Semi-Active Guidance using Event Driven Tracking

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Abstract – This paper proposes the use of an active laser imaging system for semi-active missile guidance. The missile uses an address-event representation seeker, which records the pixel position and the time of arrival of the laser pulses (events). Accurate timing information of the events allows the target to be tracked and generates a closed-loop guidance solution. The paper models an example engagement, where a missile intercepts an unguided surface-to-surface rocket.

Keywords: Burst Illumination Laser (BIL) imaging, Address Event Representation (AER) imaging, missile guidance, Counter Rocket-Artillery-Mortar.

1 Introduction

This paper proposes a method for semi-active missile guidance using a pulsed laser and an address-event representation imager operating as a seeker. Pulsed laser sources can be used in imaging systems to illuminate objects that are covered by obscurants – smoke, clouds or fog – this type of imaging system is often referred to as a Burst Illumination Laser (BIL) imager [1]. The key to separating the foreground obscurants from the objects of interest (targets) in the background is to shutter the image so that the returned laser energy that reflects from the foreground (a range ‘gate’) is removed. The range-gating of the return signal generally requires an accurate time reference and an estimate of the range to the target. A guidance method based on this approach, such as the one proposed here, should be robust to the presence of smoke and fog.

The solution examined in the current paper is the use of an Address-Event Representation (AER) imager to provide the time reference for the return pulse. The AER sensor provides a sequence of ‘events’ [2], which specify the location of an object (within the image) and the timing of the event – the returned laser signal – with an accuracy far better than the typical frame rate of a standard imager and without the extra complication of a shuttered range gate.

The example that is studied here is where the AER sensor assumes the role of a missile seeker and the laser pulses are produced by a ground-based target tracking system. The ground-based tracking system illuminates the target with regularly spaced pulses (at a particular laser wavelength) and the reflected energy is used by the seeker to guide the missile onto the target – known as semi-active guidance [3]. The target in this case is an unguided ballistic target based on a 107 mm spin-stabilized, surface-to-surface rocket [4]. The interceptor is a generic 50 kg guided weapon with a two-stage boost-sustain rocket motor. Both systems are modelled using six-degree of freedom models with aerodynamics based on standard approximate models [5].

The interceptor model is used to generate representative trajectories, which can then be used to generate measurement data for use with the BIL-AER seeker/tracker system. It is used to demonstrate that a BIL-AER system can be used to produce a closed-loop guidance solution for such an interceptor.

2 Proposed BIL-AER Sensor System

The system consists of two parts: a ground based target tracking system and an interceptor. The ground-based tracker is equipped with a pulsed laser system, which can be used to illuminate the target. It is a standard tracking system. It is not modelled directly and it is assumed to track the target accurately enough to keep the target illuminated throughout its flight and it is assumed to produce regular laser pulses at pre-defined intervals. The interceptor has an inertial navigation system to estimate its own position and an AER imager/seeker, which provides the target information: the time of flight for the laser pulse (from ground-based tracker to the target and back to the seeker) and the line of sight to the target.

2.1 Burst Illumination Laser (BIL) Imaging

The major advantage of Burst Illumination Laser (BIL) imaging is it can be used to ‘see through’ cloud and obscurants. In conventional BIL imaging, a laser is used to illuminate a target and the reflected laser energy is collected and imaged using a conventional camera [1] (although the camera will often be an infrared imager and the laser is an infrared rather than a visible band laser). The illumination source and the imager are co-located so that the reflected light from the illuminated area can be range-gated to remove the reflections from obscurants in the foreground. The fact that the laser and the imager are co-located simplifies the determination of the range to the target and the range-gating process because the emission of the pulse and the shuttering of the imager can use the same time reference. The problem is more pronounced if the imager and the laser source are physically separated.
and do not necessarily share a common time reference. The use of a shutter to gate the return signal is required to remove the reflections from obscurants between the imager and the target – assuming that any obscurants are not sufficiently dense to stop the laser signal completely. In the system considered here, the timing information is provided by the timing of the events produced by the AER imager – as discussed in the next section – and no shutter or range gate is required. The foreground reflections and the target reflections can be separated by the arrival time of the ‘events’. There are similarities to other laser imaging systems, such as 3D ‘Flash’ Ladar cameras [6] and Geiger mode Ladar systems [7]. A 3D Flash Ladar system uses a staring array and a pulsed laser illuminator and records the time of flight of the laser signal at each pixel – however, the reset time of the pixels is normally set globally and only a single event will be recorded per frame (typically standard image frame rate) [6]. This makes looking through obscurants difficult. Geiger mode Ladar cameras, by contrast, can generate a sequence of events – which are recorded at different times – but each pixel has a separate timing/readout circuit [7]. Here, the event based signal representation and the global timing of an AER imager provides a simple signal representation and readout circuit structure, which should be more amenable to implementation in a missile seeker.

