PRECISION TARGETING USING GPS/INERTIAL-AIDED SENSORS

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ABSTRACT

Precision weapons including miniature GPS/inertial guidance systems have become the mainstay of the DoD arsenal. These "smart" weapons can be delivered to target with unprecedented accuracy, without requiring expensive seekers for terminal guidance. GPS-guided weapons are in development for gun-launched, air-to-surface and even mortar munitions.

In order for these precision weapons to be effectively deployed, the precise target coordinates must be included in the call-for-fire. Historically, sensors have relied on georegistration techniques using ground truth to derive target coordinates. This method is time consuming and can be unreliable in poor visibility conditions when ground reference data is hard to observe.

Under contract to the US Navy, NAVSYS has developed the capability to determine precise target coordinates without relying on ground truth by using GPS/inertial-aided sensors. In this paper, this "smart sensor" technology is described and test data taken in the field is presented that demonstrates the performance of the high accuracy GPS/inertial alignment algorithms and sensor calibration performance.

INTRODUCTION

In a dynamic battlefield environment, there is a core need to be able to rapidly process imagery data from airborne surveillance sensors and extract target coordinates in a timely fashion. Previous image-based targeting system implementations have used stereo photogrammetric techniques to determine the 3-D relative position of image features to the camera location. These require intensive data-processing to resolve for position and rotation angle changes between the stereo images and also rely on known reference points from a database to establish the absolute location of target features.

With the precision geolocation capability provided by the Global Positioning System (GPS) and the advent of miniaturized, low cost inertial sensors, it is now possible to deliver imaging sensors with embedded georegistration capability, avoiding the need for extensive image analysis to extract precise target coordinates. NAVSYS have developed a mobile precision video targeting system using this technology and are currently developing a man-portable targeting sensor with the same capability. These "smart sensors" provide timely, accurate targeting data without requiring any external georeferenced data.

MOBILE PRECISION TARGETING SYSTEM

NAVSYS has integrated a high resolution digital camera with our GPS/inertial technology to provide a mobile precision targeting system, the GI-Eye. This derives the precise position and 3-D attitude of the optical sensor which enables the target coordinates to be extracted from the digital images using the passive video triangulation. This system concept allows for rapid and accurate geo-registration of objects remotely without the need for any known registration points within the image. The GI-Eye sensor is shown in Figure 1 and a specification for the product can be found in reference [1].

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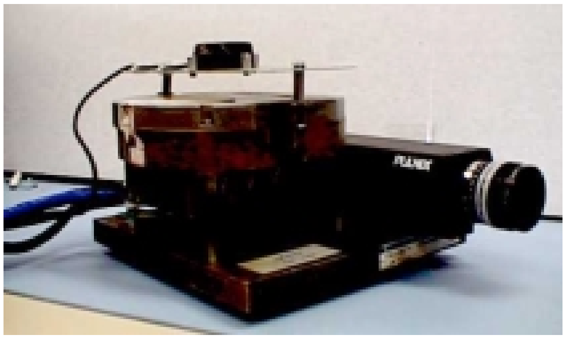

Figure 1 GI-Eye GPS/Inertial/Video Sensor Assembly

MAN-PORTABLE TARGETING SENSOR

NAVSYS are also currently developing a man-portable targeting sensor, SPOTS, which is designed to allow precision target coordinates to be extracted from a single location. This requires the use of a rangefinder device to observe range in addition to the GPS/inertial derived position and azimuth data.

Current generation man-portable targeting systems include the Target and Location Designation Hand-off System (TLDHS) being deployed by the U.S. Marine Corps. This system provides an autonomous targeting capability, but the accuracy of the system is currently limited by its ability to derive the azimuth to the target. The TLDHS system uses a magnetic compass to determine heading and tilt sensors to determine the complete 3-D attitude. Using a compass, magnetic north can be measured to at best 0.5 degrees (10 mrads). Under contract to the US Navy, NAVSYS are developing a man-portable targeting sensor (SPOTS) which uses GPS/inertial data to derive the target azimuth to an accuracy of 0.05 degrees (1 mrad).

