NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.320

PRECISION GUIDED MUNITIONS.

TECHNOLOGY AND OPERATIONAL ASPECTS

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Published September 1982
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ISBN 92-835-1434-3

Printed by Technical Editing and Reproduction Ltd
5-11 Mortimer Street, London, W1N 7RH
The theme of this symposium was devoted to the technology and operational aspects of Precision Guided Munitions (PGM).

In the face of the WPF (Warsaw Pact Forces), of overwhelming numerical superiority, it is absolutely essential to utilize, effectively, high kill probability weapons systems referred to as PGM's. The target environment includes such elements as tanks, APC's (Armored Personnel Carriers), SPH's (Self-Propelled Howitzers), air defense systems, WPF concrete airfield runways. The tactical importance of destruction of this array of WPF ground forces elements with high kill probability weapons is important in and of itself. There are other facets to this tactical requirement. One of these is that the advance of WPF ground forces can be expected to occur at a highly rapid rate unless deterred by high kill probability PGM's. While a PGM would ordinarily be expected to be more costly than conventional munitions, a PGM will generally be far more cost-effective.

Therefore, it is clear that the Conference Proceedings of such a meeting on the guidance and control systems issues of such PGM's is of great timely importance to NATO.
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by R.F. Chandler, E. Panuska and M. Starks

* Published in CP.320 (SUPPLEMENT)
** Not presented at the symposium.
The paper discusses the computer methodology called the Scenario Analysis Model (SAM). This model was developed by the US Army Materiel Systems Analysis Activity (USAMSAA) to analyze the effects of terrain and battlefield induced obscuration on potential Precision Guided Munition (PGM) capabilities from various weapon/designator positions. The paper discusses the model inputs which include digitized terrain, digitized paths, obscurant data, target data, and position coordinates. Currently, four scenarios located in the PULDA area of Germany are available for analysis. Summaries of the scenarios are included. The output of the SAM is useful in understanding the impact of scenario dependent factors on overall PGM utility. Some of the SAM output statistics are discussed. In particular, the degradation effects of obscuration on line-of-sight (LOS) duration times, distributions of path segment lengths, and ranges to the target are presented for forward observer positions in the four scenarios. In addition, the degradation effects of obscuration on tanks, TOWs, DRAGONs, and helicopter LOS duration times for one scenario are presented.

2. METHODOLOGY

The computer methodology, SAM, analyzes the effects of the battlefield environment on given LOS duration times from various weapon positions. The SAM requires the following input elements for the analysis of scenarios and weapon systems:

- digitized terrain and vegetation maps,
- digitized target paths defined over the terrain of interest,
- tables of obscurant data defining the type, location of occurrence, and number of rounds and volleys of all transient obscurants within the battlefield,
- tables of target data defining the target type and engagement starting time, velocity time-history and path for each target in the battle,
- position coordinates for all observer and weapon positions during game duration.
The simulation defines the instantaneous position of all targets within the scenario in the following manner: The RED attack vehicles are moved at a given velocity along their specific paths over the given terrain maps. The model determines, at a given sampling interval, if a clear LOS exists between a BLUE weapon position and each RED target. The targets to which a clear LOS exists are then checked against the obscurant tables. If the obscurant lies on the LOS between the weapon position and target, the target is considered to be obscured. The simulation's data output maintains a visibility time-history of each target relative to selected weapon positions. The visibility time-history contains data for the terrain and vegetation intervisiblility and obscuration due to transient aerosols. Statistics are derived from the visibility time-histories. Typical data generate include distributions of range at which line-of-sight to an advancing threat occurs, distributions of distance or target travel while exposed, and the resulting exposure times. The data are generated reflecting the effects of terrain, vegetation and obscuration.

3. SCENARIO DESCRIPTIONS

3.1 HUNFELD Scenario.

The HUNFELD Scenario was developed by the USAMSAA Tactical Operations Analysis Office (Reference 2). This scenario examines a portion of a Warsaw pact attack to overrun West Germany and to destroy NATO forces south of HUNFELD.

Figure 1 is a computer plot of the HUNFELD Scenario. This figure exemplifies the level of detail found in the digitized paths of the scenarios. Observe the four avenues of approach, east and south of HUNFELD. Three mechanized infantry companies travel on three of the paths to the Haune River where they proceed to dismount in order to cross the river. The tank company travels the fourth path to an overwatch position. There are forty vehicles traveling on the paths. Also shown in Figure 1 are the three FO locations. Observe that FO 11 is located in the area of the northern platoon; FO 12 is located in the area of the central platoon; and FO 9 is located in the area of the southern platoon. Scenario data are shown in Table 1, for comparison with the other scenarios.

3.2 Obscuration Scenario.

The Obscuration Scenario was developed by USATRASANA and approved for use in a Battlefield Obscuration Analysis by TRADOC (Reference 3). The appropriate map sheets and associated description of the scenario were used by USAMSAA to generate computer inputs to the SAM. The Obscuration Scenario is located north of HUNFELD. It examines a RED tank regiment of 137 vehicles in the attack against a BLUE armored task force. Additional data are shown in Table 1.

3.3 Covering Force Scenario.

The Covering Force Scenario was developed by Science Applications, Inc. (SAI) under the technical supervision of USAMICOM and USAMSAA (Reference 4). The Covering Force Scenario is situated northeast of HUNFELD. The composition of the RED force for this scenario is a reinforced tank regiment, while the BLUE covering force operation consists of an armored cavalry squadron. Details are provided in Table 1. The Covering Force Scenario consists of three areas of BLUE defensive positions. They are area Red, area White, and area BLUE. This paper discusses the results of Area Red only.

3.4 Quick Stop Scenario.

The Quick Stop Scenario was developed by Computer Science Corporation (CSC) under the technical supervision of USAMICOM (Reference 5). The Quick Stop Scenario is situated in the SONNEBERG area of FULDA in West Germany. The composition of the RED force for this scenario is a motorized rifle regiment consisting of three motorized rifle battalions and a tank battalion. BLUE defenders consist of an armored cavalry troop with two armored cavalry platoons and two tank platoons. Additional data are listed in Table 1.

3.5 Comparison of Scenarios.

Scenario data for the four scenarios are shown in Table 1. Observe that the number of RED attack vehicles in the four scenarios varies considerably, from 40 to 254 vehicles. Similarly, the number of BLUE defender positions also varies. The amount of RED artillery support and total rounds fired is relatively limited in the USAMSAA HUNFELD South Scenario. On the other hand, the amount of BLUE artillery support is extensive for the USAMSAA-USAMICOM Covering Force (area RED) scenario. The vehicle speeds vary from 2.38 m/sec to 5.72 m/sec. Finally, the game times vary from 35 minutes to 90 minutes. These differences in scenario characteristics, as well as the differences in terrain features, influence the line-of-sight distributions, as will be discussed in section 5.

4. CONDITIONS AND ASSUMPTIONS USED IN THE SCENARIO ANALYSIS

Ammunition expenditures were based on standard artillery rates of fire and on available round expenditure data provided with each scenario. RED and BLUE artillery expenditures are summarized in Table 2.

Observe the quantitative differences in the scenarios' artillery expenditures. The HUNFELD South Scenario and the Obscuration Scenario have approximately the same game
FIGURE 1 HUNFELD SCENARIO
<table>
<thead>
<tr>
<th></th>
<th>USAMSAA's HUNFELD South</th>
<th>USATRASANA's Obscuration I</th>
<th>USAMSAA-USAMICOM Covering Force (Area RED)</th>
<th>USAMICOM Quick-Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RED Force</strong></td>
<td>Motorized Rifle Battalion</td>
<td>Tank Regiment</td>
<td>Reinforced Tank Regiment</td>
<td>Motorized Rifle Regiment</td>
</tr>
<tr>
<td>Number of Vehicles</td>
<td>40</td>
<td>137</td>
<td>184</td>
<td>254</td>
</tr>
<tr>
<td>Number of Paths</td>
<td>12</td>
<td>21</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>RED Artillery</td>
<td>4-122mm Bns, 1/3-130mm Bns, 1-MRL Bn</td>
<td>2-152mm Bns, 5-130mm Bns, 3-122mm Bns, 2-MRL Bns</td>
<td>2-122mm Bns, 1-152mm Bns, 1-MRL Bn, 3-120mm Mortar Btries</td>
<td></td>
</tr>
<tr>
<td><strong>BLUE Force</strong></td>
<td>Mechanized Infantry Company Team</td>
<td>Armor Task Force</td>
<td>Armored Cavalry Squadron</td>
<td>Armored Cavalry Troop</td>
</tr>
<tr>
<td>Number of Defender Positions</td>
<td>33</td>
<td>89</td>
<td>98</td>
<td>46</td>
</tr>
<tr>
<td>Number of FOs</td>
<td>3</td>
<td>4</td>
<td>12*</td>
<td>3</td>
</tr>
<tr>
<td>BLUE Artillery</td>
<td>1-155mm Bn, 1-8in Btry, 2-155mm Btrys</td>
<td>2-155mm Bns, 1-8in Bn, 1-MLRS Bn, 1-107mm Mortar Co</td>
<td>1-155mm Btry</td>
<td></td>
</tr>
<tr>
<td><strong>Average Vehicle Speed (m/sec)</strong></td>
<td>4.85</td>
<td>3.91</td>
<td>2.38</td>
<td>5.72</td>
</tr>
<tr>
<td><strong>Scenario Range (meters)</strong></td>
<td>9500</td>
<td>10,500</td>
<td>14,000</td>
<td>16,000</td>
</tr>
<tr>
<td><strong>Game Time (min)</strong></td>
<td>35</td>
<td>40</td>
<td>90</td>
<td>86</td>
</tr>
</tbody>
</table>

*Includes 4 primary and 8 alternate positions.
<table>
<thead>
<tr>
<th></th>
<th>USAMSAA's HUNFELD South</th>
<th>USATRASANA's Obscuration I</th>
<th>USAMSAA-USAMICOM Covering Force (Area RED)</th>
<th>USAMICOM Quick Stop Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RED Prep (HE)</strong></td>
<td>6480-122mm rds</td>
<td>1032-130mm rds</td>
<td>7128-122mm rds</td>
<td>1710-122mm rds</td>
</tr>
<tr>
<td>(SMOKE)</td>
<td></td>
<td></td>
<td>10206-130mm rds</td>
<td>540-152mm rds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4528-152mm rds</td>
<td>1710-120mm rds</td>
</tr>
<tr>
<td><strong>RED Arty (HE)</strong></td>
<td>288-130mm rds</td>
<td>1978-122mm rds</td>
<td>1926-122mm rds</td>
<td>144-122mm rds</td>
</tr>
<tr>
<td>(SMOKE)</td>
<td></td>
<td>2700-130mm rds</td>
<td>1926-122mm rds</td>
<td>180-120mm rds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1080-152mm rds</td>
<td>1512-152mm rds</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>630-120mm rds</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RED MRL</strong></td>
<td>2880 rockets</td>
<td>80 rockets</td>
<td>7160 rockets</td>
<td>5040 rockets</td>
</tr>
<tr>
<td><strong>BLUE Arty (HE)</strong></td>
<td>1092-155mm rds</td>
<td>720-155mm HE rds</td>
<td>1336-155mm rds</td>
<td>680-155mm rds</td>
</tr>
<tr>
<td>(DPICM)</td>
<td></td>
<td></td>
<td>352-8in rds</td>
<td></td>
</tr>
<tr>
<td>(SMOKE)</td>
<td></td>
<td>66 COPERHEADS</td>
<td>1416-155mm rds</td>
<td></td>
</tr>
<tr>
<td><strong>BLUE MLRS</strong></td>
<td></td>
<td></td>
<td>284-8in rds</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>18-155mm rds</td>
<td></td>
</tr>
<tr>
<td><strong>Rounds:</strong></td>
<td>7692</td>
<td>3096</td>
<td>33060</td>
<td>9482</td>
</tr>
<tr>
<td><strong>Rockets:</strong></td>
<td>2880</td>
<td>80</td>
<td>7664</td>
<td>5040</td>
</tr>
<tr>
<td><strong>% Smoke Rounds</strong></td>
<td>0</td>
<td>32</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>
time (see Table 1), however, the artillery expenditures are considerably different. Similarly, the Covering Force Scenario has a much higher expenditure than does the Quick Stop Scenario for comparable time periods. In addition, the Obscuration I Scenario's artillery expenditure consists of 32 percent smoke, where the other scenarios have less than 8 percent or no smoke expenditures.

Table 3 defines the dimensions and time duration of dust and debris generated by artillery fires as used in the analysis. These estimates are inferred from tests conducted at Dugway Proving Ground (USA), available United Kingdom data, US Army Smoke Project Manager tests, Ft Sill, Oklahoma (USA) tests, and the USAMSAA tests at Aberdeen Proving Ground, Maryland (USA). The dimensions and time duration of artillery smoke obscuration are shown in Table 4. These estimates were used to analyze the obscuration effects of artillery delivered smoke rounds, and were obtained from the Smoke Project Manager tests and the JTAC Smoke Effectiveness Manual (Reference 6). For each smoke type in Table 4, there are two periods of time durations listed, representing changes in cloud dimension as the cloud is transported and diffused over time.

Assumptions made in the analysis are as follows:

- During the attack, RED vehicles are assumed to travel with a vehicle-unique velocity time history in column formation along assigned paths.
- The weapon/observer position height was assumed to be 1.5 meters for the LOS calculations.
- The targets were assumed to be a point target 1.5 meters above ground level.

5. FINDINGS

Typical statistics obtained from the model include distributions of ranges at which LOS to an advancing threat occurs, the distance targets travel while exposed, and the resulting exposure times. The data are generated reflecting the effects of terrain, vegetation and artillery induced obscuration.

Figure 2 compares the LOS duration times for the four scenarios considering terrain and vegetation effects only, and then with obscuration effects added. This figure represents the cumulative overlapping of LOS duration times for groupings of vehicles within 50 meters of each other, that is, the continuous duration time during which there is at least one vehicle in the LOS path segment. The data shown are mean data representing all of the forward observers for each scenario. Observe that the Obscuration Scenario and the Quick Stop Scenario are plotted as one set of curves. For all intents and purposes, these two scenarios have identical LOS duration time distributions.

From the figure, one can determine the probability that the LOS duration time will be greater than any given time increment. Data were taken from the figure for three probabilities (75 percent, 50 percent, and 25 percent) in order to compare the four scenarios. These data are presented in Table 5. In addition, the maximum LOS duration time found in each scenario is presented. For example, in the HUNFELD Scenario, considering natural terrain and vegetation obscuration only, there is a 50 percent probability that LOS duration time will exceed 120 seconds, while the greatest duration time is 1050 seconds.

Table 6 presents similar data on LOS segment lengths, while Table 7 shows a comparison of ranges at which LOS begins. These tables contain data for the three probabilities, the four scenarios, and the two obscuration conditions of Table 5. Additionally, the maximum LOS segment length and the maximum range at which LOS begins are presented for each scenario. A discussion of the data from the previous tables is presented in the following paragraphs.

Observe in Figure 2 and Table 5 that the distribution of LOS duration times varies among the four scenarios. The HUNFELD South Scenario has the least number of vehicles traveling the shortest LOS path segments, resulting in the shortest LOS duration times. The Obscuration Scenario and the Quick Stop Scenario have similar LOS duration times. The distribution of LOS path segments in these two scenarios are also approximately the same. The Quick Stop Scenario has almost twice as many vehicles traveling along its paths; however, the vehicles are traveling almost 50 percent faster than those found in the Obscuration Scenario. This tradeoff results in similar LOS statistics for the "terrain only" case. Likewise, for the "obscuration added" condition, the threefold increase in number of rounds fired in the Quick Stop scenario is offset by the larger area over which they are delivered; hence, similar LOS duration times and segment lengths result. Finally, the Covering Force Scenario has the longest LOS duration times. This scenario has the slowest average vehicular velocity, and a biased distribution of vehicles on paths. That is, 34 percent of the vehicles are on but two of the 18 paths. Thus, there are a large number of vehicles moving slowly over LOS path segments on only two paths, resulting in long mean LOS duration times.

