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IMPACTS OF NAVIGATION AND SENSOR ACCURACIES ON COMBAT VEHICLES

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ABSTRACT

This paper discusses the impacts of the navigation accuracy and sensor accuracy on combat vehicles and some potential improvements. Two of the combat vehicle subsystems are the fire control subsystem for weapon engagement and the target locating subsystem for fire support. The fire control subsystem is required to comply with the hit probability requirements that depend on position sensor accuracy, rate gyro sensor accuracy and the Euler angle accuracies of the Inertial Navigation Unit (INU), in addition to many other factors. The paper reviews the kinematic lead correction estimation and its error sources. Rate gyro sensors are widely used in the target Line of Sight (LOS) stabilization and the weapon Line of Fire (LOF) stabilization. This paper presents a solution that can remove the components in the rate gyro signals related to earth rotation rate and trim down the fire control subsystem drifting errors significantly. Fire control subsystems also use the pitch and roll angles of an INU for LOS and LOF cant angle correction, so no cant sensor is needed.

The target locating subsystem needs to meet Target Location Error (TLE) requirements that rely on the Euler angle and position accuracies of an INU, the Global Positioning System (GPS) positioning accuracy, the target range measurement accuracy and the angular position sensor (measuring the LOS angles) accuracies. The error sources of the target locating subsystem discussed in this paper are the INU/GPS position errors, the INU Euler angle errors (especially the heading/azimuth error), the Universal Transverse Mercator (UTM) based target location computation errors, and the target range error. Based on these insights, this paper provides some improvements on the target locating accuracy.

This paper concludes that the navigation systems and the sensors can be improved or upgraded for better fire control subsystem and target locating subsystem performances. Some of the insights and improvements presented in this paper can be applied to many combat vehicles to enhance their lethality.

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INTRODUCTION

Combat vehicles consist of several subsystems, such as lethality subsystems, survivability subsystems, mobility subsystem, command and control subsystem and power management subsystems. Each subsystem provides key capabilities for the combat vehicles to complete their missions. This paper discusses the impacts of the navigation accuracies and sensor accuracies on the direct fire control subsystem and the target locating subsystem. The direct fire control subsystem is composed of the weapons, target acquisition sights, weapon Line Of Fire (LOF) controllers, Line Of Sight (LOS) controllers and Soldier Machine Interfaces (SMI). The modern fire control subsystem computes digital fire control solutions with sophisticated LOS to LOF corrections, automatically slaves the weapon LOF to the tracked LOS and achieves precision engagements with little soldiers' efforts. The fire control subsystem relies on rate gyro sensor accuracies, angular position sensor accuracies and the Euler angle accuracies of the Inertial Navigation Unit (INU), in addition to other sensors and drive stabilization, in order to meet the hit probability requirements for stationary and on-the-move scenarios.

Modern fire control subsystems allow any measurable error-producing effects to be accounted to increase the hit probability, from air density and wind, to wear on the barrels and distortion due to heating. These effects exist for any types of guns and cannons. Fire control computers have started appearing on smaller and smaller platforms, and can be used to aim machine guns, small cannons, guided missiles, rifles, grenades, rockets—any kind of weapon that can have its launch or firing parameters varied.

Fire control subsystems are often interfaced with sensors (such as sonar, radar, Infra-Red Search and Track (IRST), Laser Range Finders (LRF), anemometers, wind vanes, thermometers, barometers, etc.) in order to cut down or eliminate the amount of information that must be manually entered in order to calculate an effective fire solution. Sonar, radar, IRST and LRFs can give the subsystems the LOS direction and/or range to the target. A combat vehicle can be equipped with an optical sight so that an operator can simply point at the target, track it and fire a weapon, with the fire control subsystems taking care of the weapon pointing/steering control and LOS to LOF corrections. Typically, weapons fired over long ranges need environmental information. The farther a munition travels, the more the wind, temperature, air density, etc. will affect its trajectory, so having accurate information is essential for a good ballistic lead solution.