The SPOTS system components and interfaces are illustrated in Figure 2. A GPS receiver is included which provides the location of the targeting sensor and also provides the raw information from which the inertial attitude data is derived. A Micro-Electro-Mechanical Sensor (MEMS) Inertial Measurement Unit (IMU) is used to derive the attitude of the target relative to the sensor using the targeting optics. A laser rangefinder is also included which observes the range from the sensor to the target. The data from each of these components is integrated into a portable computer which derives the target coordinates as an output from the SPOTS sensor.

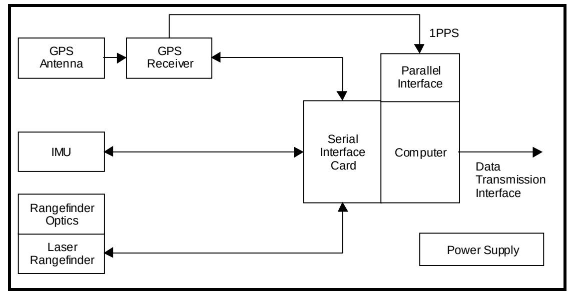

Figure 2 SPOTS System Components

In Figure 3, the SPOTS sensor assembly which is currently being built under our Navy funded effort is shown. This uses the Leica rangefinder and optics, integrated with a MEMS IMU and GPS receiver card using NAVSYS' InterNav integrated GPS/inertial software package[2.]

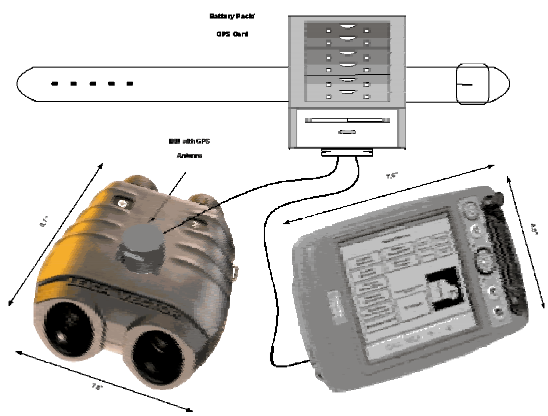

Figure 3 SPOTS Targeting Sensor Assembly

TARGET OBERVATION EQUATIONS

The accuracy of the final targeting solution is a function of the accuracy of the core observation components. In this section, the observation equations which are used to derive the solution accuracy are derived with a system error model for the targeting sensors.

The estimated line-of-sight to the target in the navigation (North, East, Down) frame can be computed by transforming the pixel derived line-of-sight vector in camera axes to the navigation frame using the inertial attitude data.

Equation 1

$$l^{(C)} = [p_x \quad p_y \quad f]/\sqrt{p_x^2 + p_y^2 + f^2}$$

where p_x and p_y are the target pixel coordinates derived from the image data, and f is the focal length of the camera (in pixel units). In the case of a simple optical device, such as the sight on a rangefinder, the line of sight in the sensor frame simplifies to the following equation.

Equation 2

$$l^{(C)} = [0 \quad 0 \quad 1]$$

The alignment between the sensor frame and the inertial body frame is fixed and is defined by the matrix C_C^B. The direction cosine matrix derived from the inertial data to transform from body to navigation frame coordinates can be used to compute the line-of-sight from the camera location to the target location in navigation frame coordinates.

Equation 3

$$l^{(N)} = C_B^N C_C^B l^{(C)}$$

The target coordinates can be estimated from the sensor location data (x_k), the line of sight to the target ($l^{(N)}$) and the estimated range (R) to the target.

Equation 4

$$x_T^{(N)} = x_k^{(N)} + R\ l^{(N)} \qquad R = |x_T - x_k|$$

TARGET SOLUTION ERRORS

The target solution errors can be computed from the following equation based on the error in the initial solution accuracy, the range error and the pointing error to the target.

Equation 5

$$\tilde{x}_T = \tilde{x}_k + \tilde{R} l^{(N)} + \hat{R} \tilde{l}^{(N)}$$

The pointing error to the target is a function of the alignment error (θ) in the system. This can be derived through the following equation.

Equation 6

$$\tilde{l}^{(N)} = \tilde{C}_C^N l^{(N)} = [-\theta \times] l^{(N)} = [l^{(N)} \times]\theta$$

Substituting this expression for the pointing error into Equation 5, gives the following expression for the target solution error.