Observe that obscuration decreases the LOS duration times for the 50 percentile case, approximately 25 percent for the HUNFELD South and Quick Stop Scenarios. It reduces the Obscuration I Scenario's LOS duration time by approximately 40 percent and the Covering Force Scenario by 55 percent. This is to be expected considering the fact that
1. Covering Force Scenario with Terrain Masking
2. Covering Force Scenario with Obscuration Added
3. Obscuration I/Quick Stop Scenarios with Terrain Masking
4. Obscuration I/Quick Stop Scenarios with Obscuration Added
5. HUNFELD Scenario with Terrain Masking
6. HUNFELD Scenario with Obscuration Added

**FIGURE 2 COMPARISON OF LOS DURATION TIMES**

LOS DURATION TIME (SEC)
### TABLE 3 ESTIMATES OF ARTILLERY DUST AND DEBRIS OBSCURATION DIMENSIONS AND TIME DURATIONS

<table>
<thead>
<tr>
<th>Number of Rounds</th>
<th>Time Duration (Sec)</th>
<th>Width (Meter)</th>
<th>Depth (Meter)</th>
<th>Height (Meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>155mm 6 round volley</td>
<td>50</td>
<td>275</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>155mm 8 round volley</td>
<td>50</td>
<td>365</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>8 inch 4 round volley</td>
<td>50</td>
<td>250</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>MLRS 24 rockets</td>
<td>50</td>
<td>212</td>
<td>156</td>
<td>35</td>
</tr>
<tr>
<td>107mm 6 mortar rounds</td>
<td>50</td>
<td>210</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>122mm 6 round volley</td>
<td>50</td>
<td>275</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>130mm 6 round volley</td>
<td>50</td>
<td>275</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>152mm 6 round volley</td>
<td>50</td>
<td>275</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>MRL 40 rockets</td>
<td>50</td>
<td>306</td>
<td>220</td>
<td>35</td>
</tr>
</tbody>
</table>

### TABLE 4 ESTIMATES OF ARTILLERY SMOKE DIMENSIONS AND TIME DURATIONS

<table>
<thead>
<tr>
<th>Smoke Types and the Number of Rounds</th>
<th>Time Duration (Seconds)</th>
<th>Width (Meters)</th>
<th>Depth (Meters)</th>
<th>Height (Meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>155mm 6 round volley</td>
<td>0-210</td>
<td>198</td>
<td>93</td>
<td>66</td>
</tr>
<tr>
<td>155mm 6 round volley</td>
<td>210-330</td>
<td>102</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>122mm 6 round volley</td>
<td>0-210</td>
<td>156</td>
<td>78</td>
<td>54</td>
</tr>
<tr>
<td>122mm 6 round volley</td>
<td>210-330</td>
<td>102</td>
<td>48</td>
<td>18</td>
</tr>
<tr>
<td>HC Smoke Pot</td>
<td>0-240</td>
<td>150</td>
<td>220</td>
<td>150</td>
</tr>
<tr>
<td>HC Smoke Pot</td>
<td>240-360</td>
<td>350</td>
<td>170</td>
<td>115</td>
</tr>
<tr>
<td>107mm 6 round mortar volley</td>
<td>0-120</td>
<td>225</td>
<td>108</td>
<td>74</td>
</tr>
<tr>
<td>107mm 6 round mortar volley</td>
<td>120-240</td>
<td>160</td>
<td>77</td>
<td>53</td>
</tr>
</tbody>
</table>
### TABLE 5 LOS DURATION TIMES DISTRIBUTION

<table>
<thead>
<tr>
<th>Percent of LOS Duration Times are &gt; Secs</th>
<th>HUNFELD South</th>
<th>Obscuration I</th>
<th>Covering Force</th>
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<td>90</td>
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<td>25%</td>
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<td>Maximum LOS Duration Time</td>
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<td>870</td>
<td>1800</td>
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<p>| Percent of LOS Duration Times are &gt; Secs | Quick Stop | |
|-----------------------------------------|------------|
| Terrain Only  | Obscuration Added |
| 75%                                     | 300        | 210 |
| 50%                                     | 450        | 330 |
| 25%                                     | 630        | 420 |
| Maximum LOS Duration Time               | 4170       | 2850 |</p>
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<td>Obscuration Only</td>
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<td>75%</td>
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<tr>
<td>Maximum LOS Duration Time</td>
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<td>700</td>
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<tr>
<td>Maximum LOS Duration Time</td>
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the Covering Force Scenario had more rounds expended than the other three scenarios and the Obscuration I Scenario has such a high percentage of smoke rounds.

From Table 6, for the 50 percent probability and terrain only condition, three of the scenarios have path segment lengths greater than 300–400 meters. The HUNFELD Scenario has shorter path segment lengths because the tactician positioned two of the three forward observer's along the river bed at low vantage points. The FOs were considered to be platoon or mortar FOs and were not to be equipped with Ground Laser Designators (GLDs).

This emplacement limited LOS engagement opportunities, resulting in short LOS path segments. Although the other three scenarios have similar distributions of path segment lengths, the Obscuration Scenario and the Quick Stop Scenario have considerably longer maximum segment lengths. This can be attributed to the following factors. The Obscuration Scenario represents the tactical paths as straight lines, which do not follow the natural terrain features. These straight lines, which do not take advantage of the concealment afforded by paths along terrain features, are more likely to be visible. Similarly, in the Quick Stop Scenario, the RED forces maintain high approach speeds while traveling over secondary roads, which are basically straight lines with high visibility.

Regardless of the amount of total obscuration or the path segment lengths resulting from terrain and vegetation only, the path segment length distributions resulting from obscuration effects are approximately the same for all four scenarios. As expected, given its large volume of ammunition expenditure, the Covering Force scenario shows the greatest drop in path segment length when artillery obscuration is considered. Similarly, the Obscuration I scenario, with a large percentage of the smoke munitions, also shows a relatively large drop in path segment length. On the other hand, the HUNFELD scenario, with short unobscured segment lengths, is affected to a much lesser degree by HE munitions.

From Table 7 observe that the Quick Stop Scenario has consistently longer ranges at which LOS begins, compared to the other three scenarios. Those three scenarios are geographically located in the HUNFELD area of FULDA where the Three Sisters mountains preclude many longer range LOS opportunities. The Quick Stop Scenario, however, is located in the SONNEBERG area of FULDA, where the absence of mountains affords longer LOS opportunities. Note also that obscuration has little impact on the average range at which LOS begins. This occurs because the obscuration is not eliminating ranges at which LOS begins but is eliminating the total time the path segment is visible. However, the obscuration effects do eliminate the maximum range path segment for the Obscuration I Scenario.

Results similar to Tables 5, 6 and 7 are also available for other weapon systems. From these data, Table 8 was generated. This table presents the percent degradation of the LOS duration times due to battlefield obscuration for Forward Observers, TOWs, DRAGONs, Tanks, and Helicopters in the Obscuration I Scenario. The LOS duration times representing the 50 percent statistics were used, i.e., 50 percent of the LOS duration times are less than and 50 percent are greater than the indicated times. The statistics reflect differences in range capability for the various systems. Observe from Table 8, that the Helicopter's Initial Position and First Fallback Position have the least degradation for all systems shown. These positions are in front of the BLUE defensive positions and therefore in front of most of the artillery fire and obscuration effects. The Helicopter Second Fallback positions, however, are behind the defensive positions and thus the obscurations due to incoming artillery are directly in front of their positions. This results in considerable obscuration degradation (≤60%). The tanks, TOWs, and DRAGONs with their relatively short range capability are on the front line and experience approximately 50 percent degradation. The FOs are positioned to maximize survivability and visibility and therefore their visibility is not degraded to the extent of the other ground weapon systems.

6. SUMMARY

The SAM allows a scenario to be analyzed for a multitude of positions in order to evaluate the effects of positioning on the total potential kill power of an engagement system. In addition, the automated techniques allow several scenarios to be evaluated quickly and in a consistent manner. Several combinations of atmospheric conditions, weather, and smoke types can be incorporated into the analysis. For the scenario analyzed, the data from the Obscuration I Scenario and to Quick Stop Scenario represent the most likely LOS engagement opportunities for FOs in the FULDA area. The Covering Force Scenario represents the maximum LOS engagement opportunities. However, it should be emphasized that these statistics only represent the FULDA area, which can be described as open rolling terrain. In particular, studies performed in the NORTHDA area, where the terrain can be described as open and flat, show LOS opportunities were quite poor for FO positions equipped with GLDs. Finally, the SAM methodology has been shown to be a useful tool in the analysis of weapon system performance in realistic battlefield situations by quantifying the impact of terrain positioning and obscuration on engagement opportunities.
<table>
<thead>
<tr>
<th>Percent of Range That are &gt; Meters</th>
<th>Terrain Only</th>
<th>Obscuration Added</th>
<th>Terrain Only</th>
<th>Obscuration Added</th>
<th>Terrain Only</th>
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<table>
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<th>Quick Stop Terrain Only</th>
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<tr>
<td>75%</td>
<td>5000</td>
<td>3100</td>
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<tr>
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<td>8500</td>
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<tr>
<td>Maximum Range at Which LOS Begins</td>
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<td>Obscuration I Scenario (50% Statistics)</td>
<td>LOS Duration Time (Sec)</td>
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<td>----------------------------------------</td>
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<td>Forward Observers</td>
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<td>TOWs</td>
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<td>DRAGONs</td>
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<td>Tanks</td>
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<td>Helicopter's Initial Position</td>
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<td>Helicopter's Second Fallback Position</td>
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<td>330</td>
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BIBLIOGRAPHY


APPLICATION OF AN AIRBORNE ENGAGEMENT SYSTEM
TO BATTLEFIELD SURVEILLANCE AND ATTACK CONTROL

by

Donald D. Neuman
The MITRE Corporation
Bedford, MA 01730

1.0 SUMMARY

The airborne engagement system being discussed is a surveillance and attack control system designed to
detect, locate, track, and control weapons against time sensitive targets, moving and stationary, located
up to 150 km or more beyond the Forward Line of Own Troops (FLOT). As indicated in Table 1, the primary
system functions are surveillance and threat assessment, attack planning, attack control, and post attack
assessment. Utilizing a single airborne platform, the system will be able to continuously target broad
regions and plan and control attacks within these regions. As illustrated in Figure 1, the concept uti-


2.0 SYSTEM OVERVIEW

The airborne engagement system being discussed is a surveillance and attack control system designed to
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regions and plan and control attacks within these regions. As illustrated in Figure 1, the concept uti-


3.0 SURVEILLANCE

The heart of the airborne engagement system is the Pulse Doppler multimode airborne radar with its
side looking electronically scanned antenna. The radar is capable of time interleaving a Moving Target In-
dicator (MTI) mode having low range resolution, an MTI mode having high range resolution and a Synthetic
Aperture Radar (SAR) mode. The low resolution MTI mode is utilized when searching an extended range swath
in a single antenna beam dwell (50 km to 100 km typical) in order to reduce the number of range cells per
beam dwell requiring processing. The high resolution MTI mode is utilized when monitoring relatively small
areas (typically a few kilometers in range and a few beam widths in azimuth) for attack planning or
attack control purposes. SAR imagery is utilized primarily to maintain track continuity on moving targets
of interest that stop, to improve the accuracy of the estimated location of stationary targets identified
by other less accurate sources and for post attack assessment purposes. SAR operates in a spotlight mode
only and it requires cueing. To obtain a SAR image at the furthest range, the radar beam must dwell in the
target area substantially longer for SAR imagery than for MTI target detection. Therefore, when utilizing
the system in circumstances requiring high throughput, such as for surveillance and interdiction of moving
columns of a large assault force, the SAR mode of the radar is used only to augment MTI information and not
as a primary mode of the system.

4.0 WEAPON DATA LINK

In addition to detecting surface targets, another time interleaved radar mode is employed in the ter-


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For missiles, where the time between launch and munitions dispense is only a few minutes, the weapon communication region is established on the terminal phase portion of the missiles trajectory. Any changes in target behavior is communicated to the missile during the initial exchange of data with the radar. If target behavior changes occur subsequent to that time, at such times as they occur. More precisely, the system will recompute and transmit to the weapon a new interdiction point based upon missile arrival time, missile maneuver capability, current target location and latest predicted target velocity.

For attack aircraft, where the ingress time can be substantially greater than missile flight time, two to four communications regions are established en route to the target area allowing for timely changes in mission or changes in interdiction points and times to be communicated to the aircraft. To further allow for uncertainties in aircraft arrival time, attack aircraft are provided three interdiction points and times of arrival for a primary target array and also for a secondary target array.

Although utilizing the radar to perform the surveillance function consumes radar time that could be used to perform the surveillance function, it provides a straightforward means to achieve a robust data link to the weapon. This is achieved by utilizing the radar's high gain directional antenna and the attendant relative radiated power transmitted by the radar coupled with radiation of a waveform appropriate for the communications function. Utilizing the multimode for weapons communications eliminates the need for a separate special purposed data link aboard the aircraft to achieve this function.

5.0 RADAR PRODUCTS

A summary of the radar modes and products is listed in Table 2 and illustrated in Figure 2 for a specific point along the flight path of the radar platform. The large pie shaped area shown in Figure 2 represents the coverage area scanned by the radar. Radar data for the total region is generated using the low range resolution MTI mode. In order to present the data to the operators in a comprehensible form, the total area is divided into 4km squares and data within each square are grouped together. The operator is presented a colorgraphic display that indicates by color the level of activity within each square. Essentially the display graphically informs the operators which regions contain little moving target activity, moderate moving target activity, and substantial moving target activity.

The activity indicators serve to focus the operator's attention on high activity areas which can then be examined more closely. This is indicated by the large rectangular areas within the overall coverage area termed sector search areas. These areas, which are operator selectable in size, are scanned using the low range resolution MTI mode. Within these areas, individual target returns are displayed to the operators.

Activity patterns may be such as to cause an operator to plan to attack a target array which is detected passing through a selected route segment, called an attack planning area. The attack would take place in a second area further along the target's route called an attack control area. These attack planning and attack control areas are also operator selectable in size and location and need not be within the sector search areas. It is expected that these areas will be much smaller than the sector search areas and are depicted as small rectangular areas in Figure 2. Within these areas, the high range resolution MTI mode is employed.

SAR imagery data may be generated in the attack control areas to aid in maintaining track continuity for targets that stop moving, or as indicated in the figure, separate areas may be established explicitly for generation of SAR images for stationary target detection.

Finally, as already described, a portion of radar capacity is used for weapons location and communications which is depicted in the figure by symbols representing missiles and aircraft.

6.0 CAPACITY AND PRIORITIES

In order to minimize the time the radar searches areas of little interest to operators, and to provide a system responsive to multiple users simultaneously, a service request technique will be implemented to gain maximum advantage from the multimode nature of the radar and its electronic scan capability. The technique limits radar coverage only to areas designated by operators for a specific function (such as attack control or sector search). To achieve this attribute, radar time is programmed in increments of beam dwells; a beam dwell being the time required for the radar main beam to remain focused at a specific pointing angle to achieve an adequate signal-to-noise ratio for detection, location, and velocity resolution of any targets at that pointing angle. The minimum number of beam dwells is utilized to satisfy any service request at which time the radar automatically goes on to satisfy the next service request. Service requests are coupled with a priority scheme to manage overloads and allow the most time critical functions to interrupt less critical functions.

The service request/priority scheme will operate in the following manner. Approved service requests are placed in storage until such time as the area of interest is within radar coverage (and for weapons, also within the expected time window). At that time the request will be moved into a queue that corresponds to its priority. While priorities are programmable, it is anticipated that communications to weapons in flight will have highest priority. Servicing the attack control areas which contain the targets to be interdicted by the inflight weapons will likely have second priority. Attack planning would come next followed by sector search. General surveillance of the entire coverage volume for activity indications will likely have lowest priority, with other types of service requests (e.g., SAR imagery) falling between those stated.

Each type of request will have an associated revisit interval. The revisit intervals will be programmable. When the revisit interval elapses, the service request becomes active. If it has highest priority of all active requests, it interrupts the current request at the conclusion of the current beam dwell and is serviced next. Otherwise, it waits its turn to become the highest priority active request. Requests of the same priority are serviced sequentially. In this manner, all requests are serviced at the conclusion of their revisit interval until system overload develops, at which time the lower priority requests get serviced at less frequent intervals and system throughout slows down.
To avoid system overload, an operator position is assigned a manager function to approve service requests prior to their entering the automatic part of the process. All operators, as well as the manager, will be automatically provided radar time utilization status indicating the percentage of time currently being consumed by the radar and a breakdown of that time by function and area. The manager utilizes this data to restrict requests when the system is nearing its capacity and to generally manage utilization of the radar resource.

The final operational system will be dynamically responsive to the needs of the operators. Use of radar time can be varied from exclusive dedication to wide area surveillance with no weapons communications to exclusive support of attack control in limited areas and all possible intermediate combinations.

7.0 SYSTEM ARCHITECTURE

An approach for integrating the concept into operational theaters is shown in Figure 3. The radar and associated signal processing will be installed on a test aircraft along with the data processing, memory, operator work stations [color graphic displays, tabular displays, entry and retrieval capability] and communications necessary to perform the operations and control functions aboard the aircraft. As is indicated in the figure, the system is partitioned such that the interface between the Radar subsystem and the Operations and Control subsystem is via the Communications subsystem. The Radar subsystem has as its output portions of radar history within any designated area. The data is passed to the Operations and Control subsystem by the Communications subsystem and is also broadcast by the Communications subsystem over a secure jam resistant data link to receiving elements on the ground. These elements are located at appropriate command and intelligence facilities. The data is broadcast omnidirectionally and can be received by all elements within line-of-sight of the airborne platform. The receiving elements, termed Command and Control Interface (C2I) elements, will be able to perform all the functions performed by the airborne Operations and Control subsystem except for attack control, which is done only in the airborne element due to considerations of timing and coordination.

Because all target location data generated by the radar exists both on-board the aircraft and at multiple ground facilities; because each facility can perform the surveillance, threat assessment, and attack planning functions; and because each facility can generate radar service requests tasking the radar to service the needs of the facility; the command structure and responsibilities associated with use of the system are very flexible, easily changed to be responsive to the needs of the commander, and minimally limited by system design constraints. For example, the airborne platform can be used in rapid deployment situations where little or no ground based command capability exists. In this case, it can operate as a self contained surveillance, command and control facility that accompanies deployed forces. Alternatively, where ground based command and control facilities exist, C2I elements might be located at these facilities. In this case, higher command authority could partition the responsibilities between the facilities which could then independently task the radar, select targets of primary importance to their mission, pick interdiction points if so instructed by the higher command, and assign the control to intercept the targets. In this case, the weapon launch pairing would be transferred to operators aboard the airborne platform for execution. Another alternative is to provide target priorities to the airborne operators and allow them to pick the specific targets and select the interdiction points. The airborne operators would request weapon allocations and targeting approval from the parent command facility. In addition, weapons can be preallocated to the airborne element with the parent facility only retaining veto authority over weapon-target pairings. Any of the above alternatives could be implemented by change of operating procedure only. No changes to system hardware or software would be necessary.

The remaining portions of Figure 3 show the transponder aboard the weapons (the Weapons Interface element) and the voice communication that goes along with the digital data communications (except to missiles). As previously described, communications to the Weapons Interface element is achieved by using the radar in a digital data link mode.

