GUIDANCE AND CONTROL OF ARTILLERY PROJECTILES WITH MAGNETIC SENSORS

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This article deals with a new system to ensure Guidance and Control (G&C) of an artillery projectile without the use of a complete standard Inertial Measurement Unit system (IMU). Nexter Munitions is interested in new technology based on magnetoresistive sensors due to their size, high resistance to extremely severe environments and their price. This new system replaces the three axis gyros of the inertial measurement unit by a three axis magnetic sensor unit ("gyrofree IMU") strapped down in the principal axis of the projectile. It is called an "electronic compas"

The system is based on the hypothesis that the "terrestrial magnetic field" vector, at a specific date, remains constant for several miles around the firing position. In flight, the real time comparison of this field and the magnetic field measured in projectile axis provides the attitude and rotation rate of the projectile.

A real time algorithm has been developed to estimate and correct magnetic disturbances in flight.

The performance of such a system is improved by the use of the accelerometers. First estimations show that miss distance precision could then be to less than a few meters in approximately more than 98% of the cases : as long as the longitudinal axis of the projectile is out side of a 10° cone around the local earth magnetic field vector. This level could be increased if the scenario is adjusted to geographic localisation of firing.

In parallel with guidance and control algorithms development, Nexter Munitions has been conducting demonstrations.

NOMENCLATURE

X_O, Y_O, Z_O	space -fixed system of axis, positioned at firing point
X_P, Y_P, Z_P	projectile body-fixed system of axis, at the projectile center of gravity
$\vec{H}_E$	local earth magnetic field (3-D vector)
$\vec{H}_0$	earth magnetic field (3-D vector), in space-fixed system of axis
$\vec{H}_P$	earth magnetic field (3-D vector), in body-fixed system of axis
H_{O_X}, H_{O_Y} , H_{O_Z}	X, Y and Z components of $\vec{H}_0$
H_{P_X}, H_{P_Y}, H_{P_Z}	X, Y and Z components of $\vec{H}_P$

H_{P_T}	transversal magnetic field in body-fixed system of axis
B_{Hp_x}	bias estimation for longitudinal body-fixed axis
ψ, θ, φ	Euler's angles of yaw, pitch and roll.
M_{OP}	transformation matrix from space to body-fixed axis
$\dot{\psi}, \dot{\theta}, \dot{\varphi}$	yaw, pitch and roll rate of change in fixed system of axis
p, q, r	roll, pitch and yaw rotation rates in body-fixed axis
b, c, d, e, f, g	generic functions
ε	angle of the cone around axis of Earth magnetic field vector $\overrightarrow{H_E}$

INTRODUCTION

This article deals with a new system to ensure guidance and control of an artillery projectile without the use of a classical IMU system including accelerometers and gyros. In spite of recent technical progress in inertial measurement unit systems, it is still difficult to develop accurate gyros supporting artillery accelerations which can reach more than twenty thousand 'g'. In addition, the few systems that actually appear in this field are promising but still remain very expensive.

So the objective is to develop a system which can ensure the same functions as the gyros for guidance and control. This means that this system has to provide the autopilot with data related to projectile attitude and its angular rates during the different phases of the flight.

With these technical and operational constraints, Nexter Munitions is interested in the new technology based on magnetoresistive sensors : these are miniaturized, g-hardened[2], cheap and off-the-shelf. This objective has been reached and the three axis gyros of the inertial measurement unit can be replaced by a three axis magnetic strapped down sensor.

This article presents the hypothesis and the method developed. Then, it describes the flight scenario defined to evaluate the availability to guide and control a projectile with the electronic compass. First performance estimations is presented, followed with limitation of use, mainly depending on geographical location on Earth. The last part presents the first steps of experimentation of this system.