2.2 Address Event Representation (AER) Imaging

The Address-Event Representation (AER) imager is a novel form of camera – one where the intensity of the scene is not sampled at regular intervals, rather the photocurrent generated by the light falling on each pixel is integrated until it reaches a threshold level [2]. Once the pixel has exceeded this threshold level an event is triggered which is recorded as a time and a pixel position. These events encode the light intensity of the scene in the times that the threshold-crossing events occur. The intensity is related to the frequency of pixel activation events. The result is a sequence of asynchronous events rather than a regular set of two-dimensional samples that would be obtained from a conventional imager – see Figure 1. Bright areas can produce very large numbers of closely spaced events, and dark areas produce few if any threshold crossings.

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Figure 1 – Schematic representation of (a) conventional fixed frame rate imager and (b) address-event representation imager.

Figure 2 – Diagram of scenario with obscurants between the laser/seeker and the target. The reflected energy from the obscurants is temporally separated from the reflection from the target. The event generated by the target reflection provides an estimate of the time of flight from the laser source and the two-dimensional position in the seeker image.
For a BIL-type system, as long as the reflected laser pulses are sufficiently strong to trigger a threshold-crossing event, the relative time of flight of the laser pulses from the ground-based tracker to the target and then to the AER seeker is encoded in the event timings. The timing information from the events generated by a sequence of illumination pulses provides estimates of the range rate (closing velocity) and the range (if the interceptor has been locked onto the target before launch – the initial pulse measurement and an initial target location from the fixed tracker will provide a time reference).

The sensor/seeker is mounted on gimbals to keep the target within the field of view. It will generate angular measurements of the target position within the field of view of the sensor (from the gimbal angles and pixel-event locations). This angular information gives the line of sight to the target and its differential gives the line of sight rate – both of which can be used in a guidance system. The data can then be combined with the data from the inertial navigation system (position, velocity, attitude and angle rates) to convert these measurements into earth-oriented axes.

The proposed configuration is shown in Figure 2. In this example, the events generated by obscurants will occur in advance of the events from the background scene. As long as the obscurants are sufficiently transparent to allow enough of the illumination pulse to be reflected back to the detector, then the reflected light will generate events in the detector. The timings of these events will depend on the total time of flight from the illumination source to the target area and back to the detector, as a result they will encode relative range information for the seeker/interceptor and the target.

For simplicity, it is assumed that the background illumination level in the waveband of the sensor is sufficiently low that is will not generate events, and the laser energy is sufficiently high that the laser will trigger events in the seeker in all of the cases considered here. The main seeker performance parameters of relevance here are the number of events that can be processed in a given period of time and the angular resolution of the imager. The response time of the sensor and the minimum period between adjacent events limits the range/time of flight accuracy of the sensor, and the angular resolution sets the accuracy of the line of sight measurements.

### 3 Scenario

The scenario considered here is a Counter Rocket-Artillery-Mortar (C-RAM) example, where a relatively short-range surface-to-surface projectile is being fired at a location and there is a missile defence unit, which may engage the projectile whilst it is in flight [8]. Clearly, the projectile is small and can be assumed to be travelling quite fast (> Mach 1). The interceptor therefore needs to accelerate rapidly and close on the target as soon as possible and, preferably, before it has reached the apogee of its trajectory because the closer the target projectile is to the location being fired upon, the more likely it is that shrapnel or other material will still fall on the location.

For simplicity, a single target model is used and the payload and damage mechanism of the interceptor is not considered – the only requirement in the current paper is to guide the interceptor as close to the target projectile as possible as quickly as possible. In addition, it is assumed that the interceptor and the target projectile model lie in a plane – i.e. the interceptor is relatively close to or has been otherwise deployed to protect the location being targeted by the unguided projectile. This simplifies the engagement geometry somewhat but it still provides realistic trajectory data to test the accuracy of the BIL-AER seeker/tracker.

#### 3.1 Target Model

The target projectile in this paper is a 107 mm spin-stabilized surface-to-surface rocket. This type of weapon is relatively common [4]. It has a limited range (limited to around 8 km) but it is simple to deploy and it does not require a sophisticated launcher or aiming system. The projectile is modelled by a six-degree of freedom model with approximate aerodynamics given by reference [5].