8.0 AIRBORNE PLATFORM

A line drawing of one version of the radar platform aircraft is shown in Figure 4. In this version, there are 15 operator stations. The radar and its associated signal processors are shown in lower forward position of the fuselage. In this version, two antennas are shown, one on each side of the aircraft (only one antenna would be active at any time) rather than a single antenna on gimbals. The choice of approach, as well as the specific antenna location, is still under investigation.

9.0 SCREENING

To aid in execution of attack planning, several automated aids will be provided to the operators. One of these aids is a digitized data base. This data base will be used in connection with knowledge of the aircraft's current location to predict and display areas currently screened from the radar's field of view. This data will also be used in conjunction with actual and trial flight profiles to predict and display those portions of the aircraft flight path from which selected surface points are visible and also those portions of a specified march route visible from each portion of the flight path.

Another aid is the storage of target detections for a one hour time period allowing operators to play back in compressed time one hour of radar history within any designated area. The operator can visually integrate these data trails to aid in maintaining target track continuity in areas of sporadic visibility, estimating march routes, estimating target speed, and developing an overall situation awareness.

The operator can designate the route of march of a target array, initiate an attack planning symbol at the location of the latest radar returns from the target array, and elect to have the symbol automatically extrapolated along the designated route at a speed determined from manually repositioning the symbol over successive radar returns or from the targets radial velocity measured by the radar. Observation of the discrepancy between the current symbol location and the location of current radar data from the target allows the operator to correct the symbol's position and velocity. The symbol can be used to maintain
situational awareness in poor visibility areas prior to the target array being automatically tracked in the attack control area. The symbol is also used to predict the time of arrival of the target array at selected interdiction points along the designated march route.

10.0 TEST PROGRAM

The description given in the preceding paragraphs applies to a self contained test system. At present, two systems are being flight tested that are not self contained. These systems are being tested using surface launched missiles and direct attack aircraft as the weapons systems. An overview of the test system is shown in Figure 5. For each of these systems the "front end" of the radar is housed in an F-111 with the electronically scanned antenna center line mounted on gimbals allowing it to look out either side of the aircraft. The output from the F-111 basically is digitized video data which is transmitted via wide band data link to a ground based Data Processing and Control Station (DPCS). Signal processing, data processing, and operator work stations are located in this facility. The radar performs wide area surveillance, detects and tracks moving target arrays, locates inflight weapons, communicates current target location data to the weapons, and generates Synthetic Aperture Radar imagery for stationary target detection and location. Pictures of each of the test aircraft with their associated antenna pods are shown in Figures 6 and 7.

The current test program includes multiple launch of two types of missiles against a remote controlled moving array of tanks. Each missile type has a self-contained onboard navigational capability to steer to the objective area and make terminal phase maneuvers to correct for weapon-target registration errors. During these tests, the radar locates the missile during terminal phase, locates the target array, and communicates the latest target location data to a missile. The missile uses the data to correct its trajectory and adjust the time of munitions dispense.

The test program also includes use of a direct attack aircraft for the weapon system. For these tests an F-4 is used as the attack aircraft. The navigation-weapon delivery computer aboard the F-4 has been modified to accept target location data from a transponder located aboard the aircraft and also has been modified to adjust its guidance solutions to include time-of-arrival constraints. The direct attack test conditions are shown in Figure 8. The orderly race track pattern shown in the figure represents the radar platform flight path. The more random pattern represents the F-4 flight path and is intended to indicate that the flight path is unconstrained except for the requirement to pass through points A and B within certain time limits. As is shown in the figure, the radar tracks the target array and communicates this data to the F-4 at points A and B allowing the navigation system onboard the F-4 to generate steering and weapon release commands. These tests will be flown at minimum altitude (a few hundred feet) to evaluate the ability of the system to achieve first pass target acquisition and blind weapon delivery.
Table 1
System Functions

- Surveillance and Threat Assessment
- Attack Planning
- Attack Control
- Post Attack Assessment

Table 2
Radar Modes and Products

- MTI Reports
  - Low Range Resolution
    - activity indications
    - sector search
  - High Range Resolution
    - attack planning
    - attack control

- SAR Imagery and Stationary Target Reports

- Weapons Location and Communications
Figure 1. Concept

Figure 2. Coverage Areas
Figure 3. System Architecture

Figure 4. Test Vehicle Installation
Figure 5. Test Concept

Figure 6. Test Aircraft
Figure 7. Test Aircraft

Figure 8. Direct Attack Test Scenario
SUMMARY

This paper presents recent seeker technology developments for application to autonomous target acquisition munitions. First, basic design approaches for infrared seekers are discussed and the use of two colors to achieve countermeasures and non-target discrimination is introduced. Experimental field test results show the degree of autonomous performance achieved under a variety of battlefield conditions. Next, millimeter wave seekers suitable for use on small diameter missiles, munitions and RPVs are described and the results of experimental hardware operating at 35 GHz and 140 GHz are shown. Finally, in view of the unpredictability of battlefield conditions two concepts for multi-mode terminal guidance are introduced and explored experimentally. A common aperture millimeter wave/two-color infrared seeker is described which combines a 140 GHz sensor with a two-color mid-infrared sensor for optimum battlefield performance. For air defense suppression applications, an experimental passive microwave/infrared seeker is discussed.

INTRODUCTION

For the past decade the Pomona Division of the General Dynamics Corporation has been developing a seeker technology base directed at achieving autonomous target acquisition and terminal homing for tactical "hit to kill" guided missiles. The principal operational applications are the defeat of stationary and moving ground targets, such as armored vehicles, mobile air defense systems and short-range air targets, either of rotary or fixed wing type. The primary seeker problems that need to be overcome are the effects of severe background clutter, acquisition of non-targets, potential countermeasures and adverse weather conditions.

Summarizing the principal problems and noting their potential effect on the performance of a missile seeker we can propose some trends for seeker design parameters that would point us in the direction of meeting our goals. These are shown in Figure 1.

It can be seen from the potential solution column in the figure that the principal source of performance improvement is achieved by selecting a very small instantaneous field of view (IFOV), in the case of an IR sensor, or a narrow antenna beamwidth in the case of an RF sensor. This overriding fact has led us to not design of high resolution seekers capable of being used in relatively small diameter tactical missiles or munitions. In addition, because of the potentially serious effects of countermeasures and non-targets on the operational effectiveness of such weapons, some additional forms of target discrimination will be required. First, infrared wavelength seekers will be discussed, then millimeter wave and finally, multi-mode seekers.

INFRARED SEEKERS

A simple high resolution image scanning seeker is depicted in Figure 2. The small instantaneous field of view (IFOV) of the optical system is circularly scanned to cover or encode the total field of view (TFOV). This is then scanned in a spiral fashion starting from the outside to generate the target acquisition field of view.

The general effect on target-to-background clutter ratio as a function of the instantaneous field-of-view of the seekers optical system is shown in Figure 3. The improvement in target-to-clutter ratio as the instantaneous field of view is reduced to between 1 and 2 milliradians is significant, especially under the most cluttered backgrounds represented by the lower bound of the shaded region in the figure. However, the basic disadvantage of using this high a resolution is the increased difficulty of scanning a sufficiently large acquisition area in the short time interval that one has to automatically acquire the desired target. Usually this time interval is a few seconds or less.

One method of overcoming this disadvantage is to employ multiple detectors mounted in a common optical system to simultaneously cover a larger field of view. However, this increases the complexity and particularly the cost of the seeker and makes cryogenic cooling of the detectors at the focal plane of the optical system more difficult. A method employed at the General Dynamics Pomona Division for simplifying multiple detector seeker design makes use of infrared fiber optics to act as a transmission line for the infrared energy from the focal plane of the optical system to remotely mounted and cooled multiple detectors. This is illustrated in Figure 4 where four detectors are utilized in a common optical system to increase the total field of view and generate the tracking error signals.

The detector/cryostat assembly is replaced by a fiber optics assembly giving an uncluttered focal plane and the detectors with their associated cooling components are located at a convenient place in the seekers' electronics section behind the gyro-optics assembly. This also allows the detectors to be in any convenient format, in-line or square. The overall transmission efficiency through the fibers is approximately 50 percent in the mid-infrared (3 to 5 microns) wave band. A number of materials have been investigated for use as infrared fibers and currently Arsenic Trisulphide (As₂S₃) is being employed in experimental seeker heads. Arsenic Triselenide (As₂Se₃) is being investigated for broad band infrared applications (3 to 14 microns).

These fibers are made in the Pomona Division Advanced Manufacturing Operation from raw materials by heating the material up to approximately 700 degrees centigrade and pulling the fibers. The As₂S₃ fibers are shown in Figure 5. The fiber diameter is approximately one hundredth of a centimeter (0.01 cm)
or 2 to 3 mils. One good manufacturing run yields enough fibers to last for a year or so.

The basic infrared sensor described so far will respond to any sufficiently hot target within the sensors total field of view (TFOV) making it susceptible to acquiring a variety of countermeasures and non-targets. In order to eliminate most of the undesired targets, a spectral discrimination capability is added to the sensor. Measurements of the infrared spectral signatures of various countermeasures and objects in the 2 to 5 micron waveband show that many non-targets have a peak radiant intensity at the shorter wavelength part of the spectrum, while desired battlefield targets such as tanks, etc., have a peak radiant intensity at longer wavelengths. These characteristics are shown in Figure 6 as a function of wavelength in the mid-infrared portion of the spectrum. Consequently, if the relative amount of energy is measured in the shorter and longer (2 - 3 micron/3 - 5 micron) portions of the spectrum, then this ratio can be employed as a countermeasure or non-target discriminant; e.g., if the ratio of energy in the short wavelength band to that in the long wavelength band is greater than 1, then it is most probably a countermeasure or non-target and should be rejected. If the ratio is less than 1, it is most probably a valid target.

This technique, illustrated in Figure 7, can be easily incorporated in the image scanning sensor by either adding an additional set of fiber optic transmission lines and appropriate filters or by employing sandwich detectors with suitable internal filters. The sandwich detector approach is preferred because of the spatial and temporal coincidence of the target acquisition and non-target rejection channels. This type of two-color seeker has been extensively field tested from a helicopter platform and has yet to acquire a countermeasure or non-target. Figure 8 illustrates a frame from a parallel mounted television camera which has a simulation of the four detector scanning pattern superimposed upon it. Automatic acquisition of an armored vehicle target has just occurred and the seeker is tracking the target. A summary of results from several hundred test sequences is given in Figure 9. It can be seen that the probability of acquisition and tracking of moving armor is extremely high and even under stationary and engine idling conditions a very acceptable probability of acquisition is achieved.

MILLIMETER WAVE SEEKERS

The second window in the frequency spectrum that is suitable for relatively small diameter missile seekers is the millimeter wave-band from approximately 30 to 300 GHz. As can be seen from Figure 10 several choices of operating frequencies are available, each with differing degrees of atmospheric attenuation.

If antenna apertures of 15 to 20 centimeters in diameter are practicable, then the 35 GHz band can be employed with only minor effects on propagation due to the atmosphere. Radar-type seekers with solid state transmitters can be readily designed to obtain adequate target acquisition range with reasonable cost and complexity. For example, an active radiometer capable of acquiring armored vehicle targets is shown in Figure 11.

The term active radiometer is used to indicate that the transmitter illuminates the target area with wide band (200 MHz) frequency modulated pulses with a duration of 40 nanoseconds. This technique is used to reduce the effects of target glint and thereby improve the seeker terminal aim-point accuracy. In addition, the receiver can be operated in a fully radiometric mode during the terminal phase, if desired, to provide an improved estimate of the target centroid. This type of millimeter wave seeker has been most successfully employed on remotely piloted vehicles (RPVs) which have a target engagement phase at the end of their mission.

For missiles with diameters in the 7 to 10 centimeter range, 140 GHz is currently under investigation. 140 GHz was chosen on the basis of maximum antenna resolution; i.e., less than two degrees half-power beamwidth, with acceptable atmospheric and adverse weather attenuation for terminal guidance. The availability of solid state sources with sufficient power output was also an important factor. Figure 12 shows an experimental 140 GHz homodyne seeker module consisting of a solid state transmitter and modulator, a circulator and mixer.

This is a frequency modulated/continuous wave (FM/CH) type radar employing a linear frequency deviation in the solid state transmitter of 50 MHz. Approximately 7 mw average power output at 140 GHz is obtained from a voltage controlled oscillator/frequency doubler combination. An indium phosphide Gunn oscillator, which produces approximately 75 mw at 70 GHz, drives a silicon varactor chip. A conversion efficiency of approximately 10 percent is achieved.

The target-reflected signals are mixed with a small portion of the transmitted signal in a diode mixer with approximately 9.5 db conversion loss. This experimental seeker is capable of acquiring a tracked vehicle target at ranges of greater than 1 km. The range resolution is approximately 1 meter and sub-doppler components of the return can be readily detected. This latter capability could be used to aid in target classification or discrimination.

MULTI-MODE SEEKERS

It is well known that under certain operational conditions encountered on the battlefield, all forms of single mode terminal guidance seekers suffer some degree of degradation in acquisition range and terminal accuracy. Infrared systems can be severely restricted by clouds, fog and smoke. Millimeter wave systems can be severely affected by chaff, corner reflector decoys and, to a lesser extent, by rainfall and fog depending on the actual operating wavelength selected. The principal effects of these conditions on infrared and millimeter wave seekers are shown for comparison in Figure 13.

In addition, depending on the missile trajectories and aspect angles to the target, the response of the targets to the sensor may be obscured or reduced in some way which would reduce acquisition range or not allow acquisition at all. For example, at very low angles of attack towards the front of a tank, the warmer parts; e.g., the engine compartment and exhaust system, are obscured from the seeker's field of view by the gun turret. Conversely, at very high angles of attack the millimeter wave radar type seeker tends to have
reduced capability to separate low profile targets from background clutter. The characteristics of infrared and millimeter wave seekers are summarized in Figure 14.

It is apparent that both forms of seeker are complementary in operation and performance and that a dual mode seeker employing both wavebands could perform effectively under a large fraction of the likely operational and environmental conditions encountered on the battlefield. The question is, can these two technologies be merged together within the confines of a small missile seeker head and still achieve the desired performance at an acceptable cost and a high degree of reliability?

One approach to millimeter wave/infrared sensor integration that is being evaluated at General Dynamics Pomona Division is to employ a common Cassegrainian optical system consisting of a primary aspherical reflector and a canted secondary reflector. An experimental version of this concept is shown in Figure 15. The secondary reflector is rotated by a small, electrically driven, pancake motor to develop the tracking error signals for both modes. The millimeter wave energy is transmitted and received by a small horn antenna and the infrared energy is received by fiber optics transmission lines supported at the horn aperture by a dielectric plate. The fiber optics are similar to those described earlier for the two-color infrared image scanning seeker. The addition of the fiber optics to the 140 GHz antenna feed does not appear to cause any appreciable loss in millimeter wave energy and the fibers can be exited through the waveguide wall without any significant loss in infrared energy. The experimental sensor shown in Figure 15 has been field tested against tracked targets and the expected target detection ranges have been obtained confirming the practicability of the common aperture approach. A complete seeker has been designed and is currently being assembled for extensive field testing with armored vehicle targets under a wide range of simulated battlefield conditions and adverse weather.

Another type of dual mode or perhaps trimode seeker should be described. This specifically addresses the problem of air defense suppression in which the initial missile guidance mode is radio frequency homing on air defense missile fire control radars.

This small anti-radiation seeker uses a rolling, two-port microwave interferometer antenna system mounted around the infrared terminal homing seeker as shown in Figure 16. The infrared seeker is an image scanning type similar to that described earlier. The missile has single plane guidance and control and the angle-of-arrival ambiguities normally associated with an interferometer antenna are resolved by the rolling airframe. Phase processing of the received signals is employed that does not require the antenna to be directed at the radiation source and provides sufficient angle measurement accuracy to position the infrared seeker gyro-telescope within plus or minus one half of a degree (±0.5 degree) of the target line-of-sight. When the infrared seeker has achieved acceptable target lock-on, guidance control is switched to the infrared seeker. If a loss of target lock occurs then the anti-radiation homing/infrared guidance sequence is recycled.

CONCLUSIONS

The experimental seeker concepts and designs described show that autonomous armored target acquisition and terminal guidance can be achieved by means of infrared and millimeter wave seekers small enough to fit into precision guided munitions. Advanced versions employing countermeasures and non-target discrimination techniques have been demonstrated on common aperture multi-mode seekers, potentially capable of operating effectively under a wide range of adverse battlefield conditions, appear to be feasible.