DEVELOPMENT OF THE METHOD

The basic hypothesis of this concept is to consider that the "earth magnetic field" vector $\overrightarrow{H_E}$, at a given time, remains constant within a radius of several miles around the firing position[1]. This information can be stored before firing in a specific memory of the projectile data-processor (called $\overrightarrow{H_0}$) and compared at each time with the measurements (called $\overrightarrow{H_P}$) implemented during the flight :

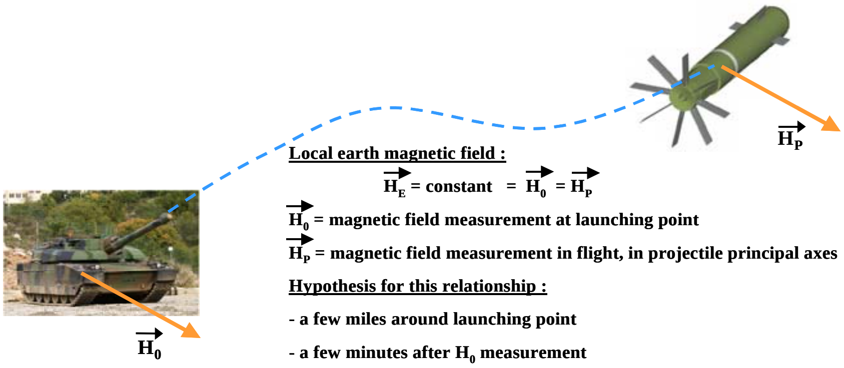

Figure 1. Electronic compass basic hypothesis : Earth magnetic field $\overrightarrow{H_E}$ is constant in flight.

The relationship used for the comparison of $\overrightarrow{H_0}$ and $\overrightarrow{H_P}$ is classical :

$$\overrightarrow{H_0} = M_{OP} * \overrightarrow{H_P} \tag{1}$$

This relationship reveals the M_{OP} rotation matrix which only depends on the projectile attitude angles. As Whaba[3] demonstrated it in the seventies, the eq. (1) system has an infinite number of solutions. It needs additional information to be reduced to a unique solution.

Without additional sensor, it is necessary to find something else to solve this problem. For a typical artillery projectile flight, we can observe that the yaw angle remains constant during the ballistic phase of the flight. In fact, during such a so short flight (less than a few kilometers), the influence of the Coriolis force can be neglected. Based on this a priori knowledge of the yaw angle, the eq. (1) can be solved during ballistic flight and also during a pre-programmed controlled flight. The dynamic behaviour of the projectile is supposed to be known with the required level of accuracy. Thus, yaw angle evolution is estimated before flight and stored in the onboard calculator memory. Pitch angle can be obtained with H_{P_X} or, but as for yaw, it could be obtained with pre flight simulation. This solution will be preferred and pitch evolution will be stored in the onboard calculator memory. Roll angle "φ" is obtained with transversal measurements H_{P_Y} and H_{P_Z} :

$$\varphi = \operatorname{atan}\left(\frac{H_{P\_Y}.\mathrm{e} - H_{P\_Z}.\mathrm{d}}{H_{P\_Z}.\mathrm{d} + H_{P\_Y}.\mathrm{e}}\right) \tag{2}$$

with (d, e) functions of yaw angle, pitch angle and $\overrightarrow{H_0}$.

This straightforward step by step resolution gives all attitude angles of the projectile in real time, without requiring estimation techniques which have typically a long time of convergence. Last step to obtain angular rate of the projectile is to solve the system below :

$$\left|\begin{array}{c}\dot{\theta}\\ \dot{\psi}\\ \dot{\varphi}\end{array}\right. = \left|\begin{array}{c} r.\sin(\varphi) - \text{q}.\cos(\varphi)\\ (\, r.\cos(\varphi) + \text{q}.\sin(\varphi)\,) \,/\, \cos(\theta)\\ p - \dot{\psi}.\sin(\theta)\end{array}\right. \tag{3}$$

Before such a resolution, it is necessary to verify that all the expression rates are valid. Roll angle estimation is restricted by arctangent limitations to +/-2π variations. This induced a sudden discontinuity for roll estimations near 2π values. A correction is done for each detection of an extreme difference (roughly equals to 2π) between two successive roll angle estimations. After several attitude estimations, rotation rates are given to the autopilot to ensure navigation, guidance and control without the assistance of gyros.