The parameters for the projectile are:

<table>
<thead>
<tr>
<th>Diameter</th>
<th>107 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>83.6 cm</td>
</tr>
<tr>
<td>Initial Mass</td>
<td>18.8 kg</td>
</tr>
<tr>
<td>Mass of Fuel</td>
<td>6.6 kg</td>
</tr>
<tr>
<td>Rocket Burn Time</td>
<td>16.0 sec</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>150.0 sec</td>
</tr>
<tr>
<td>Max Speed</td>
<td>Mach 1.1</td>
</tr>
<tr>
<td>Nose Fineness Ratio</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 1 – Target Projectile, 107mm Rocket.

#### 3.2 Interceptor Model

The airframe for the interceptor is based on existing guided weapons in the 50 kg class. This is motivated by the fact that guided weapons are often built around existing airframes and existing launchers – although the semi-active guidance algorithm and the BIL-AER target tracker is not dependent on the specifics of the interceptor. The interceptor six-degree of freedom model is used to generate a representative trajectory and the associated measurement noise. It has a two-phase, solid-fuel rocket motor and it is canard controlled and fin-stabilized. The initial boost phase of the motor accelerates the interceptor to around Mach 2.2 and the second sustain phase ensures that the missile does not lose speed too quickly, maintaining speeds in excess of Mach 1.7. This allows it to engage the target early in the ballistic trajectory. The canards provide enough lift and lateral acceleration to guide the interceptor onto the target projectile.

The interceptor is assumed to have a weapon grade inertial navigation system, which is relatively accurate over short distances and for short duration flights, and a
BIL-AER seeker. The interceptor is locked onto the target before launch and it uses the regularity of the laser illumination pulses to provide a time reference, which in turn allows the target range and closing velocity to be estimated – see section 4.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>170 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.63 m</td>
</tr>
<tr>
<td>Initial Mass</td>
<td>50.0 kg</td>
</tr>
<tr>
<td>Mass of Fuel – Boost</td>
<td>15.0 kg</td>
</tr>
<tr>
<td>Mass of Fuel – Sustain</td>
<td>15.0 kg</td>
</tr>
<tr>
<td>Rocket Burn Time – Boost</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>Rocket Burn Time – Sustain</td>
<td>10.0 sec</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>250.0 sec</td>
</tr>
<tr>
<td>Max Speed</td>
<td>Mach 2.2</td>
</tr>
<tr>
<td>Nose Fineness Ratio</td>
<td>2.0</td>
</tr>
<tr>
<td>Separation Interval</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>Canard Area</td>
<td>0.00177 m²</td>
</tr>
<tr>
<td>Maximum Canard Deflection</td>
<td>15.0 degrees</td>
</tr>
<tr>
<td>Fin Area</td>
<td>0.0071 m²</td>
</tr>
</tbody>
</table>

Table 2 – Interceptor, 50 kg guided missile.

The measurements are used to provide guidance commands via standard Proportional Navigation (PN) guidance [9] of the form:

\[
\mathbf{a_c} = \frac{N}{R^2} \left((\mathbf{r}_t - \mathbf{r}_{tgt}) \times (\mathbf{v}_t - \mathbf{v}_{tgt})\right) \times \mathbf{v}_t
\]

\[
= \frac{N}{R^2} \left((\mathbf{r}_{tgt} \times \mathbf{v}_t) \times \mathbf{v}_t\right)
\]

where \(\mathbf{a_c}\) is the commanded acceleration, \(N\) is the navigation constant (\(N = 8\) in the examples shown here), \(R\) is the range from the interceptor to the target, \(\mathbf{r}_t\) is the position of the interceptor, \(\mathbf{r}_{tgt}\) is the position of the target, \(\mathbf{v}_t\) is the velocity of the interceptor, \(\mathbf{v}_{tgt}\) is the velocity of the target, \(\mathbf{r}_{los}\) is the line of sight vector and \(\mathbf{v}_c\) is the closing velocity of the engagement. To this commanded acceleration, a gravity bias term is added to ensure that the interceptor is not pulled ‘under’ the target in the terminal phase of the engagement.

\[
\Delta r(t) = \mathbf{r}_0 - \mathbf{r}_{tgt}(t) + \mathbf{r}_{tgt}(t) - \mathbf{r}_i(t)
\]