ACKNOWLEDGEMENTS

The author would like to recognize the significant contributions of several General Dynamics Pomona Division technologists to the work described in this paper. In infrared technology, S. Domen and G. L. Henshaw have long pioneered high resolution infrared image scanning and the application of infrared fiber optics. In millimeter waves, G. N. Hulderman and J. B. Winderman have played a key role in the development of components and systems throughout the millimeter wave band suitable for precision guided munitions.
### Problem

- Background Clutter
  - Terrain, Vegetation
  - Structures
- Nontargets
  - Farm Machinery, Buildings
  - Burning Vehicles
- Countermeasures
  - Flares, Jamming
  - Decoys
- Weather Conditions
  - Rain, Fog, Low Clouds
  - Snow

### Effect

- Low Probability of Autonomous Target Acquisition at Tactically Useful Ranges
- Significant Reduction in Weapon Effectiveness
- Significant Reduction in Weapon Effectiveness
- Moderate to Severe Loss of Autonomous Acquisition Range

### Potential Solution

- Increase Target Signal-to-Clutter Ratio by Increasing Angular and Range Resolution
- Increase Nontarget Resolution and Rejection by Spectral or Range Discrimination
- Minimize Field-of-View or Antenna Beamwidth, Reject by Spectral Discrimination
- Maximize Detection Range by High-Resolution, Multiple-Mode, Multi-Spectral Sensors

**Figure 1. Seeker Design Trends**

**Figure 2. Infrared Image Scanning Seekers**
FIGURE 3. TARGET/BACKGROUND CLUTTER AS A FUNCTION OF IFOV FOR A TANK TARGET

FIGURE 4. SEEKER HEAD WITH FIBER OPTICS COUPLING
FIGURE 5. ARSENIC TRISULPHIDE FIBERS

FIGURE 6. SPECTRAL SIGNATURES OF VARIOUS INFRARED SOURCES
Figure 7. Two-color infrared image scanning seeker head

Tracking Scan Pattern

Figure 8. Two-color infrared field tests
<table>
<thead>
<tr>
<th>TARGET TYPE</th>
<th>PROBABILITY OF SUCCESSFUL DETECTION AND TRACKING:</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOVING ARMOR</td>
<td>1.00</td>
</tr>
<tr>
<td>IDLING ARMOR</td>
<td>0.88 TO 0.59</td>
</tr>
<tr>
<td>DECOY SOURCE</td>
<td>0</td>
</tr>
</tbody>
</table>

FIGURE 9. TWO-COLOR INFRARED IMAGE SCANNING SEEKER PERFORMANCE

FIGURE 10. THE MILLIMETER WAVE SPECTRUM - ATMOSPHERIC ATTENUATION
- ACQUISITION RANGE 1.8 km
- ANTENNA DIAMETER 20 cm
- PEAK POWER 6 WATTS
- PULSE WIDTH 40 nsec
- GIMBAL ANGLE ±45° AZ
  ±30° EL
- BLIND RANGE <15 METERS

FIGURE 11. 35-GHz ACTIVE RADIOMETER SEEKER

FIGURE 12. EXPERIMENTAL 140 GHz HARDWARE
<table>
<thead>
<tr>
<th>CONDITION</th>
<th>INFRARED</th>
<th>MILLIMETER WAVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEAR WEATHER</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>SMOKE AND DUST</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FOG</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>RAIN, MODERATE</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CHAFF</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>RADAR CORNER REFLECTORS</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>FLARES, BURNING FUEL, SUNGLINTS</td>
<td>(X^{(1)})</td>
<td>X</td>
</tr>
</tbody>
</table>

\(X = \text{UNIMPAIRED OPERATION}\)  \((1)\) TWO-COLOR IR SENSOR

**Figure 13. Infrared and Millimeter Wave Seeker Performance Under Various Battle-Field Conditions**

<table>
<thead>
<tr>
<th>MILLIMETER WAVE MODE</th>
<th>INFRARED MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DETECTION OF REFLECTIVE OBJECTS</td>
<td>DETECTION OF HEATED SURFACES</td>
</tr>
<tr>
<td>WIDE AREA SEARCH AT MODERATE SCAN RATES</td>
<td>HIGH ANGULAR RESOLUTION TRACKING</td>
</tr>
<tr>
<td>GOOD PERFORMANCE IN FOG AND PARTICULATES</td>
<td>GOOD PERFORMANCE IN RAIN AND CHAFF</td>
</tr>
<tr>
<td>RANGE AND/OR MOVING TARGET CAPABILITY</td>
<td>DISCRIMINATION CAPABILITY AGAINST FLARES, BURNING FUELS, AND SUNGLINTS</td>
</tr>
<tr>
<td>NOT RESPONSIVE TO FLARES AND BURNING FUELS</td>
<td>NOT RESPONSIVE TO RADAR CORNER REFLECTORS</td>
</tr>
<tr>
<td>DETECTION LITTLE AFFECTED BY TARGET ORIENTATION</td>
<td>DETECTION NOT A FUNCTION OF PHYSICAL TARGET SIZE</td>
</tr>
</tbody>
</table>

**Figure 14. Infrared and Millimeter Wave Seeker Characteristics**
FIGURE 15. COMMON APERTURE MILLIMETER/INFRARED SENSOR

FIGURE 16. DUAL MODE RADIO FREQUENCY/INFRARED SEEKER
RADAR SEEKERS FOR PRECISION GUIDED MUNITIONS

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SUMMARY

Radar precision guided missiles have been in continuing and extensive development since World War Two. The advantages of radar guidance compared with electro-optical guidance are effectiveness in bad atmospheric conditions, good range resolution and long range capability: the disadvantages have been poor angular resolution and complexity.

Radar guided missiles were first developed for use against air targets, later against ship targets and then against radar targets.

Over the past decade there has been vigorous development of radar guidance for munitions against battlefield targets. Picking out a target on the battlefield from "clutter", the unwanted signals from objects which are not targets, is a much more severe problem than in the case of air or ship targets and calls for more complex signal processing than before. Despite this added complexity most radar seekers for future battlefield munitions will have to be very much lower in size and cost than present radar seekers.

This paper aims to give a general perspective on the evolution of radar guidance, utilizing the astonishing current advances in electronic technology, so as to overcome past disadvantages of radar guidance and to solve the problems of battlefield targets.

INTRODUCTION

Figure 1 lists the contents of this paper. First, systems in operation: some current anti-air and anti-ship radar guided systems will be described. Second, advances in the technology of signal processing, microwave antennas and circuits and of inertial reference systems. Third, future systems for anti-air, anti-radiation and anti-land targets. Fourth, conclusions will be given of the way ahead with an example of an evolution of radar seekers.

SYSTEMS IN OPERATION

First then, some systems presently in operation. Figure 2 shows the Sea Dart missile being launched from a guided missile destroyer. Sea Dart was one of the earliest homing missiles to use advanced tracking radar techniques in its target seeker. Figure 3 shows the forebody of the large - about 40 cm diameter - coaxial ram jet, Sea Dart missile, which contains the MSDS semi-active radar 'target seeker' - or 'homing head' as it is sometimes called.

After Sea Dart came the much smaller, 20 cm diameter missile, Sky Flash, the two, white, cruciform missiles on a Swedish Viggen, shown in Figure 4. Sky Flash was a more demanding application of complex tracking radar techniques. The MSDS semi-active radar seeker of Sky Flash - it is just under 20 cm in diameter, is shown in Figure 5. Figures 6,7 and 8 are shots from a film of Sky Flash in a particularly difficult low level air to air engagement where the problem of clutter is very severe: look-down shoot-down from a fighter at medium altitude. In Figure 7, the streak - top right - is Sky Flash in its steep dive just before precisely hitting the target.

Now for the Sea Skua anti-ship missile: Figure 9 shows four being carried on the Lynx helicopter. It is a semi-active homing system. In such systems the target is illuminated by a radar at the launcher, the semi-active seeker in the missile only receiving the echo. Thus, semi-active homing missiles are dependent, throughout flight, on other simultaneous operations at the launcher. Figure 10 shows the Sea Skua radar seeker detached from the missile. The bulkhead is about 25 cm in diameter.

Another anti-ship missile, is shown in Figure 11. Sea Eagle, mounted on a Buccaneer. It is a large missile, using active radar homing guidance. In active homing the seeker includes the transmitter which illuminates the target. Thus the complete homing guidance system is selfcontained in the missile. After launch, an active homing missile has the capability of attacking a target on its own - without further dependence on the launch platform. A typical, large, anti-ship active radar seeker - about 35 cm in diameter - which incorporates a computer that can be modified is shown in Figure 12. The development of this seeker gave much experience in fully utilising such a facility.
ADVANCES IN TECHNOLOGY

Now consider the advances in technology which are allowing the development of much smaller and more effective radar seekers for the future, dealing first with signal processing (Figure 13). First, thick film hybrids are replacing printed circuit boards as motherboards. They can also form analogue circuits. At the bottom of the photo of Figure 14 is a thick film hybrid, about 5 cm long, doing a similar job to the conventional printed circuit board with soldered discrete components, about 18 cm long, at the top. The pattern of conducting tracks which interconnect active and passive circuit elements in the thick film hybrid, is similar to that of the printed circuit board, but reduced in scale. The reduction in area for analogue circuits can be about 10 to 1 and for digital circuits about 4 to 1.

The second item on signal processing in Figure 13 is: IC'S (integrated circuits), LSI (large scale integrated circuits) and VLSI (very large scale integrated circuits). These components are used for digital signal processing and for storing data. Figure 15 shows a closer view than in the previous photo in Figure 14 of a thick film hybrid. The small black squares are silicon integrated circuits. One is magnified to show the details of the integrated circuit. Just as the pattern of tracks and components, of the thick film hybrid, is reduced in scale from that of the printed circuit board, so is the pattern on this, one millimetre square, silicon chip, reduced from that of the thick film hybrid - but very much more so. Figure 16 shows an even more microscopic pattern - a close up of a large scale integrated circuit about 2.5 mm long. Silicon chips of around this size can contain as many as 10,000 transistors. LSI are the heart of the pocket calculator and such like. Figures 17 and 18 illustrate the impact of this revolution in signal processing on radar seeker hardware: the first is typical of current in-service equipment: - PCB carrying discrete soldered components: the second shows an equivalent equipment using thick film hybrid with LSI.

Figure 19 lists the advances in the technology of microwave antennas and microwave circuits. First, stripline transmission which is very much smaller and lower cost than waveguide. One form is "microstrip", thin film metal conducting tracks deposited on a rigid insulating substrate. The white rectangle - about 8 cm long - in the middle of the assembly shown in Figure 20 is a quite complex microwave circuit in microstrip.

Returning to Figure 19, another form of stripline transmission is "triplate". As in microstrip, conduction is along a thin film metal track but the substrate can be flexible plastic. Figure 21 shows a diagrammatic exploded view of an antenna array and its associated microwave comparator circuit in triplate. Figure 22 is a photograph of the final hardware - a quite thin antenna and microwave system (appropriate to a 125 mm diameter missile).

Continuing the advances in microwave systems, item 2 in Figure 19 is microwave integrated circuits. In the hybrid form these circuits incorporate semi-conductor chip devices bonded into the thin film metal tracks of the stripline. Figure 23 is an example: the white substrate is about 5 cm long. In the monolithic form of MIC both the thin film tracks and the semi-conductor devices are formed on a common semi-conductor substrate - offering a remarkable potential for both miniaturisation and low cost, high volume production. Figure 24 is a diagram showing the construction of a particular monolithic MIC (at 10 GHz). Figure 25 is a photograph of the surface of the actual circuit, which is only about 1 mm long. A further area of advancing microwave technology is Item 3 of Figure 19 - phased array antennas. Figure 26 illustrates the elementary principle of a particularly attractive form of antenna - conformal arrays - which comprise radiating elements on the outside of the nose of a guided munition. An illustration of Item 4 of Figure 19 is given in Figure 27. This is a photo of a solid state transmitter, small enough to be mounted (as shown) on the back of a triplate antenna appropriate to a 150 mm diameter missile.

For millimetre wave systems, Item 5 of Figure 19, there has been a continuing advance in the availability and performance of devices. Figures 28 to 39 show examples of the various millimetre wave components required for active radar seekers. Figure 40 shows the layout of a typical possible design. There have also been striking advances in inertial reference technology (Figure 41). This technology is of basic importance to target seekers in their task of guiding missiles very accurately in optimum trajectories in space. First, miniature gyro and accelerometers which can be incorporated into miniature seekers. Figure 42 shows the small, single unit, DART gyro, which can now replace two GRH4 gyros. Second, small, low cost, strap-down 'IN' (inertial navigation) systems. Figure 43 shows an example. These devices of items one and two of Figure 41 can be used - Item 3 - for seeker antenna stabilisation in space. The last item - four - is another application of item two - 'IN' systems - for inertial mid-course guidance systems with update of target position.

This completes the account of advanced technology and leads into future anti-air target systems: Item 4 of Figure 41 dealt with above, as will now be explained, is a vital element for these systems.

FUTURE ANTI-AIR SYSTEMS

In future air to air and surface to air guided missiles (Figure 44), active homing (Item 1) will be used to allow; launch and leave, high fire power and improved interoperability. However, the range of an active seeker will generally only be a fraction of the aerodynamic range of the missile, calling for a mid-course guidance phase to precede terminal active homing. The small, low cost, inertial navigation systems referred to earlier can now provide (Item 2) missile inertial navigation for mid-course guidance. To account for manoeuvre of the target after missile launch (Item 3) a launcher to missile data link is needed to give the missile an update of the target course. Notice that the shorter seeker ranges of these terminal homing systems, allow operation at lower radar wavelengths - down to millimetre waves.

Some examples will now be given of small anti-air seekers for future systems.
Figure 45 shows the gimbaled antenna - the disc is the antenna - of a radar seeker small enough to go into a 125 mm diameter missile. This is a reduction in size to about 60% in linear scale and to about 25% in volume of the Sky Flash gimbaled antenna. It is an example of what can now be achieved by the application of the advanced microwave and inertial reference technology outlined above.

Figure 46 shows a model, incorporating the gimbaled antenna of Figure 45, of a complete radar seeker for a 125 mm diameter missile. Its overall miniaturisation - it is only about one quarter the volume of the Sky Flash seeker - is due to the use of the advanced technology previously outlined - in signal processing, thick film hybrids and LSI - as well as microwave circuits and in inertial reference components.

BATTLEFIELD PRECISION GUIDED MUNITIONS

Now for future anti-radiation and anti-land target seekers - both categories coming under the general heading of battlefield precision guided munitions (Figure 47). The conventional battlefield forces of the Warsaw Pact have built up to levels well above those of NATO. In recent years, attention has been drawn to a possible counter to this threat: exploit advanced technology to achieve revolutionary improvement in the NATO conventional forces through a variety of precision guided munitions. One class of targets in the Warsaw Pact forces is ground to air defences - anti-aircraft artillery and surface to air missile systems. A second type of target is groups of armour and a third is fixed targets of high value.

FUTURE ANTI-RADIATION SYSTEMS

Munitions to counter the first class of targets - Warsaw Pact ground to air defences - will now be considered.

The radars of these surface to air missile and gun defences can be attacked by using (Figure 48) anti-radiation seekers in missiles, drones or shells to cause these munitions to home on to a radar.

This sketch in Figure 49 illustrates the many different waveforms transmitted from the many different types of radar in the battlefield. An anti-radiation seeker must pick out one particular waveform from one particular radar so as to home the missile on to that radar - a complex problem. However, the advances in electronic technology already described together with extensive experience in applying them in the fields of electronic warfare and electronic support measures have considerably expanded the potential for anti-radiation seekers.

Figures 50 and 52 show some examples of the sort of broadband antenna systems required by anti-radiation seekers. Figure 53 shows a 250 mm diameter anti-radiation seeker, and Figure 54 a model of a 155 mm guided shell incorporating an anti-radiation seeker.

FUTURE ANTI-LAND TARGET SYSTEMS

Having dealt with the special case of radiating land targets, now consider more generally the requirements for radar seekers and sensors for medium and long range, stand-off missiles against land targets (Figure 55). These requirements include, first, sensors for navigating medium and long range missiles. Second, target seekers for the terminal guidance of these large, medium and long range missiles, against a group of tanks or against fixed targets (e.g. bridges). The third point listed, is that both the above sensors for navigation, and the seekers for terminal guidance, will use techniques for high resolution imaging, either millimetre wave radar or synthetic aperture radar, or both.

The use of radar for navigation and for target seeking against land - and sea - targets goes back to World War 2 when airborne radar was used for all-weather ground mapping - i.e., producing an image of features on the ground by a scanning radar beam - so as to navigate a bomber aircraft and also to seek its target.

The angular resolution of an airborne radar and hence the degree of image detail it can reveal, can be improved by an advanced form of radar, termed 'synthetic aperture radar', sometimes also termed 'doppler beam sharpening'. Its operation is illustrated in Figure 56. Image resolution along the beam is by range, and across the beam, by doppler discrimination.

Figure 57 is an example of a map from a modern SAR airborne radar, (supplied by Marconi Research Labs). It is of a river estuary. Roads and hedges are clearly defined with an image resolution down to a few metres.

Now consider the radar seekers and sensors required for small, precision guided, sub-munitions against armoured vehicles (Figure 58). First, there are three types of sub-munition, terminally guided (TGS), sensor fuzed (SFSM) and sensor aided sub-munitions (SASM). Second, their seekers or sensors must be small, low cost in high volume production and, to get adequate angular resolution, must operate at millimetre or sub-millimetre wavelength.

Figure 39 is a model of a millimetre wave seeker for a 100 mm diameter TGSM (terminally guided submunition).

CONCLUSIONS

Figure 60 summarises the way ahead. First, advances in electronics continue to allow: improvements in performance and reliability; reduction in size allowing modular design; and reduction in cost. Second, digital processors with software control allow improved use of sensor and pre-launch data and gives flexibility. Third, modernising the guidance system during the lifetime of a weapon system is becoming increasingly practicable. And fourth, multi-sensor seekers, combining radar, anti-radiation and IR sensors in the one seeker, could greatly improve performance in a number of important ways.
Finally, Figure 61 shows an evolution of radar seekers. The three on the left are anti-air target radar seekers which in general terms do a similar job. The large one on the left is Sea Dart - technology vintage 1962 - the next is Sky Flash - vintage 1972 - the next on the right is the 125 mm seeker described earlier - technology vintage 1976. The fourth seeker - last on the right is the active, 100 mm diameter, anti-armour seeker. The dramatic reduction in size mainly reflects the advances in electronics which I have outlined, but experience and improvements in system design have contributed. As well as the great reduction in size the later seekers also have greatly increased signal processing capability with consequent improvements in performance.