Equation 7

$$\tilde{x}_T = \tilde{x}_k + \tilde{R} l^{(N)} + [\hat{R} l^{(N)} \times]\theta$$

GPS POSITION ACCURACY

The sensor position accuracy is a function of the GPS positioning accuracy. This is summarized in Table 1 for the following different positioning services provided by GPS

GPS Standard Positioning Service (SPS)

The GPS SPS accuracy is deliberately degraded by the addition of Selective Availability (SA) error and is currently at a level of 100 m 2DRMS. The equivalent CEP is roughly 42 meters, as derived from the following equations and assumptions.

Equation 8

$$CEP = 0.588(\sigma_x + \sigma_y)$$

Equation 9

$$2DRMS = 2\,HDOP\,\sigma_{PR} = 2\sqrt{\sigma_x^{\ 2} + \sigma_y^{\ 2}}$$

If the error distribution is assumed to be circular (i.e. σ_x=. σ_y) then the following relationship exists between these error measures.

Equation 10

$$CEP = 1.177\sigma = 1.177(2DRMS/2/\sqrt{2}) = 0.42\,(2DRMS)$$

GPS Precise Positioning Service (PPS)

The GPS PPS has a specified 3-D accuracy of 16 meters Spherical Error Probable (SEP). Under typical geometry conditions, the vertical error is roughly twice the error in the other dimensions (the average VDOP=2 while the average HDOP=1.5). Results from conventional targeting systems using the PPS (such as the TLDHS) indicate that an average CEP for the GPS system is roughly 8 meters.

GPS Wide Area Augmentation Service (WAAS)

The FAA have developed a wide-area differential GPS service that provides real-time corrections to the GPS system errors through a geostationary satellite broadcast. This system is designed to support precision aircraft operations down to SCAT-1 landings. Test data from Stanford University has indicated that the system performance provided from this service is consistently within 1.5 m CEP. A military version of this system could be expected to provide the same level of performance.

Table 1 GPS Positioning Accuracy

GPS Service	SPS	PPS	WAAS
CEP	42 meters	8 meters	1.5 meters

RANGING ACCURACY

With the man-portable SPOTS system, the range to the target is given from the laser rangefinder. This has a specified accuracy of +/- 1 meter to distances of 1 km, which is equivalent to a range error of roughly 0.67 m (1σ).

With the mobile GI-Eye system, shown in Figure 1, the targeting solution is computed using a video triangulation technique to solve for the range to the target. This is illustrated in Figure 4. From multiple observations of the same target from different sensor locations, the position of the target can be extracted using a triangulation algorithm.

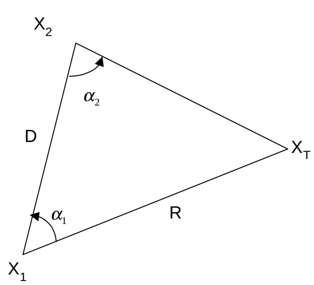

Figure 4 Video Triangulation Geometry

From simple trigonometry, the following relationship can be derived from the line of sight data to the target solution and the distance between the two sensor locations.

Equation 11

$$\frac{R}{\sin\alpha_2} = \frac{D}{\sin(\pi - \alpha_1 - \alpha_2)}$$

This can be used to solve for the estimated range to the target.

Equation 12

$$\hat{R} = \left| x_1 - x_2 \right| \frac{\sin\alpha_2}{\sin(\pi - \alpha_1 - \alpha_2)}$$

The accuracy of the estimated range becomes a function of the accuracy of the sensor location data and the geometric factor from the triangulation solution (G).

Equation 13

$$G = \frac{\sin\alpha_2}{\sin(\pi - \alpha_1 - \alpha_2)}$$

In Figure 5, the geometric range factor (G) is shown as a function of the distance traveled, scaled by the range to the target, assuming a symmetrical triangulation solution (i.e. R_1=R_2). To achieve a geometry factor of 1, the distance traveled needs to be equal or greater to the range to the target.