However, this range is not measured directly because the interceptor does not have a common time reference with the ground-based tracker – although it does need to know the interval between the laser pulses. The measured quantity in this case is:

\[
\Delta R(t) = c t_b + \left| \mathbf{r}_0 - \mathbf{r}_{tgt}(t) \right| + \left| \mathbf{r}_{tgt}(t) - \mathbf{r}_i(t) \right|
\]

where \(c\) is the speed of light and \(t_b\) is a time bias. In this equation, the position of the ground-based tracker is known, the position of the interceptor is known (from its on-board inertial navigation system), and it is necessary to find the target position and the closing velocity \(\mathbf{v}_c\) between the interceptor and the target. To find the time bias, the interceptor must be locked on to the target prior to launch, where the ground-based tracker provides an initial target position estimate and the seeker detects at least one of reflected pulses from the target (although in practice a
number of pulses can be used to improve the estimate of the time bias. This provides an estimate of $\Delta r$.

$$\Delta X(t) = |Z_0 - Z_i(t)|$$

from the inertial navigation system and the launch location. These three measurements provide the information required to fix the target position, the length of one side of the triangle in Figure 4, the combined length of the other two sides and one internal angle. If the length of the two unknown sides are written as $\alpha \Delta r$ and $(1-\alpha)\Delta r$ (with $0 \leq \alpha \leq 1$) then $\alpha$ can be found from:

$$\alpha(t) = \frac{(\Delta r(t)-ct_b)^2 - \Delta X(t)^2}{2(\Delta r(t)-ct_b)[(\Delta r(t)-ct_b) - \Delta X(t)\cdot\cos\theta(t)]}$$

This then provides enough information to fix the target position and successive measurements (when filtered) provide an estimate of the velocity of the target, both of which can be used to find the closing velocity for use in the guidance system using (1).

The initialization of the interceptor, locking on before launch, to provide an estimate of $t_b$ is not ideal. The accuracies of the position and velocity estimates during flight are dependent upon the accuracy of the initial time bias. Although the estimation of $\alpha$ and hence the range to the target is sensitive to random fluctuations in the value of $t_b$, it is relatively insensitive to a fixed error in the time bias. This is true as long as the trajectory of the target is at an angle to the line of sight between the ground-based tracker/illumination source and as long as the interceptor line of sight angle to the target does not change too rapidly. The unguided projectile has a limited range as a direct fire weapon and is more suited to an indirect, ballistic path so the first condition will normally be valid, and a PN guidance law controls the rate of change of the line of sight angle, which means that the second condition is also likely to be true.

5 Results

AER imagers are relatively new and the ones that have been reported in the literature have tended to be small scale with a limited number of pixels [2]. However, an application that requires a larger, higher resolution sensor is likely to promote the development of larger sized imaging arrays based on the AER principle. For the purposes of the present paper, it is assumed that the sensor can be scaled up to a size that is at least comparable to current conventional BIL sensors or other infrared imagers. The seeker system parameters and angular resolution are listed in the table below.

The inertial navigation system for the interceptor is likely to be a low-cost, weapon grade inertial system with relatively poor accuracy [10]. The time of flight of the interceptor is relatively short, so the errors are dominated by the initialization errors in position, velocity and attitude – see Table 3.

<table>
<thead>
<tr>
<th>Seeker Field of View</th>
<th>3 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pixels</td>
<td>512 x 512</td>
</tr>
<tr>
<td>Angular Resolution of Seeker</td>
<td>0.1 mrad (1 $\sigma$)</td>
</tr>
<tr>
<td>Event Timing Error</td>
<td>0.02 $\mu$s (1 $\sigma$)</td>
</tr>
<tr>
<td>INS Position Error (Initial)</td>
<td>0.1 m (1 $\sigma$)</td>
</tr>
<tr>
<td>INS Velocity Error</td>
<td>0.05 m/sec (1 $\sigma$)</td>
</tr>
<tr>
<td>INS Attitude Error</td>
<td>0.5 mrad (1 $\sigma$)</td>
</tr>
</tbody>
</table>

Table 3 – Sensor parameters and standard errors (1 $\sigma$) used in simulations.

The estimated $\alpha$ values from (5) are used to find the position of the target projectile relative to the interceptor. These measurements are then filtered using a Kalman filter [11,12] for the relative position $\delta \mathbf{z} = (\mathbf{z}_{fg} - \mathbf{z})$ and the rate of change of the relative position, i.e. the closing velocity $d(\delta \mathbf{z})/dt$.

$$X(t) = \left[\delta x, \delta y, \delta z, \delta v_x, \delta v_y, \delta v_z\right]^T$$

and has a covariance matrix for the state errors $S_\delta(t)$. The measurement matrix is:
The state and covariance prediction is:

\[
H(t) = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
\end{pmatrix}
\]

and the plant (prediction) matrix is:

\[
F(t) = \begin{pmatrix}
1 & 0 & 0 & dt & 0 & 0 \\
0 & 1 & 0 & 0 & dt & 0 \\
0 & 0 & 1 & 0 & 0 & dt \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\end{pmatrix}
\]

where \( dt \) is the interval between measurements. The filter is then an iterative process, measurement-update-prediction for the state and the estimated state covariance matrix [11,12].