ACKNOWLEDGEMENT

Acknowledgement is made to the UK Ministry of Defence Procurement Executive and particularly to staff of the Royal Signal and Radar Establishment, for sponsoring and contribution to the developments described in this paper.
1. SYSTEMS IN OPERATION
   Anti-air
   Anti-ship

2. ADVANCES IN TECHNOLOGY
   Signal processing
   Microwave antennas and circuits
   Inertial reference systems

3. FUTURE SYSTEMS
   Anti-air
   Anti-radiation
   Anti-land targets

4. SUMMARY
   The way ahead
   Example of evolution of radar seekers

FIGURE 1 - RADAR SEEKERS FOR PRECISION GUIDED MUNITIONS

FIGURE 2 - SEA DART LAUNCHED FROM HMS BRISTOL

FIGURE 3 - SEA DART SEEKER

FIGURE 4 - SKY FLASH ON ROYAL SWEDISH AIR FORCE VIGGEN

FIGURE 5 - SKY FLASH SEEKER
FIGURE 6 - SKY FLASH LOOK DOWN SHOOT DOWN FIRING SEQUENCE - LAUNCH

FIGURE 7 - SKY FLASH LOOK DOWN SHOOT DOWN FIRING SEQUENCE - NEAR TARGET

FIGURE 8 - SKY FLASH LOOK DOWN SHOOT DOWN FIRING SEQUENCE - TARGET HIT

FIGURE 9 - FOUR ANTI-SHIP SEA SKUA MISSILES ON LYNX HELICOPTER

FIGURE 10 - SEA SKUA SEEKER

FIGURE 11 - SEA EAGLE ON BUCCANEER
1. **THICK FILM HYBRIDS**
   - Replacing printed circuit boards as motherboards
   - Analogue Circuits

2. **I.C.'S, L.S.I., VLSI**
   - For digital signal processing
   - For storing data

---

**FIGURE 12** - ANTI-SHIP ACTIVE SEEKER

**FIGURE 13** - ADVANCES IN TECHNOLOGY - SIGNAL PROCESSING

**FIGURE 14** - PRINTED CIRCUIT BOARD AND THICK FILM HYBRID

**FIGURE 15** - THICK FILM HYBRID WITH MAGNIFIED VIEW OF AN INTEGRATED CIRCUIT

**FIGURE 16** - LARGE SCALE INTEGRATED CIRCUIT

**FIGURE 17** - PAST SIGNAL PROCESSING HARDWARE - PCB AND DISCRETE SOLDERED COMPONENTS
1. Stripline transmission
   - Microstrip  Triplate
2. Microwave integrated circuits (MIC's)
   - Hybrid  Monolithic
3. Phased array antennas
4. Miniature Transmitters
5. Millimetre wave systems

FIGURE 18 - FUTURE SIGNAL PROCESSING HARDWARE -
THICK FILM HYBRID AND LSI
(ASSEMBLY 90 MM WIDE)

FIGURE 19 - ADVANCES IN TECHNOLOGY -
MICROWAVE ANTENNAS AND
MICROWAVE CIRCUITS

FIGURE 20 - MICROWAVE CIRCUIT - MICROSTRIP
(FOR 125 MM DIAMETER MISSILE)

FIGURE 21 - TRIPLATE MICROWAVE ANTENNA AND
COMPARATOR - EXPLODED VIEW

FIGURE 22 - TRIPLATE ANTENNA AND MICROWAVE
CIRCUIT

FIGURE 23 - HYBRID MICROWAVE INTEGRATED
CIRCUIT
FIGURE 24 - MONOLITHIC MICROWAVE INTEGRATED CIRCUIT - DIAGRAM (1.4 MM LONG)

FIGURE 25 - MONOLITHIC MIC - PHOTO

FIGURE 26 - CONFORMAL PHASED ARRAY ANTENNAS

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(30 MM WIDE)

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(FOR MIXERS AND DETECTORS)
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FIGURE 35 - 35 GHz POWER DIODE OSCILLATOR
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(20 MM CUBE)

FIGURE 37 - VARIOUS MMW COMPONENTS 
CLOCKWISE FROM LEFT: 95 GHz OSCILLATOR, 
100 MM 95 GHz ANTENNA REFLECTOR, ANTENNA 
FEED, 35 GHz OSCILLATOR COMBINING SIX 
DIODES, 95 GHz MIXER, 35 GHz CW 
OSCILLATOR

FIGURE 38 - 95 GHz MICROWAVE SYSTEM - SINGLE 
SUM CHANNEL - MICROSTRIP HYBRID MIC 
(30 MM WIDE)

FIGURE 39 - 95 GHz MICROWAVE SYSTEM - 
DOUBLE SUM CHANNEL (FOR DUAL 
POLARISATION) MICROSTRIP 
HYBRID MIC

FIGURE 40 - 95 GHz SEEKER

FIGURE 41 - ADVANCES IN TECHNOLOGY - 
INERTIAL REFERENCE SYSTEMS

1. Miniature gyros and accelerometers
2. Small, low costs, strap-down IN systems
3. For seeker antenna stabilisation
4. For inertial mid-course guidance 
systems with update of target position
1. Active homing to allow:
   - Launch and leave
   - High fire power
   - Interoperability

2. Missile Inertial Navigation for:
   - Mid-course guidance

3. Launcher to missile data link to give:
   - Update of target course

Battlefield Precision Guided Munitions
Against Warsaw Pact forces
1. Ground to Air defences
   - AA
   - SAMS

2. Groups of armour

3. Fixed targets
ANTIB-RADIATION SEEKERS FOR:

- Missiles
- Drones
- Shells

FIGURE 48 - ANTI-RADIATION SEEKERS

FIGURE 49 - THE ANTI-RADIATION HOMING PROBLEM (ARTIST'S IMPRESSION)

FIGURE 50 - VARIOUS BROADBAND SPIRAL ANTENNAS (FROM 25 MM DIAMETER TO 125 MM SQUARE)

FIGURE 51 - MONOPOLE BROADBAND SPIRAL ANTENNA ARRAY

FIGURE 52 - BROADBAND CONFORMAL ARRAY (100 MM DIAMETER)

FIGURE 53 - 250 MM DIAMETER ANTI-RADIATION SEEKER
1. Sensors for navigating medium and long range missiles.
2. Seekers for terminal guidance of medium and long range missiles.
   Against a group of tanks
   Against fixed targets (e.g., bridges)
3. The above seekers and sensors use techniques for high resolution imaging.
   Millimetre wave radar
   Synthetic aperture radar (SAR)

FIGURE 54 - MODEL OF 155 MM DIAMETER ANTI-RADIATION SHELL

FIGURE 55 - RADAR SEEKER AND SENSORS FOR STAND-OFF MISSILES AGAINST LAND TARGETS

FIGURE 56 - SYNTHETIC APERTURE RADAR (SAR) OR DOPPLER BEAM SHARPENING (DBS) (ARTIST'S IMRESSION)

FIGURE 57 - MAP BY MODERN AIRBORNE SYNTHETIC APERTURE RADAR

1. TYPES OF SUB-MUNITIONS
   Terminally guided sub-munition (TGSM)
   Sensor fuzed sub-munitions (SFSM)
   Sensor aided sub-munitions (SASM)

2. SEEKERS AND SENSORS
   Small
   Low cost in high volume production
   Millimetre wave

FIGURE 58 - RADAR SEEKERS AND SENSORS FOR PRECISION GUIDED MUNITIONS AGAINST ARMOURED VEHICLES

FIGURE 59 - MODEL OF A 100 MM DIAMETER TERMINALLY GUIDED SUBMUNITION
ADVANCES IN ELECTRONICS CONTINUE TO ALLOW
- Improvements in performance and reliability
- Reduction in size - modular design
- Reduction in cost

DIGITAL PROCESSORS WITH SOFTWARE CONTROL ALLOWS
- Improved use of sensor data
- Improved use of pre-launch data
- Flexibility

MODERNISHING GUIDANCE SYSTEM DURING LIFETIME OF
WEAPON SYSTEM

MULTI-SENSOR SEEKER
- Radar/Anti-radiation
- Radar/IR

FIGURE 60 - THE WAY AHEAD

FIGURE 61 - SEA DART
- SKY FLASH
- 125 MM DIAMETER SEEKER
- 100 MM DIAMETER SEEKER
ADVANCED IMAGING TECHNIQUES FOR HIERARCHIES OF INTELLIGENT PGMs

by

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Abstract

Levels of intelligence in PGMs are determined as a functional involving false alarm probabilities and non target detection error probabilities. For an apriori specified mission a minimal PGM IQ is needed; to help guarantee this minimal value advanced image processing techniques have been developed. Here it is assumed that the munition is fitted with a strapdown navigation and guidance system and a necessary imaging sensor such as IR. Baseline imaging procedures are described common to all intelligence levels with additional methods given for PGMs with larger IQ's. A recently developed Imaging Algebra is applied to PGM systems; here operators are employed for image enhancement, restoration, segmentation, classification, and registration. Many of these new operators are based on counterparts in classical mathematical disciplines such as topology, linear and abstract algebra, and functional analysis.

Among the baseline operators described and used in PGM applications are those that avail themselves of additional information such as known distance to target, or target in motion. Here masking techniques and size fitting operations prove quite useful. At the opposite end of the spectrum is when little additional information is known about the target except for its various views at different aspect angles. Here heavy use is made of harmonic analysis and interpolation of pattern classes.

The operators described, along with stochastic procedures, help render the desired intelligence level. Preliminary algorithm design shall be conducted for real time digital process implementation. This will go hand-in-hand with computer architecture determination. Here an upwards intelligence compatible combination array and pipeline processor is proposed using state-of-the-art processing technology along with LSI/VLSI technology.

Introduction

Levels of intelligence are to be assigned to families of robots specifically families of Precision Guided Munitions PGMs. This Intelligence Quota (IQ) could be determined in a similar way as is done for human beings namely by testing. Beginning tests and subsequent evaluation can be achieved by faithful modeling and successive simulation of PGMs targets and environment. IQ Validation will only result by field testing, and strict inferential statistical procedures must be utilized throughout. The latter statement is crucial since we will assume, that different PGMs in a single fixed family will have identical IQ's. We will use the hypothesis that the PGMs are self propelled and contain a (Strapped Down) Inertial Navigation/Guidance System along with image sensing devices such as Infrared (IR) or millimeter radar like Synthetic Apperture Radar (SAR). Implicitly assumed also are: actuators and servos along with engines to control the motion and sustain it; quantities of submunitions to destroy the targets; and finally computer (s) which when programmed with the proper software will make the necessary decisions. Different families of PGMs are fitted with various qualities and/or quantities of the above mentioned items thereby "causing" the different IQ levels previously mentioned.

Figure 1 illustrate the basic ingredients of PGMs discussed here within

<table>
<thead>
<tr>
<th>Actuators</th>
<th>Inertial Navigation System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servos</td>
<td>Imaging Sensors</td>
</tr>
<tr>
<td>Engines</td>
<td>Software</td>
</tr>
<tr>
<td>Computer</td>
<td></td>
</tr>
<tr>
<td>Submunitions</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1

The IQ rating will provide a rank ordering of PGM families indicating how clever the PGMs are in searching for, identifying tracking and destroying designated targets without human intervention. Our main thrust will be in discussing imaging techniques which will aid in this mission, however before this is done we will further outline the IQ test for PGMs.
The IQ Test

An overview of the IQ testing and grading procedure shall now be given. Absolute quantities such as range, speed, initial weight volume, shape etc may influence the IQ however these types of attributes may be separately evaluated as a function of the PGM family. Subjecting PGMs from different families physically or by way of simulation to identical controlled target/clutter/environment conditions makes the evaluation of the IQ a structured medium difficult task. The score for the test is a functional involving false alarm and target non detection errors. The quantity and quality of targets hit must also be taken into account. The software most heavily influences this outcome. As soon as potential targets are identified and classified by the PGM their location is recorded along with estimates of their velocities. Standard prediction techniques are incorporated in the software to provide these estimates based on observations and target mobility models. Using different cueing and queueing algorithms will indeed influence the score. Pointers to potential targets are queued up in single or multiple lines waiting to be serviced (bombed). Cueing algorithms will "specify the organization of these lines" and indeed will rank order the targets as a function of numerous criteria. Cueing factors include; target importance, speed of target, location of target, manuavability of PGM, number of munitions remaining in PGM, time, distance traveled. This cueing algorithm also determines the scheduling protocol to service the target queues. Steering commands are given to direct the PGM to the prioritized rank ordered targets and the control system takes over to make sure the service is completed.

Various scenarios should be employed in this testing. Different densities of target and clutter along with distinct camouflage. Susceptibility of the PGM to destruction by the enemy should also be taken into account particularly for PGMs with non-self contained radiating devices such as the SAR. Testing should be faithful to real life conditions while also being exhaustive enough to fully utilize the hardware and software. The software which seems easiest to test; but most prone to lowering of IQ is the Imaging and Pattern Recognition Algorithms. We will shortly introduce a systematic precise and vigorous Algebra for Imaging which should prove beneficial, before this is done we will review the functions of the Imaging/Recognition Algorithms.

The Real Time PGM Imaging and Classification Process

The aspect of image processing with which we shall concentrate is imaging for PGM recognizer systems. Here an image of a three dimensional set of objects is obtained, and from this we want to make a decision as to whether or not some prespecified target is a member of this set. All of this of course must be performed in real time, that is, the absolute difference in time from which the object is sensed to when a decision is made must be less than a prespecified amount. This prespecified amount of time may change with different applications, but this predetermined time limit can not be exceeded. We don't have a guarantee that every target can be detected in real time by only processing imaging information, however in many cases some can. The capability of detecting or not is a function of numerous things, among them are: the overall set of objects which could possibly be viewed, and how similar they may be to the targets we wish to detect; the different possible aspect angles used in viewing the set of objects, intuitively the more aspect angles the more difficult the detection becomes; the type of sensor(s) used and how much distortion and noise it has; the algorithms and procedures employed along with the computer organizations and architecture; the time allotted for the real time detection; the accuracy required which as previously mentioned involve the false alarm probability and undetected object probability. In any case systems for object recognition using Imaging techniques are quite sophisticated. The Imaging task being so involved is best explained as submodules, as illustrated below in figure 2. It should be mentioned that the actual process need not be performed in the order illustrated, and every module may not be utilized.

---

**Figure 2** Imaging Operations For Recognizer

---
Beginning with the first module the Imaging sensor would output a signal as a function of time and from this by applying mathematical procedures an image is formed. The mathematics associated with the manufacturing of an image is called Image Creation and is depicted in the Figure 2. Also in this diagram are some of the other possible imaging procedures needed in the recognition. Image Restoration is the process of cleaning up an image for noise and distortion produced by the sensor and possibly by the computer itself in creating the image. The objective of the restoration is to produce an estimate $\hat{f}$ of the perfect image $f$. So Image Restoration corrects possible errors in previous steps. On the other hand Image Enhancement is used in avoiding possible errors which might occur in future steps. It is used with the idea of making successive steps easier to perform and the ultimate answer as correct as possible. These two steps together are termed Image Pre Processing. Specifically in the Enhancement stage important easy to use characteristics or important easy to use "features" of the Image might be enhanced or developed which would make the Segmentation step possible. Image Segmentation is a principle step in the understanding of an Image. Here the original image is often partitioned into subsets (or subimages) of mutually exclusive pieces such that their union is the original image. Each piece containing an image of a minimal number of objects (hopefully a single object) and is used in subsequent target identification procedures.

Image Registration refers to the recording of relevant conditions during the time at which the Image is being formed. Such conditions may be the time, the velocity of the sensor in an inertial frame the attitude of the sensor and so on. The purpose of linking this information with the image is many fold. Among the diverse reasons might be: The use of the data in further removal of distortions due to motion; the additional use of the registered information in helping to detect or identify objects, for instance if the distance from the object to the sensor is known one might use relative size as a possible feature; the use of this registered data is most important if numerous images of the same objects are taken. In this case one wants these replicas to be taken under identical circumstances which is usually physically impossible due to motion. Consequently the registered data is used along with mathematical procedures to adjust the images such that they seem to represent the objects under similar conditions. This is particularly important in detecting the motion of objects. The cuing procedure might give extra priority for target motion. The Image Classification Operations are used in the actual determination as to whether any pre specified object(s) are in the observed set of objects. In actuality a simple yes or no is not what is desired, rather in the our case for each object in the original set sensed one wants an identification of that object along with a number between zero and one indicative of the accuracy of that identification; with numbers closer to one denoting a higher degree of belief in this identification. Also desired as a part of this procedure is an estimate of the location of the targets along with instantaneous velocities. In any case there are a large number of steps involved from when the object is interrogated by the sensors to when the actual Detection Decision is made. A digital computer which performs these steps in real time usually must have an architecture custom made or developed hand in hand with the algorithms which perform the functions associated with each of these blocks. Consider Figure 3. In this diagram the digital processor is a Multiple Instruction Multiple Data (MIMD) also called a Multiprocessor, or a Combined Single Instruction Multiple Data (SIMD) and Multiple Instruction Single Data (MISD) type processor. These processors may make use of pipelining and array processing. In any case due to present day speed limitations of computers this type of architecture is configured to increase the throughput and thereby meeting the real time spec of the Imaging target Recognizer.
Setting Up The Imaging Algebra

The Imaging Algebra shall now be introduced. Here the mathematical setting is provided for rigorously defining images. Among other things it is shown that an image could be viewed as a fuzzy subset of the set of all pixels. Subsequently operators are given which convert images into new images. These operators are useful for and are subsequently employed in images restoration; image enhancement; images segmentation or in the feature selection stage. Most of these operators are special in nature and many of them were developed as analogies of, or special cases of, or generalizations of concepts found in conventional mathematics courses such as Topology or Functional Analysis. It can also be shown by utilizing concepts found in Universal Algebras and Category Theory how a Universal Theory of imaging is established. This is done by viewing image and other sets of interest in image processing along with the Imaging Operators as a Many Sorted Algebra. The benefits derived from this interpretation are rigor and precision and an underlying framework for the computer architecture and organization along with the potential benefits realized by establishing isomorphisms or homomorphisms with other structures. Examples are given of only a couple of the hundreds of operators in the Imaging Algebra. These operators are depicted using the Fozyaic Graph representation and lend themselves to a real time architecture for actual image manipulation. Among the Global Operator types existing are Topological, Geometric, Arithmetic, Point Operators and Neighborhood Operators, just to name a few. Many of the conventional imaging operations can be extended or generalized and incorporated into the Algebra. We will illustrate this Algebra for only black and white images.