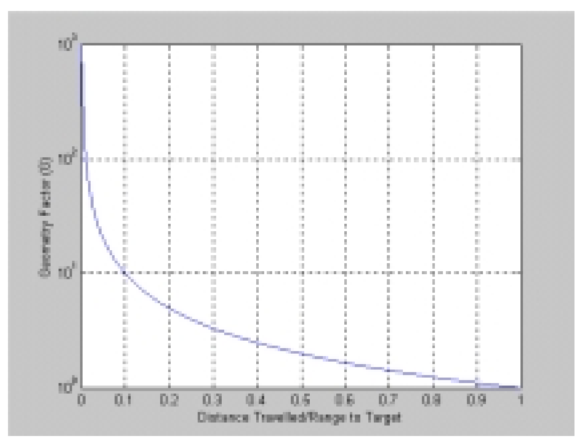

Figure 5 Geometry Factor (G) for Triangulation

In this case, where the two ranges are assumed equal ((i.e. R_1=R_2). the geometry factor and range error simplifies to the following equations.

Equation 14

$$G = \frac{\sin\alpha}{\sin(\pi - 2\alpha)} = \frac{\sin\alpha}{\sin(2\alpha)} = \frac{\sin\alpha}{2\sin\alpha\cos\alpha} = \frac{1}{2\cos\alpha} = \frac{R}{D}$$

Equation 15

$$\tilde{R} = \Delta\tilde{x}G = \Delta\tilde{x}\frac{R}{D} \quad \text{(when } R_1 = R_2\text{)}$$

With a GPS/Inertial navigation system, the delta-position accuracy is a function of the inertial velocity error, damped with the GPS position and velocity updates. Over short periods of time, this will be better than the GPS delta-position accuracy, tending to the GPS error values over longer intervals. Typically the velocity error in the GPS/INS solution is better than 0.01 m/sec. The position error and distance traveled now become a function of the velocity accuracy and velocity of the vehicle.

Equation 16

$$\tilde{R} = \Delta\tilde{x}\frac{R}{D} = \tilde{V}t\frac{R}{Vt} = \frac{\tilde{V}}{V}R$$

If the aircraft is flying at 100 knots (51 m/sec), and the velocity accuracy is 0.01 m/sec, then the range error will grow at roughly 2×10^{-4} times the range to the target using the triangulation observations.

ATTITUDE ACCURACY

The attitude error can be considered a composite of the attitude error introduced by misalignments between the targeting sensor and the attitude sensor and the error in the attitude sensor itself. Inexpensive tilt sensors can generally observe the pitch and roll angles fairly accurately (e.g. 0.1 mrad). The dominating error source becomes the ability to calibrate the misalignment angles between the sensors and to observe the azimuth (or heading) of the sensor.

NAVSYS have developed a precision calibration technique to remove the effects of misalignments between the targeting and azimuth sensors. In Figure 6, a plot is included which shows where a surveyed target location lies in the sensor image compared to where its predicted location is based on the attitude sensor data. This shows the typical errors that can be expected pre-calibration to be on the order of 5 mrad. In Figure 7 the same plot is shown following NAVSYS' calibration procedure. In this case, the alignment errors have been reduced to within 300μ rad.

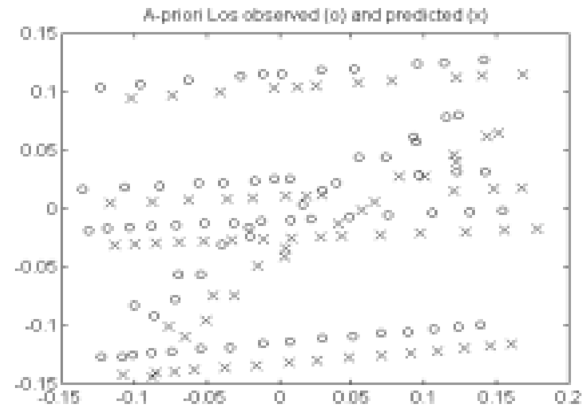

Figure 6 Observed Misalignment Errors (Pre-Calibration)