1. The predicted measurement is:

\[
Y(t|t) = H(t) \cdot X(t)
\]

2. The state and covariance update for an actual measurement \( \bar{Y} \) is:

\[
X(t) = X(t) + K \cdot (\bar{Y} - \bar{Y}(t))
\]

\[
S_x(t) = (I - K \cdot H(t)) \cdot S_x(t)
\]

where:

\[
K(t) = S_x(t) \cdot H(t)^T \cdot (H(t)S_x(t) \cdot H(t)^T + R(t))^{-1}
\]

and \( R(t) \) is the measurement covariance matrix.

3. The state and covariance prediction is:

\[
X(t + dt) = F(t) \cdot X(t)
\]

\[
S_x(t + dt) = F(t) \cdot S_x(t) \cdot F(t)^T + Q(t)
\]

where \( Q(t) \) is the process noise [11,12]:

\[
Q(t) = \begin{pmatrix}
\frac{1}{2} (dt)^4 & 0 & 0 & \frac{1}{2} (dt)^3 & 0 & 0 \\
0 & \frac{1}{2} (dt)^4 & 0 & 0 & \frac{1}{2} (dt)^3 & 0 \\
0 & 0 & \frac{1}{2} (dt)^4 & 0 & 0 & \frac{1}{2} (dt)^3 \\
\frac{1}{2} (dt)^3 & 0 & 0 & (dt)^2 & 0 & 0 \\
0 & \frac{1}{2} (dt)^3 & 0 & 0 & (dt)^2 & 0 \\
0 & 0 & \frac{1}{2} (dt)^3 & 0 & 0 & (dt)^2 \\
\end{pmatrix}
\]

where \( \sigma_a \) is the typical fluctuation in the relative acceleration over the interval \( dt \) (\( \sigma_a = 0.1g \)-0.5g for the cases considered here).

The main difference between this filter and a standard Kalman filter is that, although the laser illumination pulses are taken to be periodic and predictable when emitted from the ground-based tracker, the arrival times at the seeker are asynchronous and depend on the time of flight of the pulse. The filter’s time step therefore needs to take into account the variations in the pulse arrival time when predicting the state vector forward to the next measurement. The resultant state vectors are used directly in the PN guidance equation (1) to find the acceleration commands that will produce an intercept.

Figure 5 shows the errors in the target position as a function of time for a single delivery, together with the errors in the filtered solution. The filtered solution is slightly worse than the measurements in the initial boost phase of the interceptor’s flight but it copes well with the sustain phase when the velocity is approximately constant. The average error in the filtered target position is around 2-3 metres averaged across a number of engagements.

Figure 6 shows the distribution of miss distances for example engagement (1000 runs). The distribution of the interceptor miss distances is shown in Figure 6. In this example, the laser pulses are transmitted every 25 ms but the arrival time is dependent on the time of flight. The target projectile is detected between 4 and 6 seconds after launch, at which point the
Interceptor is locked on and then launched. The target projectile launch angle is between 32 and 40 degrees, and the interceptor launch angle is between 10 and 15 degrees. The expected (mean) error in the range measurement is 1.6 metres – slightly lower than the target position error because of correlations between the target position and the interceptor position. The median miss distance for this example is 3.1 metres, which is good but could be improved. The mean value is slightly higher (≈ 3.8 metres) due to the skewed distribution. The main limitations in this example are the response of the airframe to the applied controls and the relatively simple filter used to smooth the measurements of the target position. Both of these factors could be improved to reduce the errors/miss distances. In particular, a modified filter could be used to take the acceleration profile of the interceptor and the target into account to improve the target position accuracy and the range accuracy.

6 Conclusion

This paper has considered a novel form of semi-active guidance – one based on active laser illumination and an event-based imaging sensor. It demonstrates that this combination can be used to provide an accurate closed-loop guidance solution.

The system consists of a conventional object tracker on the ground and an interceptor. The tracker illuminates the target with regular laser pulses. The interceptor has an inertial navigation system and an Address Event Representation imager acting as a seeker. The Address-Event Representation seeker is locked onto the target prior to launch and it provides an accurate measurement of total time of flight for the laser pulse from the tracker on the ground to the target, and then back to the interceptor. This time of flight is used with the interceptor’s navigation solution and the line of sight angle to generate an estimate of the target position, which can then be filtered to remove some of the measurement noise. The filtered solution is then used to provide range and closing velocity information for a guidance system based on the proportional navigation guidance law.

References