Projectile's attitude estimation can be greatly improved by the use of the three axis accelerometers. Yaw and pitch angle estimations can be obtained by the use of acceleration measurements carried out during the flight[7]. You can see below a comparison of ψ and θ angles obtained with the two methods and with real attitude angles during the flight :

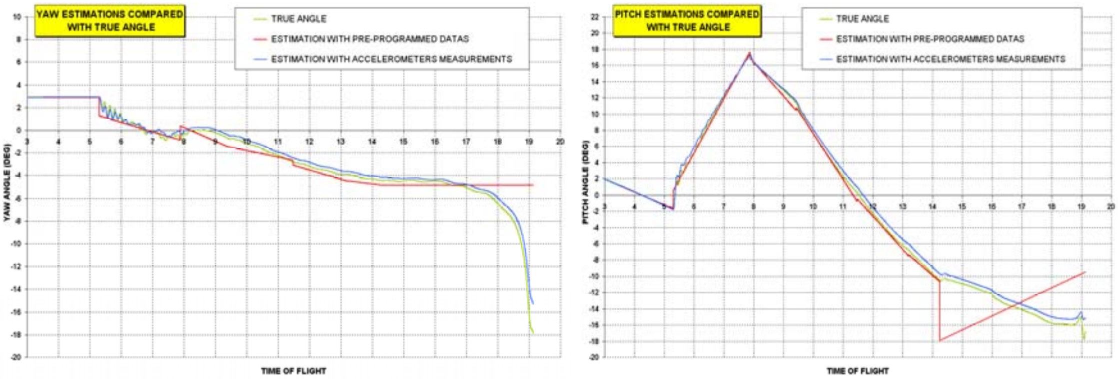

Figure 2. In-flight true yaw and pitch angles compared with both algorithm estimations

All these estimations are directly delivered to the autopilot, thus navigation with an "electronic compass" is slightly different from navigation with a standard IMU with gyros. Rotation rate estimates are only used to stabilise the projectile yaw, pitch and roll channel control loop.

PERFORMANCE EVALUATION

Scenario

Evaluation of the electronic compass capability for guidance and control will be done for a typical flight presented in fig.3 :

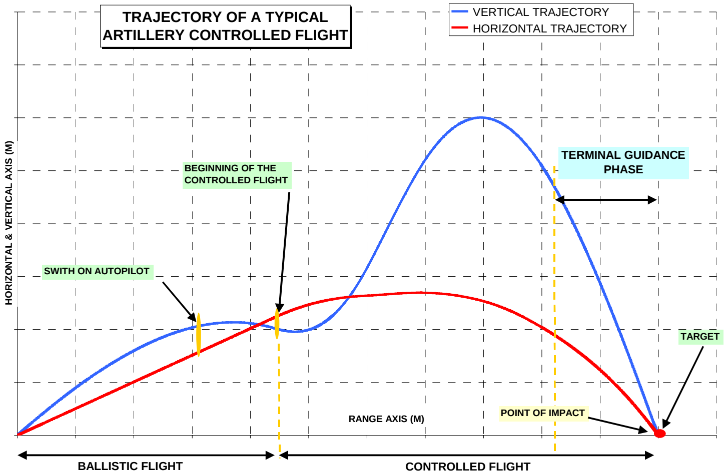

Figure 3. Typical artillery controlled flight

During the ballistic flight, the trajectory in the vertical plane is curved under the effect of gravity and the horizontal trajectory is a straight line. A lateral aiming error is introduced in order to require a correction of the trajectory to the right during the flight to reach the target. At the same time, flight altitude is increased to reach a better vertical angle for the terminal attack.