A black and white image is composed of basic building blocks called pixels. Actually each pixel can be thought of as a small square; they are located adjacent to each other as in graph paper. Each pixel is shaded a level of gray with white being the lightest and black the darkest. We will denote the level of gray using real numbers between zero and one with larger numbers representing darker gray values. Each pixel is unit wide and is centered at the integer lattice points. It is convenient to let the set of integers be denoted by \(\mathbb{Z}\). Furthermore we will denote the \(xy\) plane of pixels by \(\mathbb{Z} \times \mathbb{Z}\).

Here \([a, b)\) denotes the set of points \(x\) where \(a \leq x < b\) and \([c, d)\) denote the points in the rectangle \(c \leq y < d\). For us \([i \cdot \frac{1}{2}, i \cdot \frac{1}{2}] \times [j \cdot \frac{1}{2}, j \cdot \frac{1}{2})\) is a square and shall be denoted by the symbol \((i, j)\). Here only the center is of importance since we agreed that pixels are squares of 1 unit length. In any case \(\mathbb{Z} \times \mathbb{Z} = \{(i, j) \in \mathbb{Z} \times \mathbb{Z} \mid i, j \in \mathbb{Z}\}\) Underlining means we are talking about squares "centered" at the lattice points. These squares have gray values we will now specify in symbols.

A pixel will be denoted by giving its location as described above followed by a slash / and then the gray level.

The gray level is denoted as \(u(i, j)\) with \(0 \leq u(i, j) \leq 1\) with numbers closer to 1 representing darker gray values.

If \(U(i, j) = 0\) the pixel is white.

An image \(f\) is a set consisting of all pixels centered at all the integers. So:

\[
f = \{(x, y)/u_f(x, y), x, y \text{ integers}\}
\]

The gray level of a pixel in image \(f\) is denoted by \(u_f(x, y)\) and if \(u_f(x, y) = 0\) we will leave out this pixel. If in a discussion there are \(2^N\) levels of gray we might encode their levels as:

\[
U_f(x, y) = \frac{k}{2^N}, \quad k = 0, 1, 2, ..., 2^{N-1}, \quad N \geq 0
\]

Let us illustrate the above.

Example

Given the Image \(f\) of a square consisting of eight pixels on a white background and say there are 4 levels of gray: 0 - white

\[
\begin{align*}
1/4 & \text{ - light gray} \\
1/2 & \text{ - gray dark} \\
3/4 & \text{ - black}
\end{align*}
\]
So using the set convention previously explained we have:

\[ f = \{(3,4)/3/4, (4,4)/1/2, (5,4)/1/2, (3,3)/1/2, (5,3)/1/2, (3,2)/3/4, (4,2)/3/4, (5,2)/3/4\} \]

It should be mentioned that any element with a membership value of zero is always left out when using the set notation, furthermore a pixel of white level is never labeled 0. Also, the labeling of the pixels arrives from the labeling of the lattice points located smack in the center of that pixel. Negative location of pixels are allowed, but shall rarely be employed.

An image \( f \) could also be considered to be a function from \( \mathbb{Z} \times \mathbb{Z} \) into \([0,1]\). Using standard mathematical notation an image is an element of \( [0,1]^{\mathbb{Z} \times \mathbb{Z}} \), where the latter symbol is the set of all functions from \( \mathbb{Z} \times \mathbb{Z} \) into \([0,1]\). An image could also be viewed as a Fuzzy Set. Specifically an image consists of pixels and each pixel is a square of a certain value of gray. If we view the level of gray as a membership value for the specific square the set of all such pixels is a fuzzy set. The darker the gray the more the square belongs to the image. This interpretation is useful in certain applications. We shall now discuss translation of an image.

**Translation Operators**

The Translation Operator \( T \) is a point operator, that is it operates or modifies a fixed input pixel and determines the resulting output picture elements based only on this corresponding input pixel not on neighboring or other pixels. This operator \( T \) just moves the object a fixed integer \( i = \ldots, -2, -1, 0, 1, 2, \ldots \) units to the right and \( j = \ldots, -2, -1, 0, 1, 2, \ldots \) units up while leaving the levels of gray unchanged. An equivalent (alibi - alias) explanation is that the image doesn't change, but the labeling of the \( x \) and \( y \) pixel location is modified. The new \( x \) axis becomes \( x-i \) for fixed \( i \) above and the new \( y \) axis is \( y-j \). In any case we have

\[
T_{ij} \left( \{ (x,y) / u_f(x,y) \} \right) = \{ (x+i, y+j) / u_f(x,y) \}
\]

we could denote the output of this operator \( T_{ij} \) when applied to image \( f \) as \( f_{ij} \) so

\[
T_{ij} (f) = f_{ij} = \{ (x+i, y+j) / u_f(x,y) \}
\]
For instance:

**Example**

Say $f$ is given in figure below

$$f = \{(2,4) / 3/4, (2,3) / 1/4, (2,2) / 1/2, (3,2) / 1/2\}$$

Then $T_{31}$ when applied to $f$ above would give $f_{31} = \{(5,5) / 3/4, (5,4) / 1/4, (5,3) / 1/2, (6,3) / 1/2\}$

This is illustrated in Figure below:

![Figure 5](image.png)

**FIGURE 5**

We will end this section with a brief mathematical treatise. Based on the discussion in the introduction we can view an image as a fuzzy subset of $\mathbb{Z} \times \mathbb{Z}$.

As an instance of this refer to example below.

**Example**

For $f$ as in previous example we have:

![Figure 7](image.png)

**FIGURE 7**

clearly illustrating the fact that an image is also a function with domain $\mathbb{Z} \times \mathbb{Z}$ and range $[0,1]$.
A translation operator \( T_{ij} \) as previously discussed is a mapping taking a fuzzy subset of \( \mathbb{Z} \times \mathbb{Z} \) and outputting another fuzzy subset of \( \mathbb{Z} \times \mathbb{Z} \). So

\[
T_{ij} : \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}} \rightarrow \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}}
\]

such that for any \( f \) in \( \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}} \)

\[
f = \left\{ \left( x,y \right) \mid u_f(x,y) \right\}, \quad T_{ij}(f) = f_{ij} \quad \text{where} \quad f_{ij} = \left\{ \left( x+i, y+j \right) \mid u_f(x,y) \right\} \quad \text{.}
\]

The identity operator \( i = 0 \) and \( j = 0 \)—that is \( T_{00} \) leaves \( f \) unchanged \( T_{00}(f) = f_{00} = f \).

In order to use the Translation Operator \( T \) we must specify three things and they are two integers one for \( x \) displacement one for \( y \) translation and an image, from this point of view then \( T \) is a trinary function, that is

\[
T : \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}} \times \mathbb{Z} \times \mathbb{Z} \rightarrow \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}}
\]

Erosion Operator

The Erosion Operator \( E \) also maps a fuzzy subset of \( \mathbb{Z} \times \mathbb{Z} \) into another fuzzy subset of \( \mathbb{Z} \times \mathbb{Z} \).

It makes heavy use of the translation operations previously discussed, and actually involves two images \( f \) and \( h \). The first image is \( f \) and we wish to erode it by the second \( h \) (usually a "simpler" image made up of a small number of structural elements). We could therefore write

\[
E : \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}} \times \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}} \rightarrow \left[ 0,1 \right]^{\mathbb{Z} \times \mathbb{Z}}
\]

This of course doesn't give us any hint as to how \( E \) operates. Intuitively \( E \) will give us that part of \( f \) (possibly lightened) which contains any translate of \( h \).

Rigorously we have:

\[
E(f,h) = f \quad \ast \quad h
\]

where

\[
f \quad \ast \quad h = \bigcup_{i,j \in K} h_{ij}
\]

where

\[
h_{ij} \quad \text{are translates (as explained in the last section) of the given } h
\]

\[
K \quad \text{is a subset of the Cartesian Product of Integers (viz } \mathbb{Z} \times \mathbb{Z} \text{ in the usual sense) } K = \{(i,j)\} \text{ such that } h_{ij} \text{ is a fuzzy subset of } f \text{ (} h_{ij} \subset f \text{ in the fuzzy sense)}
\]

\[
U \quad \text{is the fuzzy union operator.}
\]

To find \( f \ast h \) is really simple all we do is find only those translates of \( h \) which are a subset (in the fuzzy sense) of \( f \) and then we (fuzzy) union them together. Let us first review the fuzzy subset and union operations.

We say \( h \subset f \) means for any \( (x,y) \in h \) it must be true that \( (x,y) \in f \) in \( f \) is such that \( u_f(x,y) \leq u_h(x,y) \).

That is \( h \subset f \) means everything in \( h \) is in \( f \) to the same or greater degree (darker shade of gray!).

We say that \( g = f \cup h \) means that \( g \) consists of all \( (x,y) \max \{ u_f(x,y), u_h(x,y) \} \) i.e. everything in \( f \) alone and in \( h \) alone with the same membership and for those in both we use the larger memberships.

The extension to

\[
U h_{ij} \quad \text{is immediate we use the supremum of all memberships viz } U h_{ij} = \left\{ (x,y) \mid u(x,y), u(x,y) = \sup_{i,j \in K} u_{h_{ij}} \right\}
\]

We will now illustrate how to use this operator.
Consider the example below:

Example

Say there are 4 levels of gray as in example 1 and let image \( f \) be depicted in Figure 8 below:

|   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|
| 9 | \( \frac{3}{4} \) | \( \frac{3}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 8 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 7 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 6 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 5 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 4 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 3 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 2 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |
| 1 | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) | \( \frac{1}{4} \) |

Figure 8

and say \( h = \{ (1,1), (11,1) \} \)

We now have to find all the translates of \( h \) which are a subset in the fuzzy sense of \( f \) above. Let us note that \( h_{3,7} \) is one of them since

\[ h_{3,7} = \{ (4,8) / 3/4, \ (14,8) / 1/2 \} \]

and if we look at the \((4,8)\) pixel of \( f \) it has gray level \(3/4\) equal to that of \( h_{3,7} \) and the \((14,8)\) pixel in \( f \) has gray level \(3/4\) greater than that of \( h_{3,7} \).

We therefore find

\[ E(f,h) = f \theta h = h_{3,7} \cup h_{5,2} \cup h_{6,4} \]

and so we obtain:

\[ f \theta h = \{ (4,8) / 3/4, \ (14,8) / 1/2, \ (6,3) / 3/4, \ (16,3) / 1/2, \]

\[ \ (7,5) / 3/4, \ (17,5) / 1/2 \} \]

The Threshold Operator

The Threshold Operator \( L \) converts an image into a new image by changing into black the gray level of all pixels which have memberships greater than or equal to some predetermined threshold; all other pixels are mapped into white. If the threshold value is \( t \),

and if we assume that black has value \( 0 \) (this could always be arranged by normalizing) then for given \( f \)

\[ L(f,t) = g \]

where

\[ f = \{ (x,y) / U_f(x,y) \} \]

and

\[ g = \{ (x,y) / 1 \text{ for those pixels } \}

\[ (x,y) \text{ such that } U_f(x,y) \leq t \}

therefore we have

\[ L: [0,1]^{2 \times 2} \times [0,1] \rightarrow \{0,1\}^{2 \times 2} \]

We will illustrate the use of the threshold operator \( L \).

Consider the example:
Example

Refer to Figure below for this \( f \) if we assume the threshold value \( t = 1/2 \) and recall here black is denoted by \( 3/4 \) we obtain Figure below when using \( L(f,t) = g \).

![Figure 9](image)

![Figure 10](image)

The Threshold Operator always renders an image which consists of only black and white pixels therefore we could write

\[
L : \left[ 0, 1 \right] ^{ZxZ} \times \left[ 0, 1 \right] \rightarrow \{0, 1\} ^{ZxZ}
\]

Polyadic Graphs and The Imaging Algebra

Polyadic Graphs consists of a set of nodes, usually drawn as circles or ovals, and edges. The edges will have one or more sources (tails) and a single target (head), each leaving from or arriving at respectively some node. The ovals indicate the "sort" of entities employed and the many tailed arrows indicate operators or functions. The head of the arrow indicates the sort of output or sort of values given by the designated operator and the many tails indicates the sort of entities needed as input to the operation. That is each of the many tails specifies exactly what sort of entity is needed before you can use the specified operator. Let us illustrate the above before we continue.

Example:
The Translation Operator can be viewed as taking three things and returning one. That is it takes an image, and two integer values, one for the movement in the position $x$ direction and one for the positive $y$ direction and returns a single image moved by this amount. This is illustrated above.

The Erosion Operator is a Binary Operator that is it works on two image inputs and yields an image out. The Translation Operator is Trinary. The Threshold Operator outputed an image only when two sort of things were presented to this operator; namely an image and a number in the unit interval called the thresholding value. The thresholding value in practice is found by using statistical techniques and will not be discussed here.

The graph in the above Figure M conveys information but does not completely specify how the operator obtains its value based on specific inputs, for this we must resort to the definitions of the operators. We should also point out that Binary Image means an image "made up of black and white." White is always for us, encoded as 0.

We will explain in what sense Image Processing could be considered to be an algebra. Hopefully this section might seem to naturally follow since most Operators and procedures described have been given in a mathematically precise and rigorous way; thereby minimizes misunderstanding and assuring identical outputs for a given procedure when using the same inputs. The mathematical treatment of imaging given throughout and highlighted in this section should also act in a unifying sense resulting in a global theory of imaging.

In short and intuitively a Many Sorted Algebra consists of different "sorts" of sets and operators which map elements from some of these sets into others.

A Many Sorted Algebra - $(S, \Sigma, \Phi, \Gamma, \gamma, S, \Delta)$ is a seven tuple that is it consists of seven ingredients. The first ingredient is: $S$ - a set of Sorts - This set for us always finite and nonempty will contain the sort of things we are dealing with, of course images for us must be one of them. Before we describe the next ingredient in a Many Sorted Algebra let us point out that: $S^*$ is the set of finite strings of elements from $S$. An element of $S^*$ consists of the concatenation (or sequence, without commas) of possibly repeated elements from $S$ as well as the empty string $\epsilon$. The Threshold Operator could be considered to consist of all functions in $S^*$ where $Z_+ \equiv S_1, S_2, \ldots, S_n$ for all $n$ non negative integer with $\epsilon$ arising from $S^* = S^\epsilon$. The second ingredient is $\alpha$, where $\alpha: S^* \times S \rightarrow Z$. For anything in $S^* \times S$ namely a two tuple say $((s_1, s_2, s_3, s_4), s_5) \in \gamma$.

This set consists of all function names and operator names which have domains indicated by the string of sorts $s_1, s_2, \ldots, s_n$ and range of the sort $S$. This set is often called a signature consequently we have the third ingredient: $\Sigma$ as is a family of signature sets: that is the sets $\Sigma_{s_1, \ldots, s_n, \epsilon}$ and $\Sigma_{\epsilon}$ are all elements of $\Sigma$.

The fourth ingredient: $\Phi$ is such that $\Phi: S \rightarrow \Sigma$. We have $\Phi(S) \equiv A_S$ and $A_S$ is itself a set; it is called the Carriet Set. Consequently we also have the fifth ingredient: $\Phi$ which is a family of Carrier Sets: that is the element of $\Phi$ are themselves sets, they are $A_S$ for each $s$ in $S$.

The sixth ingredient is $\gamma$ such that $\gamma: \bigcup \Sigma_{s_1, \ldots, s_n, \epsilon} \rightarrow A_S$, that is $\gamma$ maps the Union of all signatures sets into $S$, for any element in the union we have: $\gamma(c) : \gamma$, where if $c$ is in $\Sigma_{s_1, \ldots, s_n, \epsilon}$ then $\gamma_A: A_{s_1} \times A_{s_2} \times \ldots A_{s_n} \rightarrow A_S$ that is $\gamma$ is the name of the function and $\gamma_A$ is the n'ary function itself.

In otherwords a zero ary function is a "special element" in the carrier set of the sort $s$. So the last (seventh) ingredient is: $G$ the set of all 0'ary 1'ary, binary Trinary etc. Operators in the algebra. Let us now partially specify the Imaging Algebra based on the previous sections.

Doing this we obtained among the elements in $\Sigma$ are:

a) IMAGES
b) INTEGERS
c) UNIT INTERVAL
d) Binary Images

table content

There are other elements in $\Sigma$; however for simplicity we will illustrate the Many Sorted Imaging Algebra with just these.
Also will use the letter a to represent IMAGES, b to represent INTEGERS etc.

Now $\sum_{\mathbf{S}}^\mathbf{A}$ consists of the empty string $\varepsilon$ along with such thing as strings of length one: a, b, c, d, and strings of length two such as aa, ab, cd, etc. - strings of length three abd, aaa, etc... and so the function $\alpha$ after mapping $\sum_{\mathbf{S}}^\mathbf{S}$ into $\sum$ gives signature sets such as $\sum_{a,b}^\mathbf{A}$, $\sum_{c}^\mathbf{A}$, and $\sum_{a,b,c}^\mathbf{A}$. for instance

$\sum_{a,b,c}^\mathbf{A} = \sum_{a,b,c}^\mathbf{A}$. The Important thing is to find out what is in these signature sets. Erosion is an element of $\sum_{a,b,c}^\mathbf{A}$. It is the name of an operator which when used maps two images into a single image. Threshold is an element of $\sum_{a,b,c}^\mathbf{A}$ it too is the name of a binary operator. The name Translation belongs to $\sum_{a,b,c}^\mathbf{A}$ it yields a trinary operator. All this was depicted in figure 11 employing Polyadic Graphs.