The target locating subsystem of a combat vehicle consists of a target acquisition sight with range and LOS direction measurements, an inertial navigation unit (INU) and a target locating algorithm processor. The target location in terms of UTM coordinates (northing, easting and altitude) needs to meet precision-guided munition or call-for-fire accuracy requirements. Normally, resolvers or encoders are used to measure the LOS elevation and azimuth angles with respect to the sight installation surface. A LRF is used to measure the range between the sight and a target. A LOS range vector is transformed from the sight coordinate frame to the local geodetic coordinate frame, from which a target location is calculated. As can be seen, the target locating accuracy depends on the INU/GPS positioning accuracy, vehicle angular measurement accuracies in terms of the three Euler angles, the LOS elevation and azimuth angular measurement accuracies, the target range accuracy and the computation accuracy.

This paper will discuss some insights, practical issues and potential improvements of the fire control subsystems and target locating subsystems of combat vehicles. The detailed derivations of the fire control and target locating equations are not the focus of this paper.

IMPACTS TO FIRE CONTROL SUBSYSTEMS

This section discusses the navigation and sensor accuracy impacts to the fire control subsystems. As stated in the introduction section, the LOS-to-LOF correction determination is key to achieve the weapon's hit probability. The total correction is the sum of the following components:

- Kinematic lead correction [1]
- Ballistic lead correction
- Cant angle correction
- Ammunition dispersion correction
- Gun jump and barrel bend correction
- Weapon station velocity jump correction
- Windage jump correction
- Other corrections

In practice, these corrections cannot be achieved 100% due to inability to measure, sensor measurement errors, control loop stabilization errors, sight and aim errors, ammunition errors, and target evasive maneuvers.

Kinematic Lead Estimation and Rate Gyro Accuracy Impact

Rate gyro sensors are very important to a fire control subsystem (at least a set of four is needed), and are used in the target Line of Sight (LOS) stabilization and the weapon Line of Fire (LOF) stabilization. Different types of rate gyro sensors are available commercially, such as Dynamically Tuned Gyroscopes (DTG), Fiber Optical Gyroscopes (FOG), Microelectromechanical Systems (MEMS) gyroscopes, Ring Laser Gyroscopes (RLG), etc. Their rate sensing accuracies, sensor noises and sensor bandwidths affect the inertial stabilization errors of weapon LOF and target LOS in both elevation and azimuth directions. While a target is under LOS tracking using an optical sight, the target LOS tracking rate at the time of weapon firing can be used to estimate the kinematic lead correction for constant target moving velocity and constant range to the target approximated during the weapon projectile Time of Flight (TOF). Any rate signal latency, accuracy and noise will introduce kinematic lead correction error.

If the target LOS is in a constant angular acceleration maneuver, the target LOS angular rate and angular acceleration can be estimated based on the following equations:

$$\theta'' = f(\theta, \theta', a_T(t), R(t)) \qquad (1)$$

Where θ represents either the target LOS elevation angle or the target LOS azimuth angle (with different f functions). $a_T(t)$ stands for the target vehicle CG acceleration vector. Though its amplitude is limited by the target vehicle engine power, $a_T(t)$ can be time-varying due to evasive motion. $R(t)$ is the range vector between the target present position and the weapon muzzle position at the time of weapon firing (a fixed point). Note that the weapon muzzle position after the weapon projectile has left the barrel has no impact to the kinematic lead correction. $R(t)$ varies during the projectile time of flight if the target moves, but is irrelevant to the self-vehicle motions after weapon firing. The farther the range is, the smaller the θ'' is. For longer projectile TOF, θ'' is normally not a constant. Let

$x_1 = \theta$
$x_2 = \theta'$
$x_3 = \theta''$

We have:

$x_1' = x_2$
$x_2' = x_3$
$x_3' = \mathrm{h} = f'(\theta, \theta', a_T(t), R(t))$

Where h is the angular jerk of the target LOS and is physically bounded for a maneuvering target vehicle due to engine power limitation and the range between the vehicle and a target. The measurable variables are

$y_1 = x_1 + w_1$
$y_2 = x_2 + w_2$

Where w_1 is the resolver or encoder measurement error of the θ angle, and w_2 is the rate gyro sensor measurement error of the target LOS rate. In state space format, the above equations can be simplified to:

$$x' = Ax + Bh \quad (2)$$

$$y = Cx + w \quad (3)$$

And

$$A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

The above state space equations can be used to build either a Kalman filter or a state observer for estimating the x vector.

