of the most important questions to cope with for any GPS-only system. Success really hinges on the effectiveness of included anti-jam capabilities.

From a technical point of view, the antenna is the critical component of a GPS receiver. The gain and phase patterns are decisive for performance in a jamming environment, also for the performance of the upfinding.

4.4 Previous work on guidance and control

The first step in any study of course correcting fuzes is to establish control authority bounds for various concepts. Indeed, this was the motivation behind the early studies leading to the findings about the possible destabilizing effects of nose applied side force control (Lloyd & Brown, 1979; Murphy, 1981).

A recent general study of response to general control inputs, for both spin and fin stabilized projectiles, is (Ollerenshaw & Costello, 2008). The analysis provides closed form expressions (based on projectile linear theory) for the step response to a control force (expressed in the non rolling frame[6]) applied at the nose in any direction perpendicular to the main axis of the projectile, for both fin and spin stabilized projectiles. This type of control setting with a despun canard equipped fuze was investigated in (Regan & Smith, 1975) where maneuverability and stability bounds, expressed in terms of canard surface area and the classical gyroscopic stability factors, were derived. Large canard surface area, for increased maneuverability, stands in conflict with stability, which decreases with increased canard surface area. Another recent study of a canard controlled despun course correcting fuze is (Bakken, 2009). There, the emphasis is on maneuverability and deflection bounds and it is found that for a 155mm shell at 23.7km nominal range, a downrange correction in the interval $[-350, 200]$m and a crossrange correction of about ±300 is possible with (one version of) the proposed design. In (Fresconi & Plostins, 2008) a similar investigation is performed, also for a 155mm shell, but the achievable downrange and crossrange corrections are much larger. However, in (Fresconi & Plostins, 2008) the aerodynamics, and hence control action, of the fuze is not modeled in detail (forces, of reasonable size with respect to the gyroscopic stability bound, are simply applied at the tip of the projectile).

Potential range and accuracy improvement with canards are studied in (Costello, 1997) and course correction fuze maneuverability and concept analysis is studied in (Gagnon & Lauzon, 2007, 2008). In (Gagnon & Lauzon, 2007) a path following guidance law is employed and it is found that launch errors are easily corrected, but that wind errors are harder to compensate for, in particular varying wind conditions. Also, muzzle velocity variations were difficult to correct for with path following, which is not surprising since velocity is not directly measured and controlled with PFG. In the follow up investigation (Gagnon & Lauzon, 2008) the results were similar but it was found that

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[6] The non rolling frame, also called the aeroballistic frame, has the same Euler pitch and yaw angles as the standard body frame but has the roll angle fixed at zero,

combining drag and spin brakes is better than the four canard solution.

Predictive guidance, in the linear quadratic setting, was studied in (Ollerenshaw & Costello, 2005). It was found that it works well to compensate for initial errors. However, in (Ollerenshaw & Costello, 2005) normalized control quantities were used so it is not immediately clear if the results would change if the control quantities were to be capped be real force and moment bounds (available control authority of the fuze).

In (Pamadi & Ohlmeyer, 2006) trajectory shaping guidance was studied, where the emphasis was on terminal impact conditions. Their formulation is based on optimal control.

In (Ilg, 2008) a comprehensive investigation is made of a course correcting fuze for a spinning projectile, covering guidance, navigation and control as well as hardware implementation. Since the canard assembly considered is fixed relative to the body, a concept of oscillating canards is developed where the phase of the oscillation relative to the spin motion is modulated to provide the control action. Several guidance methods are also compared, all of which belong to the PG class. They propose proportional navigation type guidance methods as a good candidate family of guidance laws.

5 Conclusions and recommendations for further study

It is clear that the problem of adding guidance capabilities to spinning projectiles using course correcting fuzes is hampered by several severe restrictions, both physical and economical.

A major physical restriction is that the control problem is actuation limited. Since it is in general impossible to realize servos and actuators that operate on the nominal spinning frequency of the projectile, the gyroscopic stability condition has to be respected. (In other words, stability must be guaranteed by open loop characteristics of the system and not by synthesized closed loop properties.) This makes it impossible to gain ever increasing advantages with larger control surfaces and the limits for achievable control authority are in general quite narrow. (Achievable normal lateral acceleration, before instability occurs, is probably in the order of a few tenths of a g with fuze mounted canards (Lloyd & Brown, 1979).) The control actuation restriction also sets a limit on the terminal accuracy possible to achieve in an environment with varying wind conditions. (It also makes it very hard to hit even slowly maneuvering targets.)

Other major restrictions are cost and packaging requirements. Both these requirements lead to a desire of removing any components and functions that are not absolutely necessary, such as an IMU unit if the same functionality can be obtained from a GPS. It also means that each of the subsystems in a course correcting fuze has to be made so simple that it can only provide the basic functionality for which it is intended. Thus, the shortcomings of one subsystem cannot be compensated for by improving the others. In fact, when designing the overall system, a careful optimization of each subsystem has to be made, and for each subsystem the contribution to overall performance must be clearly identified.

This tradeoff is illustrated by the problem of choosing guidance strategy. Since predictive guidance with necessity uses also velocity measurements it is conceivable that it has the potential to give better performance than path following guidance (which uses only position measurements). Therefore, it would seem that with better guidance one could compensate for the limited actuation and maneuvering capabilities. However, the possible performance benefits with predictive guidance are dependent on the quality of the velocity measurements available. Since a major factor in holding down the cost of a guidance solution for a guided munition is the ability to operate without IMU unit, this means being able to obtain good quality measurements from a (filtered) GPS signal. Thus, a topic for continued research is to establish the bounds for achievable navigation errors for various GPS-only type of navigation systems. (This is particularly important for environments where jammers may be present.)

Thus, the “straitjacket” that confines the standard course correcting fuze problem severely limits the design space. One way to, at least partly, escape this restraint (while still maintaining the low-cost goal) is to consider airframes that are fin stabilized. Being able to have a nonspinning (or slowly spinning) stable airframe (which is technically easy to achieve) means that the full control authority of larger control surfaces can be exploited and better performance can be obtained, even with a simple fuze mounted control mechanism. This would make it possible to obtain the precision needed to hit penetration type targets and the maneuverability needed to hit slowly maneuvering targets without incurring the extra cost of a specially designed airframe.

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