It is a fact that these signature sets consist of many more operator names then we have identified here.

Now the function $\beta$ which maps $\mathbf{S}$ into $\mathbf{E}$ shall be discussed slightly. Since we have only so far mentioned four sorts of things we only have four carrier sets and they are:

- $\mathbf{A}$ Images $= \left\lfloor \mathbf{C}, \mathbf{I} \right\rfloor^{2*2}$
- $\mathbf{A}$ Integers $= \left\{ \ldots , -1, 0, 1, 2 \ldots \right\}$
- $\mathbf{A}$ Unit Interval $= \left[ \mathbf{C}, \mathbf{I} \right]\left[ \mathbf{C}, \mathbf{I} \right]$
- $\mathbf{A}$ Binary Image $= \left\lfloor \mathbf{C}, \mathbf{I} \right\rfloor^{2*2}$

(In the last carrier set we assumed that black is denoted by 1 as previously mentioned)

Finally $\gamma$ maps the name of the operators into actual operators which perform the said operation. For instance and referring to the actual section where the operators were defined we have for instance $\gamma$(Erosion) = $\varepsilon$ and

$\sum \gamma : \left[ \mathbf{C}, \mathbf{I} \right]^{2*2} \times \left[ \mathbf{C}, \mathbf{I} \right]^{2*2} \rightarrow \left[ \mathbf{C}, \mathbf{I} \right]^{2*2}$

Here $\gamma$ = Erosion the name and $\gamma_a = \varepsilon$ the function.

Similarly $\gamma$(Threshold) = L and

$\sum \gamma : \left[ \mathbf{C}, \mathbf{I} \right]^{2*2} \times \left[ \mathbf{C}, \mathbf{I} \right]^{2*2} \rightarrow \left\{ \mathbf{C}, \mathbf{I} \right\}^{2*2}$

The actual manner in which the respective operators convert inputs into outputs can never be found from the Image Algebra alone. In this sense the Algebra only discloses only syntactical characteristics of the operators and not symmetrical. We are now finished with our first look at the Imaging Algebra. Fourier techniques including Walsh and Haar Feature Descriptors have also been included in the Algebra, Moment Methods as well as syntactical pattern grammars were also formulated as Many Sorted Algebras. Due to the large number of Operators in the Imaging Algebra a complete description as to its variety is a difficult task. That is, when does the Commutative, Associative, Distributive laws etc. hold? For some of the more important operators these questions have been answered and a systematic investigation has been started to describe the variety.
Conclusion

Determination of IQ has been proposed for PGMs. The IQ should be found by testing as in humans. One of the main ingredients in rendering high intelligence is the sophistication of the Imaging software; in this vain the Imaging Algebra was defined.

Picture Elements or Pixels were introduced as half closed, half open unit squares and a (digital) image as a function from the set of all these pixels centered at the integer lattice points into \([0,1]\). Here gray levels are denoted as fractions between zero and one. As a consequence images can be viewed as fuzzy subsets. The translation operator was then given and illustrated followed by Erosion Operators. The latter operator is defined for images using any gray level and makes heavy use of fuzzy set theory. This was followed by the introduction to the Threshold Operator usually employed in converting an image into a binary image.

Besides the precise rigorous treatment natural to the Many Sorted Algebra the use of Homomorphisms and Isomorphisms makes this approach to Imaging universal in nature and self contained.

Reference
1. L. A. Zadeh, "Fuzzy Sets" - Information & Control (1965)
DEVELOPMENT OF LOW COST MULTIFUNCTION SENSORS
FOR LIGHTWEIGHT FIRE AND FORGET ANTITANK WEAPON SYSTEM
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SUMMARY
This paper covers the design description, operation, and preliminary evaluation of a multifunction sensing device that is capable of measuring two axes of angular rate and two axes of linear acceleration from a single instrument. The equations for obtaining three axes of angular rate and three axes of linear acceleration from a single instrument are also developed. Test data is presented that illustrates state-of-the-art performance on available multifunction sensors. Finally, methods of improving the performance of multifunction sensors are discussed.

SYMBOLS

\( xyz \) case fixed coordinate frame

\( \hat{r}_1 \) position vector of the center of gyration of the sensing element

\( \hat{a}_1 \) acceleration vector of the center of gyration of the sensing element

\( \hat{v}_1 \) velocity vector of the center of gyration of the sensing element

\( XYZ \) inertial frame

\( \hat{\omega} \) angular velocity vector of case

\( n \) rotor speed with respect to inertial space

\( n' \) rotor speed with respect to case

\( P \) center of gyration of any one sensing element

\( \hat{R} \) position vector of point \( P \) in the inertial frame

\( \hat{R}_0 \) position vector of the origin of the case frame

\( l \) length of pendulum

During the past few years, the Army has expended a considerable amount of resources for the development of inertial grade gyros and accelerometers. Past efforts, for the most part, have been aimed at developing gyros with bias stabilities of \( 1^\circ/\text{hour}(0.0003^\circ/\text{sec}) \), or better and accelerometers with long term bias stabilities of better than 100 micro-g's. A cluster of three single degree of freedom gyros and three single axis accelerometers are, typically, mounted in a strapdown, gimbaled or hybrid (strapdown and gimbaled) configuration and used to provide the guidance for medium to long range missiles.

The multifunction sensor operates on the principle of measuring Coriolis acceleration exerted on a rotating body in the presence of rotation of the spin axis in space. Figure 1 shows a typical piezoelectric ceramic "bender" beam acceleration transducer used in the design of a multifunction sensor. In Figure 2, the combination angular rate and linear acceleration sensor functional diagram is depicted. Angular rate measurements are made by utilizing two piezoelectric bender beams mounted on the rotor and oriented to sense strain about axes in a plane orthogonal to the rotor spin axis. The output signals from the two transducers are summed to provide common mode rejection. A second set of piezoelectric bender beams are mounted on the rotor and oriented to sense strain along the axes in a plane orthogonal to the rotor spin axis. Two axes of acceleration can be measured in this plane by interrogating this output signal at the proper time using a clock frequency. Angular rate and linear acceleration signals may be extracted from the rotating member via slip ring contacts or inductive pickoffs. These AC signals are amplified and demodulated to provide voltages which are proportional to angular rate and linear acceleration.

A multifunction sensor will readily provide two axes of angular rate information and two axes of linear acceleration information. A multifunction sensor can, however, be mechanized to provide three axes of angular rate and three axes of linear acceleration.
from a single sensor.

A limited amount of testing was performed on a prototype multifunction sensor. An assembled view is shown in Figure 3. This multisensor was designed to meet the performance requirements for autopilot stabilization. Tests conducted included scale factor, linearity, alignment, g-sensitivity, bias and bias repeatability for both the rate and acceleration functions. A limited amount of rate temperature testing was also conducted.

Laboratory tests conducted by the Army G&C Directorate produced results which very closely matched the results obtained by the manufacturer. Due to the limited time that the multisensor hardware was available, long duration tests were conducted about only one sensitive axis. The results of the rate test about sensitive axis "B" are shown in Figures 4 through 6 for three different rotation rates. An examination of these drift characteristics indicates that the peak-to-peak drift over a fifteen minute time period is less than 25°/hour (0.007°/sec) for each of the three rotation rates. The long term peak-to-peak drift rate with earth rate input about the "B" sensitive axis is in the neighborhood of 15°/hour (0.004°/sec) (see Figure 7). Long term drift tests were conducted over a two hour time period.

Residuals corresponding to the least squares curve fit on the rate linearity tests were bounded within ± 0.05 degree/second. This information is shown graphically in Figure 8.

Time did not permit determination of accelerometer bias stability; however, absolute bias tests were conducted. The absolute bias recorded on accelerometer axis A was -1.138 milli-g while the bias on the B-axis was determined to be -0.69 milli-g.

The multifunction sensor evaluated by the G&C Directorate provided two axes of rate and two axes of acceleration and is packaged in a cylindrical envelope with dimensions to 12 centimeters diameter and 5 centimeters length. The projected per unit cost is less than $1000 in production quantities. Two multifunction sensors would be required for a complete three axis strapdown system.

The Army is investigating the use of an air bearing suspension system to carry the multifunction sensor rotating member and thin film transistor acceleration transducers to replace conventional piezoelectric bender beams. Utilization of an air bearing support will virtually eliminate the twice spin frequency bearing noise found in conventional ball bearing devices and improve overall performance significantly.

Two additional multifunction sensors (Figure 9) have recently been procured by the Army. These sensors are a slightly miniaturized version of the prototype unit previously evaluated. Rate gyro day-to-day bias stability, accelerometer bias repeatability and rate gyro g-sensitive drift rate repeatability tests have been conducted on these two units (see Figures 10 through 15).

Multifunction sensors provide a distinct cost and logistical advantage over single sensing instruments in that spare parts are required for only one type of instrument. Reliability is enhanced by concentrating on the design of a single instrument and in the reduction of pieceparts. The size and weight of guidance systems will be reduced because of a reduction in parts count. The development of such a system will significantly reduce the life cycle cost by reducing instruments required for a three axis system from a maximum of six (three gyros and three accelerometers) to one (by judiciously extracting signals) and will provide the logistical advantage of requiring spare parts for only one type of instrument.

The remaining portion of this paper will be devoted to developing the equations that govern the operation of the multifunction sensor and the mechanization of a concept that will provide three axes of angular rate and three axes of linear acceleration from a single sensor.

In the following paragraphs the geometry of a multifunction sensor is presented. Then, an analysis is made for this sensor. The analysis serves a two-fold purpose, namely, to verify the existence of three angular rate and three acceleration signals in the outputs of the sensor, and to provide a set of analytic relationships which can be used to extract the rate and acceleration information from the outputs of the sensor.

An ideal multifunction sensor would have the following characteristics:

1. Orthogonal sensing, that is, no cross-coupling among the orthogonal axes.
2. High transducer gain and wide transducer bandwidth.
3. High signal-to-noise ratio.
4. Negligible mechanical dynamics exhibited by the sensor.

Figure 16 depicts the geometry of a multifunction sensor. The sensor has four sensing elements attached to a rotating shaft. On each sensing element are two bending sensitive solid state transducers, one on each side of the element. Bending results when a sensing element experiences an acceleration in a direction normal to its plane. A case fixed coordinate frame, xyz, is defined where the z-axis is colinear with the axis of the rotating shaft. Figure 17 defines several geometrical quantities to be used in the ensuing analysis.
Referring to Figure 16, sensing elements 1 and 3 sense body rates about the x and y axes and the body acceleration along the z axis. On the other hand, sensing elements 2 and 4 sense accelerations along the x and y axes and the body rate about the z axis.

Let \( \mathbf{\hat{n}} \) denote the position vector of the center of gyration of the sensing element number 1, while \( \mathbf{\hat{a}_1} \) and \( \mathbf{\hat{v}_1} \) denote the corresponding acceleration and velocity vectors. The rotor is rotating at a constant angular speed \( \mathbf{n} \) with respect to the inertial space; its speed with respect to the case is \( \mathbf{n}' \).

Refer to Figure 18 where point \( P \) represents the center of gyration of any one sensing element. In the Figure, \( XYZ \) is an inertial frame and \( xyz \) is a frame fixed to the sensor case. \( \mathbf{\hat{\omega}} \) is the angular velocity vector of the case. \( \mathbf{\hat{r}} \) is the position vector of point \( P \) with respect to the case frame, \( \mathbf{\hat{R}} \) is the position vector of point \( P \) in the inertial frame, and \( \mathbf{\hat{R}_0} \) is the position vector of the origin of the case frame. The acceleration of point \( P \) is given by

\[
\mathbf{\hat{a}} = \frac{d^2\mathbf{\hat{r}}}{dt^2} + \mathbf{\hat{a}_{rel}} + 2\mathbf{\hat{\omega}} \times \mathbf{\hat{v}_{rel}} + \mathbf{\hat{r}} \times \mathbf{\hat{\omega}} + \mathbf{\hat{\omega}} \times (\mathbf{\hat{r}} \times \mathbf{\hat{\omega}}) \tag{1}
\]

where \( \mathbf{\hat{a}_{rel}} \) and \( \mathbf{\hat{v}_{rel}} \) are relative to the case frame. In the following, the vector analysis notation and the matrix notation will be interchangeably used for writing convenience. The equivalence of the two is indicated by "\( \leftrightarrow \)."

Consider the acceleration \( \mathbf{\hat{a}_i} \) of the center of gyration of the sensing element number \( i \). The corresponding terms of Eq. (1) are obtained with the help of Figure 17 as follows:

\[
\frac{d^2\mathbf{\hat{R}_0}}{dt^2} \leftrightarrow \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}, \text{ the same for all } i. \tag{2}
\]

\[
(\mathbf{\hat{a}_1}_{rel}) \leftrightarrow \begin{bmatrix} -n^2l_1 \cos \left( \frac{n't-j\pi}{2} \right) \\ -n^2l_1 \sin \left( \frac{n't-j\pi}{2} \right) \\ 0 \end{bmatrix} \tag{3}
\]

\[
2\mathbf{\hat{\omega}} \times (\mathbf{\hat{v}_1})_{rel} \leftrightarrow 2 \begin{bmatrix} 0 & -u_x & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix} \begin{bmatrix} -n^2l_1 \sin \left( \frac{n't-j\pi}{2} \right) \\ n^2l_1 \cos \left( \frac{n't-j\pi}{2} \right) \\ 0 \end{bmatrix} \tag{5}
\]

\[
\mathbf{\hat{a}} \leftrightarrow \begin{bmatrix} 0 & -\hat{w}_x & \hat{w}_y \\ \hat{w}_z & 0 & -\hat{w}_x \\ -\hat{w}_y & \hat{w}_x & 0 \end{bmatrix} \begin{bmatrix} 1 & \cos \left( \frac{n't-j\pi}{2} \right) \\ 0 & \sin \left( \frac{n't-j\pi}{2} \right) \\ 0 & 0 \end{bmatrix} \tag{6}
\]

\[
\mathbf{\hat{a}} \leftrightarrow \begin{bmatrix} 0 & -\hat{w}_x & \hat{w}_y \\ \hat{w}_z & 0 & -\hat{w}_x \\ -\hat{w}_y & \hat{w}_x & 0 \end{bmatrix} \begin{bmatrix} 1 & \cos \left( \frac{n't-j\pi}{2} \right) \\ 0 & \sin \left( \frac{n't-j\pi}{2} \right) \\ 0 & 0 \end{bmatrix} \tag{7}
\]

where \( i=1 \) to 4 and \( j=i-1 \). Substituting Equations (2) through (7) into (1), the acceleration \( \mathbf{\hat{a}_i} \) of the center of gyration of the \( i \)th sensing element is
Next, consider individual sensing elements which are intended to be sensitive to accelerations in directions normal to respective planes of sensing elements. Elements 1 and 3 are intended to be sensitive to acceleration parallel to the z-axis. Therefore, the measured accelerations are

\[
a_{1m} = a_z + 2 \omega_y n_1 \sin n't + 2 \omega_x n_1 \cos n't
\]

\[
- \dot{\omega}_y n_1 \cos n't + \dot{\omega}_x n_1 \sin n't
\]

\[
+ \omega_x \omega_z n_1 \cos n't + \omega_y \omega_z n_1 \sin n't
\]

\[
a_{3m} = a_z - 2 \omega_y n_3 \sin n't = 2 \omega_x n_3 \cos n't
\]

\[
+ \dot{\omega}_y n_3 \cos n't - \dot{\omega}_x n_3 \sin n't
\]

\[
- \omega_x \omega_z n_3 \cos n't - \omega_y \omega_z n_3 \sin n't
\]

Since

\[
l_1 = l_3 = c \text{ by (4)},
\]

\[
a_{1m} + a_{2m} = 2 a_z
\]

giving the z-acceleration as

\[
a_z = \frac{1}{2} (a_{1m} + a_{2m})
\]

Also

\[
(a_{3m} - a_{1m}) \cos n't = a_{d1} (1 + \cos 2n't)
\]

where

\[
a_{d1} = (\dot{\omega}_y - \omega_x \omega_z - 2 \omega_x n) c = -2 nc \omega_x
\]

on account of the fact that \(n > |\omega|\). Similarly

\[
(a_{3m} - a_{1m}) \sin n't = a_{d2} (1 - \cos 2n't)
\]

where

\[
a_{d2} = (\dot{\omega}_x - \omega_y \omega_z - 2 \omega_y n) c = 2 nc \omega_y
\]
Note that \( a_{d1} \) and \( a_{d2} \) are the low frequency components of (12) and (13) respectively. By extracting these low frequency components, the body rates \( w_x \) and \( w_y \) can be obtained.

\[
\begin{align*}
\dot{w}_x &= -\frac{1}{2nc} a_{d1} \\
\dot{w}_y &= -\frac{1}{2nc} a_{d2}
\end{align*}
\]  

(14)  
(15)

Sensing elements 2 and 4 are intended to be sensitive to accelerations parallel to the \( xy \)-plane and normal to the sensor plane. In fact, any one of the two elements will provide the acceleration information needed. Use of both elements is for redundancy and for construction convenience. The sensed acceleration by the sensing element number 2 can be shown to be

\[
a_{2m} = a_x \cos \theta \sin \theta + a_y \sin \theta \cos \theta \sin \theta d
\]

(16)

By using phase sensitive demodulation techniques on \( a_{2m} \), one can get

\[
\begin{align*}
[a_{2m}]_{dc} &= \dot{w}_z d \\
[a_{2m} \cos \theta]_{dc} &= \frac{a_x}{2} \\
[a_{2m} \sin \theta]_{dc} &= \frac{a_y}{2}
\end{align*}
\]

(17)  
(18)  
(19)

where \([ \ ]\) means that the d-c part of the contents are inside the brackets. Therefore, the body rate \( w_z \) is given by

\[
\dot{w}_z = \frac{1}{d} \int [a_{2m}]_{dc} dt
\]

(20)

and accelerations \( a_x \) and \( a_y \) are given by

\[
\begin{align*}
a_x &= 2[a_{2m} \cos \theta]_{dc} \\
a_y &= 2[a_{2m} \sin \theta]_{dc}
\end{align*}
\]

(21)  
(22)

Equations (11), (14), (15), (20), (21), and (22) show that, in theory, the multifunction sensor considered can indeed provide information for three angular rates and three accelerations. The performance of such a sensor depends on the effectiveness of the attendant electronics and/or software for extracting the rate and acceleration information. Noise will be the limiting factor for the device.
FIGURE 1. TYPICAL FUNCTIONAL CONFIGURATION OF PIEZOELECTRIC CERAMIC "BENDER" ACCELEROMETER

FIGURE 2. COMBINATION ANGULAR RATE AND LINEAR ACCELERATION SENSOR, FUNCTIONAL DIAGRAM
FIG. 4. FIFTEEN MINUTE RATE TEST AT 80 DEG/SEC

FIG. 5. FIFTEEN MINUTE RATE TEST AT 120 DEG/SEC
FIG. 6. FIFTEEN MINUTE RATE TEST AT 180 DEG/SEC

FIG. 7. LONG TERM DRIFT TEST AT EARTH'S RATE
ENG #4 RATE LINEARITY
DATE OF TEST: 28 AUG 81

FIG. 8 LINEARITY ERROR VS. INPUT RATE
FIG. 9. MULTIFUNCTION SENSOR (DISASSEMBLED VIEW)
NOTE: TESTS WERE CONDUCTED OVER A ONE WEEK TIME PERIOD. MULTISENSOR WAS TURNED OFF BETWEEN TESTS.