The Kalman filter approach assumes full knowledge of the state space equations and the two "noise" terms h and w. Their covariance matrices could be pre-determined based on a target maneuvering behavior, the position and rate gyro sensor characteristics for "optimal" filtering. In practice, they are the only parameters that can be tuned to obtain satisfactory Kalman filter performance, in addition to the initial values of state vector covariance matrix.

The alternative approach is to build a state observer. In this specific application, the observer can be systematically tuned [2] for better state estimation accuracy and transient convergence performances. Detailed comparisons between the two approaches are out of the scope of this paper.

With the above Kalman filter or the state observer, the kinematic lead correction at the moment of weapon fire can be estimated as follows for x_3' having been close to zero for a good tracking period of time:

$$\delta_{KL} = \int_{t_{fire}}^{t_{fire}+TOF} x_2(t)dt$$

$$\doteq x_2(t_{fire}) * TOF + \frac{1}{2} x_3(t_{fire}) * TOF^2 \quad (4)$$

δ_{KL} stands for the kinematic lead correction (either azimuth or elevation) at the moment of weapon fire t_{fire} for the projectile leaving the gun muzzle.

During target evasive maneuvers, the above equation is not accurate, and can be invalid if the TOF is large. The difficulty is because both the LOS Rate and the LOS angular acceleration cannot be extrapolated for a long period of time if the target vehicle starts evasive maneuvering after the projectile has left the weapon station.

Sensor measurements, such as resolvers, encoders and rate gyros, are needed for applying the above equation (4). Reference [3] shows one supplier's resolver product data sheet. The sensor accuracies range from a few milliradians to a few microradians. Reference [4] shows another supplier's rate gyro performances. The sensitivity of the rate gyros can be as low as a few microradians per second. Better sensor accuracies can improve the estimation of the kinematic lead correction.

Earth Rotation Rate Impact

As mentioned in previous sub-section, the rate gyro sensors are used for the weapon LOF and target LOS inertial stabilization, and kinematic lead correction. The local geodetic coordinate frame is used to establish the relationship between the weapon projectile and the moving target trajectories. However, the local geodetic coordinate frame is not inertial, and the rate gyro sensor accuracies (e.g., < 10 urad/sec) are high enough to sense the earth rotation rate (which is about 72 urad/sec in amplitude). In some fire control system designs, the earth rotation rate components sensed by the rate gyros are treated as part of gyro drifting biases and are canceled through the nulling function. Operators are required to perform frequent nulling to cancel the errors, which is a distraction to combat tasks. When the vehicle turret rotates 180 degrees right after a nulling, the earth rotation rate could cause the gyro-drifting rate to double. This can be demonstrated easily when placing a combat vehicle at the earth equator on level ground, with its LOF/LOS pointing to the east direction. The earth rotation rate will be sensed by a LOS/LOF elevation rate gyro in full-amplitude of 72 urad/sec, in addition to its innate gyro bias (defined as rate_b). After a nulling action, the LOS/LOF stabilization system will record an elevation rate bias equal to (72 – rate_b) urad/sec, which is used to correct the elevation rate reading later. If we rotate the turret 180 degrees, the sensed earth rotation rate changes its sign and cannot be canceled by the nulling bias. At this setup, the LOS/LOF stabilization loop can have a drifting rate of about 2 x 72 urad/sec = 144 urad/sec. This issue exists in some combat vehicle elevation and traverse drive systems and sight systems.

For a combat vehicle with an INU installed and aligned to a target acquisition sight and LOF servo drives, the earth rotation rate components sensed by the rate gyro sensors can be removed using the following equations, in order to reduce the LOS/LOF drifting error.

Assume that the earth rotation rate vector in the Earth Centered Earth Fixed (ECEF) reference frame is

$$\omega_e = [0\ 0\ 72]^T$$

The combat vehicle location is given by its latitude angle λ. The INU pitch, roll and heading angles are represented by θ, ϕ and ψ. The INU and the sight are stationary relative to the sight installation surface. The alignment correction matrix of the INU installation reference frame to sight installation reference frame is $C_{INU-to-Sight}$.