Yaw and pitch estimations could be obtained with a pre-flight calculation, and stored onboard as a time law evolution, or with accelerometers measurements.

Implementation of Magnetic Measurements

This system can be very accurate if good measurements are available. So the magnetic sensors have to be protected as high as possible form disturbances. But the magnetic environment of the projectile is neither clean nor well known and sources of disturbance are numerous : permanent, induced magnetism and electrical current disturbance. Due to the very restricted volume available in the shell, magnetic sensors can’t be placed in magnetically non disturbed area. Misalignment, resulting from sensor cross axis[6] and assembling precision reduce accuracy of attitude estimations.

The hereby proposed solution is a light ground calibration. Many techniques are available and presented in public sources[4,5]. All the results of this calibration will be stored onboard and in-flight measurements will be corrected by software. This should be sufficient, but the effect of firing on sensor sensitivity is quite unpredictable. Thus an in flight calibration should be done. This is based on $\overrightarrow{H_0}$ estimation, by software modeling[2] or by measurement before firing. H_{P_X} and H_{P_T} can be calculated before firing and their evolution during the flight is expressed as a simple expression of time :

$$H_{P\_T}=\sqrt{H_{P\_Y}{}^2+H_{P\_Z}{}^2}=\sqrt{\left\|\overrightarrow{H_0}\right\|-H_{P\_X}{}^2}=f(\psi,\theta,\overrightarrow{H_0})=g(t) \tag{4}$$

For the correction of the transverse measurements, the shape of the projectile is designed to ensure a required value of roll rate in flight. As the projectile rolls around its longitudinal axis, transverse magnetic measurements $\mathrm{H}_{\mathrm{P\_Y}}$ and $\mathrm{H}_{\mathrm{P\_Z}}$ are sinus. Comparison of the measurements and expected values H_{P_T} of the peak to peak sinus signal gives us the bias and scale factor of transversal magnetic measurements[4].

Thus, the complete magnetic measurement correction will be done with pre-flight ground calibration plus in-flight calibration.

Performance and Restriction Of Use

Performance assessment of this concept has been carried out, taking into account many sources of disturbances : meteorology, ballistic errors and, of course, magnetic. These evaluations have been done for different firing locations, such as near the Equator or in Central Europe, for different target azimuth angles.

First evaluations have been carried out for targets at short ranges, around three and a half kilometers from firing position, with a strap down seeker delivering measurements at a sampling rate of 20 Hz. These result show that the Circular Error Probability (CEP) of the miss distance could be reduced to less than a few meters (fig. 4) if the true transverse magnetic signal available is significant compared with disturbances :

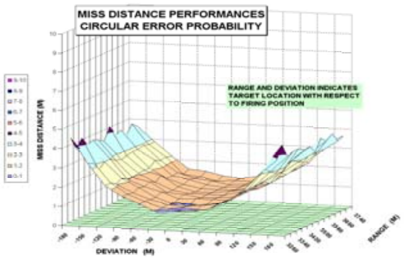

Figure 4. CEP for short distance target

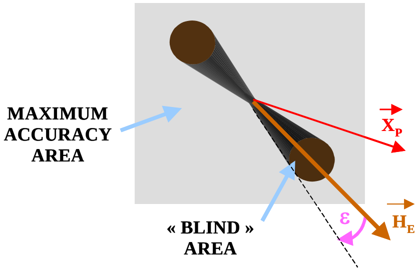

Figure 5. Restriction of use

The main restriction is encountered when the projectile flight direction is roughly the same as the earth magnetic field vector $\overrightarrow{H_E}$. For such occasions, roll estimation is most sensitive to small magnetic disturbance. This defines approximately a 10 degrees “blind cone” around local $\overrightarrow{H_E}$ (fig. 5) : it represents less than 2% of the global firing situations.