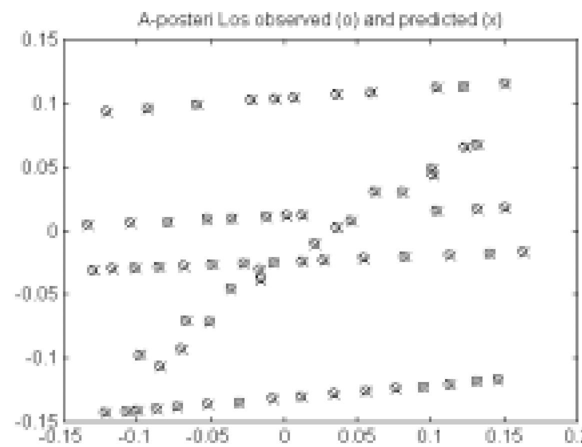

Figure 7 Observed Misalignment Error (Post -Calibration)

In current generation targeting systems, magnetic sensors are used to observe the azimuth to the target. These are affected by local magnetic perturbations and are (at best) accurate to only 10 mrad relative to true (geodetic) north. In the GI-Eye and SPOTS systems, an inertial sensor is used in place of the magnetic compass to measure heading by aligning relative to the GPS geodetic coordinate system. A precision alignment technique has been developed that allows rapid alignment of the inertial data, even for a man-portable system using low quality MEMs gyroscopes and accelerometers. In Figure 7, simulation results of this alignment technique are shown which illustrate the capability to acquire the target azimuth to an accuracy of better than 1 mrad (1σ) within 10 seconds of turn-on. Field testing has been performed using the GI-Eye system that validates these simulation results.

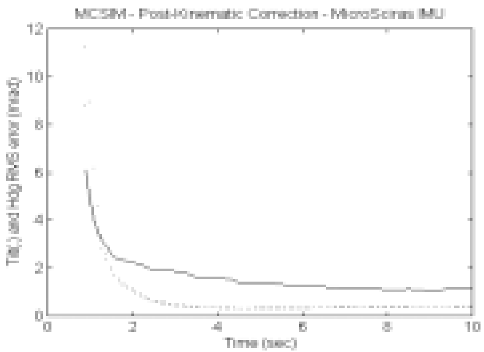

Figure 8 Monte-Carlo Simulation of Micro-Sciras Alignment Performance

TARGET SOLUTION ACCURACY

The target solution CEP can be computed from the expected position, attitude and ranging errors using Equation 7 and Equation 8. If the GPS position errors are assumed to have circular distribution, then the CEP can easiest be computed by deriving the 1-sigma distribution in the targeting sensor frame axes. In the following equations, σ_x is computed in the line-of-sight direction to the target, and so comprises the range error components, while σ_y is computed perpendicular to this direction and so includes the azimuth error. Using this definition, the following expression is derived for the target CEP.

Equation 17

$$CEP_{GPS} = 1.177\sigma_{GPS}$$

$$\sigma_x = \sqrt{\sigma_{GPS}^2 + \sigma_R^2}$$

$$\sigma_y = \sqrt{\sigma_{GPS}^2 + R\sigma_\theta^2}$$

$$CEP = 0.588\,(\sigma_x + \sigma_y)$$

In Table 2, the different errors are summarized for three different configurations of targeting sensor. In the first, it is assumed that the PPS solution is used to derive the target coordinates, a magnetic sensor is used to determine the range to the target, and a laser rangefinder is used to measure the range to the target. In the second configuration, a MEMs inertial azimuth sensor is substituted for the magnetic compass. In the third configuration, the WAAS corrected GPS solution is used. In the last configuration, a next generation version of the airborne GI-Eye targeting system is shown. This system is assumed to have an alignment accuracy of 0.1 mrad and a ranging accuracy based on a triangulation solution as shown in Equation 16 assuming an aircraft velocity of 100 knots and velocity accuracy of 0.01 m/sec. Under contract to the Office of Naval Research we are designing an aircraft targeting system with this type of projected performance.