Then the sight elevation and azimuth rate gyro corrections with respect to the sight installation surface are:

$$\omega_{Sight} = C_{INU-to-Sight} * C_{geo-to-INU} * C_{ecef-to-geo} * \omega_e$$

Where multiple reference frames are used: ECEF frame, local geodetic frame, INU installation frame and the Sight installation frame. If the sight gyro rotation axes can move with respect to the sight installation frame, then the actual rate gyro correction vector is,

$$\omega_{Gyros} = C_{Sight-to-Gyro} * \omega_{Sight}$$

Note that matrix $C_{Sight-to-Gyro}$ depends on the axis orientations of the sight rate gyros with respect to the sight installation frame.

Earth rate correction equations for the LOF stabilization system can be derived similarly.

Cant Angle Correction

Cant angle within this context is defined as the angle between the local horizontal plane and the weapon installation reference plane. The relationship between the weapon projectile and the moving target trajectories is established via the local geodetic coordinate frame. When the vehicle is on level ground (i.e., the cant angle is zero), the LOS and the LOF elevation and azimuth angles, measured with respect to their installation reference planes, equals to their corresponding angles in the local geodetic coordinate frame. Otherwise, the cant angle will affect the projectile hit point on a target.

Early fire control subsystems have cant angle sensors. With INU installed on combat vehicles, the cant angle measurement can be replaced by the pitch (θ) and roll (ϕ) angle measurements of the weapon station. Assume that the INU installation reference frame is aligned with the weapon station reference frame. Then both pitch and roll angles will affect the computation of the target LOS elevation and azimuth angles relative to the local geodetic frame. Since the ballistic lead elevation and azimuth corrections are computed relative to the local geodetic frame, we cannot ignore the cant effects when computing the LOS-to-LOF corrections relative to the weapon station reference frame. Summing the ballistic lead corrections and the LOS sensor measurements directly will introduce significant errors at high cant angle conditions.

Again, the accuracies of the weapon station pitch angle, roll angle, LOS and LOF sensor measurements affect the cant angle correction and the estimation accuracy of the total LOS-to-LOF corrections.

Position Sensor Error Impact

The total LOS-to-LOF corrections at the moment of weapon firing are an offset angle between the LOS vector and the LOF vector that can be controlled precisely by a fire control subsystem. To calculate the offset angle, we need to determine the LOS vector and the LOF vector with respect to several coordinate frames. Normally, the LOS vector is measured via position sensors relative to the sight installation reference frame. The LOF vector is measured via position sensors relative to the weapon installation reference frame. Therefore, the position sensor errors affect the total LOS-to-LOF corrections directly.

For a position measurement error of 1.0 mrad and a target at 1000 meters away, the LOF aimpoint is about 1.0 meter off the target solely due to the sensor accuracy. The accuracy requirements of position sensors should be determined based on the weapon hit probability requirement.

IMPACTS TO TARGET LOCATING SUBSYSTEM

The error sources of a target locating subsystem discussed in this paper are the INU/GPS position error, the INU Euler angle errors, the target LOS vector measurement errors, the Universal Transverse Mercator (UTM) based target location computation approach, and the target range error. Other error sources are out of the scope of this paper.

Vehicle Self-Positioning Error

The vehicle self-positioning errors directly translate into the target location errors, since the target position vector equals to the sum of the vehicle position vector plus the vehicle-to-target range vector (all in the ECEF coordinate frame). The INU alone delivers good position navigation accuracy around the earth. Its drawback is requiring a good starting position input and frequent zero-speed updates, to maintain the positioning accuracy. Integrating an INU with a GPS receiver solves this problem. However, loosely-coupled INU/GPS solutions do not meet more stringent position accuracy requirement, due to high weighting on the GPS position data in the Kalman filtering algorithm and the limited GPS receiver positioning accuracy. The horizontal positioning error of the Defense Advanced GPS Receiver (DAGR) with Precise Positioning Service (PPS) is less than 6.7 meters (95% of the time) [5]. To achieve more consistent and better navigation accuracy, this paper recommends add/enable the differential GPS (DGPS) services for combat vehicles. This change will slash the DAGR horizontal positioning error down to less-than 2.4 meters (95% of the time) [5]. Integrating the DGPS-enabled DAGR with INU can provide high precision vehicle self-position for both stationary and on-the-move.