A possible way to improve electronic compass performance is to adapt the operational flight solution depending on the local earth magnetic field orientation. This can be done because of the maneuver capabilities of the projectile.

EXPERIMENTATION

In parallel with the guidance and control algorithms development, Nexter Munitions has been conducting demonstrations from hardware in the loop test to firing experimentation (fig.6). Firing tests have been carried out with a 120 mm tank gun and initial acceleration of more than 15000 “g”. The three magnetic measurements have been recorded during ballistic flight and analyzed after recovery. Pre flight calibration of magnetic sensors was simple with a rough estimation of scale factor and bias after integration into the shell. A video tracking system (fig.7) was involved to estimate the projectile roll rate in flight :

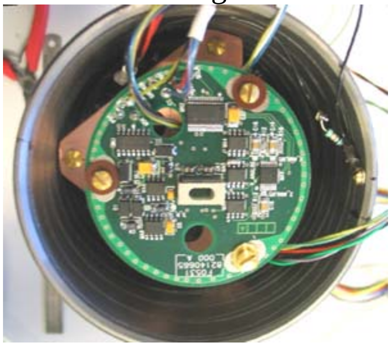

Figure 6. electronic compass integrated in a shell

Figure 7. Extract of the video tracking

The measurements have been recovered and a subsequent roll rate estimation have been deduced from signal analysis. Longitudinal axis measurement fluctuations (blue line on fig. 8) are typical of non-orthogonality and misalignment. The fitting of the integration of sensors has to be improved. Transverse Y and Z oscillation around non null value reveals bias. All these distortions directly induce roll rate fluctuations compared to the roll rate estimate based on the video tracking. The difference between the two roll rate estimations (fig. 9) is only about a third revolution per second (10% max around the nominal value obtained from the video analysis). This means that the theoretical studies and developments are promising[7] to allow the flight control of an artillery shell.

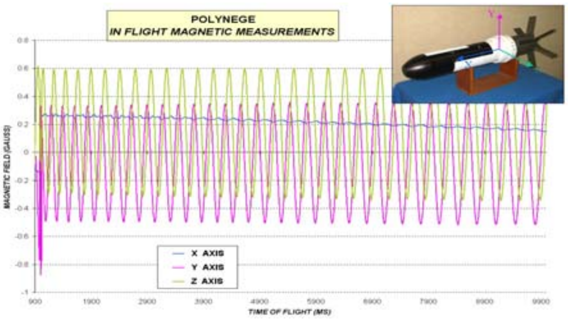

Figure 8. Three magnetic sensors measurements

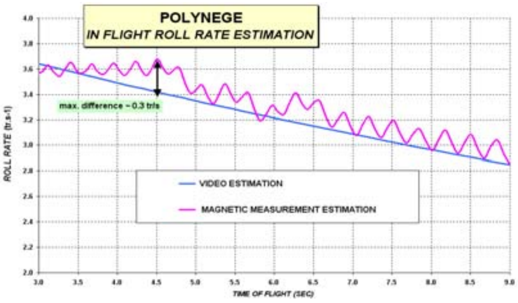

Figure 9. Roll rate estimations

CONCLUSIONS

The objective of Nexter munitions was to propose a guidance and control concept meeting the requirements of a guided artillery shell in terms of performance, robustness and cost without the use of gyros ("gyrofree IMU"). This solution is based on three magnetic sensors and complies with the aforesaid objectives. Onboard magnetic measurements are compared in real time with the local magnetic field observed at the firing point. Then the attitude of the projectile (Euler's angles) and its rotation rate (p, q, r) are obtained thanks to the use of robust algorithms. The accuracy is significantly improved with the assistance of the three axis accelerometers. The required accuracy can be reached in more than ninety two percent of firing scenarii. The "blind cone" effect can be minimised if operational flight solutions is adapted to local terrestrial magnetic field orientation. The studies described in this article are still continuing in Nexter Munitions.

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