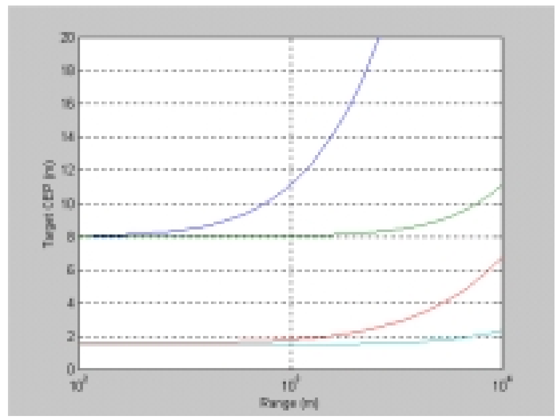

Figure 9 Targeting Accuracy (CEP) versus range (meters)

In Figure 9, the target CEP is plotted for each of these cases against the range of the sensor from the target. In Table 2, the CEP at 1 km, 2 km, 5 km and 10 km ranges from the sensor is shown for each of the cases simulated.

Table 2 Targeting Sensor Accuracies

Targeting Sensor	Case 1	Case 2	Case 3 (SPOTS)	Case 4 (GI-EYE)
GPS Accuracy	8 m (CEP)	8 m (CEP)	1.5 m (CEP)	1.5 m (CEP)
Azimuth Accuracy	10 mrad	1 mrad	1 mrad	0.1 mrad
Ranging Accuracy	0.67 m (1σ)	0.67 m (1σ)	0.67 m (1σ)	2e-4xR
CEP (R=1 km)	11.1 m	8.1 m	1.8 m	1.5 m
CEP (R=2 km)	16.4 m	8.2 m	2.2 m	1.5 m
CEP (R=5 km)	33.7 m	9.0 m	3.9 m	1.8 m
CEP (R=10 km)	63.0 m	11.1m	6.8 m	2.3 m

GI-EYE TARGETING TEST DATA

Table 2 shows that using the high accuracy targeting technology described in this paper, real-time targeting accuracies of 1-2 meters can be expected, at distances of 2-10 km from the target depending on the type of GPS/inertial-aided sensor used. NAVSYS have performed testing of the targeting accuracy of the GI-Eye system using “target” markers installed over known survey points. The GI-Eye system was configured to use a commercial wide-area differential GPS service to provide the DGPS coordinates and to use the precision GPS/inertial alignment and calibration system developed by NAVSYS to determine the precise attitude of the targets within the video sensor image. The target coordinates derived from the GI-Eye system were compared with the surveyed target location based on kinematic GPS solutions. The target errors from this testing, plotted in Figure 10, all lie within a 2 m CEP circle.

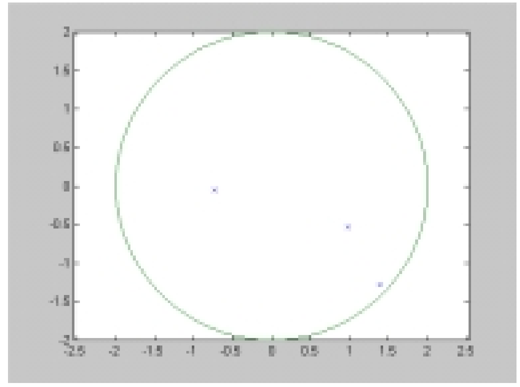

Figure 10 Target Test Data and 2 meter CEP circle

CONCLUSION

The analysis and testing performed to date under this effort has shown that it is possible to achieve target location errors (TLE) within 2 meters at distances of up to 2 km with a man-portable targeting system. This level of accuracy can be supported to greater ranges from an airborne targeting sensor. The increased precision is achieved through the use of the following capabilities.

1) Wide-area GPS corrections from a geostationary satellite broadcast are used to improve the accuracy of the GPS coordinates used to provide the targeting sensor reference location.
2) An inertial sensor is used in place of a magnetic compass and is precisely aligned using the GPS data to provide the target’s azimuth
3) The range to the target is derived either using a laser rangefinder or from passive video triangulation using the targeting sensor data

In this paper, an analysis of the system errors was presented with simulation results and field test data for the precision targeting systems being developed by NAVSYS. Work is continuing at NAVSYS on developing a man-portable targeting system (SPOTS) capable of providing target coordinates with a 2 m TLE and an airborne version of our GI-Eye targeting system capable of providing this level of performance out to extended ranges from the target.

ACKNOWLEDGEMENT

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[2] I. Longstaff et al, “Multi-Application GPS/Inertial Navigation Software,” Proceeding of GPS-96, , September 1996, Kansas City, MO