INU Euler Angle Errors

The INU Euler angles are three major inputs to the targeting equations. These errors translate into target pointing error directly. Assume that the vehicle-to-target range vector with respect to the INU installation reference frame is R_{INU} and the vehicle-to-target range vector with respect to the local geodetic frame is R_{GEO}. Then

$$R_{GEO} = C_{INU-to-GEO}(\phi, \theta, \psi) * R_{INU}$$

where ϕ, θ and ψ are the INU roll, pitch and heading angles respectively. Therefore, their accuracies affect the range vector accuracy directly.

Many companies, such as Honeywell, GE Aviation, L3, Kearfott, KVH Industries, Inc., produce INUs with different technologies and performances. There is a good summary of the INU grades, performances and costs in Table 1 of reference [6]. Table 1 below shows the approximate horizontal Target Location Error (TLE) at 1000-meter horizontal range contributed by the heading (yaw) angle error (one factor only).

Table 1. Delta Horizontal Target Location Error

Heading Error (mrad)	Delta Horizontal TLE Contribution (m)
10	10
1	1
0.1	0.1
0.01	0.01

The pitch and roll angular accuracy contribution to the horizontal TLE is nonlinear and not intuitive.

The heading accuracy of the same INU is latitude-dependent. As the latitude goes up, the true north-pointing component of the earth rotation rate vector goes down. When it is smaller than the INU rate gyro sensor error and noise, the gyro compassing function starts to fail and the estimated INU heading angle accuracy goes down significantly.

Even at the same latitude, an INU still needs initial alignment time to achieve its designed heading accuracy after the INU is powered on. The INU figures out its true heading via gyro compassing while the vehicle is stationary or via dynamic alignment using its directional velocity vector while the vehicle is moving.

In addition, the INU heading accuracy and GPS positioning accuracy go down further at the earth polar areas, due to the nonlinear ionosphere distortion of the GPS signals that cannot be corrected by the GPS satellites.

Target LOS Vector Measurement Error

The target LOS vector relative to the sight reference frame is measured via position sensors in both elevation and azimuth directions. Similar to the fire control subsystems, the position sensor errors directly contribute to the target location errors. Improving the position sensor accuracy is important in achieving high-precision target location.

Target Range Measurement Error

The range between a vehicle and a target can be measured by laser range finders or radars. For example, the range measurement accuracy of existing laser range finders varies between 1 and 20 meters. The target range error also contributes to target location error directly (mainly in the horizontal plane). Designers should determine the range accuracy requirement based on the overall TLE requirement, cost and the range error contribution relative to other error sources.

Target Location Computation Error

The target locations are normally expressed in the UTM coordinates for fire support applications. In some target locating subsystem designs, the target location is computed using equations defined in the UTM coordinate frame with a flat earth assumption. This approach is simple but introduces altitude error due to earth curvature, and additional northing and easting errors due to the UTM projection (a few meters around the meridian line of a zone and up to 10 meters near the zone boundaries).

The earth curvature induced error of the computed UTM-based altitude can be approximated as:

$$h_{curvature} = R^2 * \cos^2(EL_{Target}) * 7.852 * 10^{-8}$$

where R is the slant range to the target and EL_{Target} is the vehicle-to-target LOS elevation angle measured in the local geodetic frame. The following table shows the altitude errors at different target ranges.

Table 2. Earth Curvature Impact to Altitude

R (m)	EL_{Target} (mrad)	$h_{curvature}$(m)
1000	0	0.08
5000	0	1.96
10000	0	7.85
20000	0	31.41
30000	0	70.67

An alternative approach is as follows:

- convert the vehicle position into the ECEF coordinate frame
- add the vehicle-to-target range vector to compute the target position in the ECEF coordinate frame

- convert the target position in the ECEF coordinate frame to latitude, longitude and altitude
- convert the target latitude, longitude and altitude into the UTM coordinates with specified horizontal and vertical datums.

The alternative method eliminates the earth curvature error and the flat earth-induced UTM computation errors, and reduces the overall target location errors. The only approximation occurs between latitude/longitude/altitude and the UTM coordinate conversion, which cannot be avoided if we have to present the target locations in UTM coordinates.

CONCLUSIONS

This paper discusses the navigation accuracies and the sensor accuracies in the context of fire control subsystem and target locating subsystem performances. Some of the insights and improvements presented in this paper can be applied to enhance the lethality of many combat vehicles.

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