FIG. 10. RATE GYRO DAY-TO-DAY BIAS STABILITY (S/N 2)

FIG. 11. RATE GYRO DAY-TO-DAY BIAS STABILITY (S/N 4)
NOTE: TESTS WERE CONDUCTED OVER A ONE MONTH TIME PERIOD. MULTISENSOR WAS TURNED OFF BETWEEN TESTS

FIG 12. ACCELEROMETER BIAS REPEATABILITY (S/N4)

FIG 13. ACCELEROMETER BIAS REPEATABILITY (S/N2)
NOTE: TESTS WERE CONDUCTED OVER A ONE MONTH TIME PERIOD. MULTISENSOR WAS TURNED OFF BETWEEN TESTS.

**FIG 14. RATE GYRO-SENSITIVE DRIFT RATE REPEATABILITY (S/N 4)**

**FIG 15. RATE GYRO G-SENSITIVE DRIFT RATE REPEATABILITY (S/N 2)**
Fig. 16. A rotor configuration for the multifunction sensor.
FIG. 17. THREE VIEWS OF THE ROTOR OF A MULTIFUNCTION SENSOR
XYZ = INERTIAL FRAME
xyz = BODY FRAME
$\vec{\omega}$ = ROTATION OF xyz WRT XYZ

FIG 18. REFERENCE FRAME
A GUIDANCE LAW FOR GENERAL SURFACE TARGETS

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SUMMARY

A guidance law is proposed for low-cost tactical missiles. Analysis of this law is carried out for fast-moving surface targets and stationary targets in the presence of gravity. The law is simple to implement using the velocity-vane pursuit-guidance seeker and for the above targets is as accurate as proportional navigation.

INTRODUCTION

The proportional-navigation guidance law is used for most tactical missile applications involving high-speed maneuvering air targets. But against stationary surface targets it is usually better to employ pursuit guidance. There are two reasons for this. First, implementation of pursuit guidance, using the velocity-vane or weathercock stabilized seeker, is very simple. Second, in the presence of gravity, pursuit guidance yields a stiffer or more rectilinear flight path to the target. During stretchout maneuvers, the likelihood that the missile will hit the ground before hitting the target is therefore reduced.

Against moving surface targets pursuit guidance is unsatisfactory and proportional navigation is generally used. However, since this guidance law was developed for high-speed maneuvering air targets, it is not entirely satisfactory for slow-moving surface targets mainly because the implementation of proportional navigation is relatively complex, particularly when gravity compensation is necessary.

There is thus a need for a new guidance law for moving surface targets. This guidance law should be more accurate than pursuit and easier to implement than proportional navigation. Previous modifications to pursuit or new schemes such as proportional lead guidance do not meet these requirements. In contrast, the guidance law presented here, while it retains much of pursuit's simplicity, gives excellent performance against all surface targets. In terms of missile control deflection the law may be expressed as

$$\delta = k_p (\epsilon + \mu \gamma)$$  \hspace{1cm} (1)

where, as shown in Figure 1, $\epsilon$ is the pursuit error, $k_p$ and $\mu$ are constants, and $\gamma$ is the flight heading. Implementation using modified Paveway pursuit guidance seekers is thus particularly simple. As shown in Figure 2, basic pursuit guidance is employed following target acquisition until the error angle $\epsilon$ is about 1 degree; the canards are then nulled and the missile weathercocks rapidly into coincidence with the velocity vector. At this time a two-degree-of-freedom reference gyro is uncaged, which defines the subsequent flight leading $\gamma$ of the missile. Our main purpose in this report is to describe the theoretical performance of the modified pursuit-guidance law assuming ideal, noise-free conditions.
Figure 1. The Guidance Law

\[ \delta = k_p (\epsilon + \mu \gamma) \]

Figure 2. Implementation
PROPORTIONAL NAVIGATION AND PURSUIT GUIDANCE

Figure 3 shows a common implementation scheme for proportional-navigation guidance. The precessional motion of the spin-stabilized optical assembly is \( \dot{\theta}_g = T/H \), where \( H \) is spin momentum and \( T \) is gimbal motor torque. Making \( T \) proportional to \( \epsilon \) yields \( \dot{\theta}_g = k_g \epsilon = k_g (\dot{\theta}_t - \dot{\theta}_g) \), hence

\[
\dot{\theta}_g = \frac{\dot{\theta}_t}{1 + p/k_g}
\]  

(2)

where \( p \) denotes \( d/dt \). Thus, except for the time lag, \( k_g \epsilon \) provides a direct measure of sight-line turning rate. Employing

\[
k_p = \frac{\delta}{\epsilon} \quad \text{and} \quad k_a = \frac{\dot{\gamma}}{\delta}
\]

(3)

there follows

\[
\dot{\gamma} = \frac{\beta}{k_g} \dot{\theta}_t
\]

(4)

where

\[
\beta = k_p k_a
\]

(5)

This defines the proportional-navigation constant as \( N = \beta/k_g \).

The control law for pursuit guidance follows from Equation (1) with \( \mu = 0 \). This guidance law is easier to implement than proportional navigation, particularly when the simple velocity-vane or weathercock stabilized seeker is used to establish \( \epsilon \).

The effect of gravity on flight-path curvature for proportional navigation (\( \dot{\gamma} = 4\dot{\theta}_t \)) and pursuit (\( \dot{\gamma} = 4\epsilon \)) is shown in Figure 4. Comparison of \( y \) and \( h \) for the proportional-navigation missile indicates contact with the ground several thousand feet short of the target.* Indeed, with \( T \) now denoting total time of flight, this will always occur when

\[
\frac{T_g}{(N-1)V \sin \theta} < 1
\]

(6)

* These calculations assume a 4-g lateral acceleration limit, well above the maximum proportional navigation g command \( N \cos \theta / N-2 \). With pursuit guidance the g command is equal to the inverse of time to go.
Figure 4. Trajectory Curvature Due to Gravity

Figure 5. Miss for Pursuit Guidance
Accordingly, the proportional-navigation missile is most likely to require gravity compensation in roles involving extended shallow dive attacks at subsonic or low-supersonic speeds. Of course, the device of increasing $N$ to reduce $y$ is not acceptable.

In contrast, the pursuit trajectory, also shown in Figure 4, exhibits much less gravity sag. In this case, contact with the ground occurred just 0.05 sec before anticipated target impact. Such results emphasize that in the absence of gravity compensation pursuit guidance may outperform proportional navigation.

But pursuit guidance is entirely unsatisfactory with target motion present. For example, the miss distance against targets with constant crossing velocity is

$$\text{Miss} = (1 + r\beta) \frac{V_t}{\beta} + \frac{V_t^2}{2a}$$

where $a$ is lateral acceleration limit and $r$ is either zero (velocity pursuit) or unity (body-fixed pursuit). With $a = 4g$, Equation (7) is shown in Figure 5.*

**THEORETICAL DEVELOPMENT**

This analysis treats targets with constant crossing velocity, constant crossing acceleration, and stationary targets in the presence of gravity. The crossing cases are considered because they generally demand maximum lateral acceleration capability. The analysis also assumes small deviations from constant-bearing geometry; this enables small-angle approximations to be used throughout. Then from Equation (1) and Figure 1

$$\delta = k_p \left[ \theta + (\mu-1) \gamma \right]$$

where $\theta = (y_t - y)/(T-t)\gamma$, $T$ denotes initial time to go, and $\gamma = \dot{y}/V$. Also, from Equation (3) with a correction for gravity, $\dot{\gamma} = k_a \delta - g/V$. Thus

$$\dot{\gamma} + (1-\mu)\beta \dot{\gamma} + \frac{\beta \gamma}{T-t} = \frac{\beta y_t}{T-t} - g$$

is the differential equation describing the guidance law. For surface targets engaged close in, it is sufficient to assume

$$y_t = V_t t + a_t \frac{t^2}{2}$$

Also it is more convenient to use the miss coordinate

$$m = y - y_t(T)$$

which from Equations (9) and (10) satisfies

$$\ddot{m} + (1-\mu)\beta \dot{m} + \frac{\beta m}{T-t} = -\beta V_t + \frac{a_t}{2} (T-t) - g$$

* The calculations in this report generally assume $T = 10$ or 15 sec, $\beta = 4/\text{sec}$, and $\theta = 5^\circ$. 
Introducing the new independent variable

\[ \xi = (1-\mu)\beta(T-t) \]  \hspace{1cm} (13)

Equation (12) becomes

\[ \ddot{m} - \dot{m} + \frac{1}{1-\mu} \frac{m}{\xi} = \frac{-\beta(V_t + a_t T) - g}{(1-\mu)^2 \beta^2} + \frac{a_T \xi}{2(1-\mu)^3 \beta^2} \]  \hspace{1cm} (14)

This has the solution

\[ m(\xi) = e^{\xi/2} \left[ aW_{\lambda\eta}(\xi) + bW_{-\lambda\eta}(-\xi) \right] \]  \hspace{1cm} (15)

where \( W_{\lambda\eta} \) is the Whittaker confluent hypergeometric function, with \( \eta = 1/2 \) and \( \lambda = (1-\mu)^{-1} \).

In keeping with the near-constant bearing trajectory, assume zero initial conditions. Then, using asymptotic properties of the Whittaker function for large \( \xi_o \), the miss is

\[ m(\xi_o) = -a\Gamma(\lambda) \sin(\pi\lambda) \]  \hspace{1cm} (16)

where \( \xi_o = (1-\mu)\beta T \) and \( a \) is a linear function of \( V_t, a_t \) and \( g \).

For a constant crossing velocity target

\[ a = \frac{\mu}{\mu(1-\mu)\beta \pi} \]  \hspace{1cm} (17)

and the miss, given by Equations (16) and (17), is shown in Figure 6a. It is vanishingly small at the first four zeros of \( \sin(\pi\lambda) \); that is, for \( \mu = 1/2, 2/3, 3/4, \) and \( 4/5 \). For \( \mu = 0 \) it reduces to \( V_t/\beta \), the miss of the pursuit missile with unlimited lateral-acceleration capability. The dashed curve in Figure 6a obtained by integrating Equation (14) numerically, shows the miss for the more practical case of a 4-g acceleration limit. Lateral acceleration obtained by differentiating Equation (15) is shown in Figure 6b.

For a target with constant crossing acceleration

\[ a = \frac{2\mu-1}{\mu-1} \frac{a_t(1-3/2\mu)\xi_o}{\mu(2\mu-1)(1-\mu)^2 \beta^2 \pi} \]  \hspace{1cm} (18)

and the miss for this case, shown in Figure 7, exhibits zeros at \( \mu = 2/3, 3/4, \) and \( 4/5 \). These are the same as before except that \( \mu = 1/2 \) must now be excluded due to the presence of \( (2\mu-1) \) in the denominator of Equation (18).
For the stationary target in the presence of gravity

\[
a = \frac{\mu}{g \xi_0 \mu^{-1}} \frac{1}{\mu(1-\mu)\beta^2 \tan \theta \pi}
\]

and the miss, which in this case is referred to the ground plane, is shown in Figure 8. It is important to emphasize here that the general shape of the basic pursuit trajectory shown in Figure 3 is little changed for \( \mu \) about 1/2. Approximately zero miss is therefore possible with the new guidance law without gravity compensation.
DYNAMIC STABILITY

In the absence of autopilot stabilization the pursuit-guided missile may experience sustained angle-of-attack oscillations. These oscillations, because of control deflection limiting, are generally of bounded magnitude. They have been observed repeatedly during guided-projectile flight tests at Dahlgren.\textsuperscript{2} The influence of the present guidance law on stability is described below.

The oscillations of the missile with canard deflection $\delta$ are

$$1 \ddot{\theta}_m - M_q \dot{\theta}_m - M_a \dot{a} = M_0 \delta$$  \hspace{1cm} (20)

with the usual aerodynamic notation and where

$$\theta_m = a + \gamma$$  \hspace{1cm} (21)

as shown in Figure 1. From Equations (20) and (21)

$$\ddot{a} - 2\gamma_0 \dot{a} + \omega_0^2 a = \omega_0^2 r \delta$$  \hspace{1cm} (22)

where the frequency, damping, and trim concepts are

$$\omega_0^2 = - \frac{M_a}{I}$$ \hspace{1cm} (23)

$$\gamma_0 = \frac{1}{2} \left[ \frac{M_q}{I} - \frac{F_a}{mV} \right]$$ \hspace{1cm} (24)

$$r = (a/\delta)_{\text{trim}}$$ \hspace{1cm} (25)

For oscillating angle of attack the second part of Equation (3) must be modified to read \( \dot{\gamma} = k_a a/r \). This enables Equation (8) to be written

$$\dot{\delta} = k_p \left[ \dot{\theta}_t + \frac{k_a}{r} (\mu - 1) a \right]$$ \hspace{1cm} (26)

For slow targets at large range, \( \dot{\theta}_t \) in the above equation may be neglected compared with the angle-of-attack term. Equation (22) describing the angle-of-attack oscillations thus becomes

$$\ddot{a} - 2\gamma_0 \dot{a} + \omega_0^2 a + \omega_o^2 \beta (1-\mu) a = 0$$  \hspace{1cm} (27)

Now assume the following motion about trim

$$a = e^{(i\omega_o + \lambda)t}$$  \hspace{1cm} (28)

where $\omega_o >> \lambda$. There follows

$$\lambda = \omega_o + \frac{\beta}{2} (1-\mu)$$  \hspace{1cm} (29)
Thus, since $\lambda < 0$ for dynamic stability, implementation of velocity pursuit guidance ($\mu = 0$) is strongly destabilizing. Indeed, during guided projectile development at Dahlgren, $\beta$'s of about 4 caused $\lambda = 0$. Clearly, stability must be considered carefully before attempting to reduce the pursuit miss by increasing $\beta$. Due to the term $(1-\mu)$ in Equation (29), implementation of the new guidance law has a reduced effect on stability.

CONCLUSION

A guidance law has been presented which is particularly suited for ship-to-ship missile applications. For these targets the law possesses the best features of both pursuit and proportional-navigation guidance. As with pursuit it results in small trajectory curvature in the presence of gravity. It is also easy to implement. And as with gravity compensated proportional navigation, it results in near-zero miss.
REFERENCES


OPERATIONAL AND EFFECTIVENESS CONSIDERATIONS FOR A TERMINALLY GUIDED WARHEAD (TGW) CONCEPT FOR THE MULTIPLE LAUNCH ROCKET SYSTEM (MLRS)

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The Warsaw Pact forces in Europe represent a highly mobile, armored maneuver threat supported in depth by field artillery and air defense weapons. A candidate munition currently being investigated to increase the Field Artillery's capability against this threat is a Terminally Guided Warhead (TGW) for the Multiple Launch Rocket System (MLRS).

The United States Army Materiel Systems Analysis Activity (AMSAA) recently conducted an effectiveness analysis of a MLRS/TGW concept. The objective of this study was to examine the effectiveness of this concept under a spectrum of anticipated battlefield weather environments in a European setting. MLRS/TGW effectiveness estimates against several typical Warsaw Pact targets are developed. Additionally, the sensitivity of effectiveness to parameters expected to critically affect system performance, such as response time and target vehicle signature, are examined. The results of this study are documented in the AMSAA Technical Report No. 353 which will be published by mid 1982.

1. INTRODUCTION

The Warsaw Pact forces in Europe represent a highly mobile armored maneuver force supported in depth by field artillery and air defense weapons. The increased number of hardened vehicles in the threat force seriously degrades the capability of the Field Artillery to delay, disrupt, and destroy the enemy prior to closing in the central battle.

Today's Field Artillery would have to engage enemy vehicles with High Explosive (HE) fragmentation or Improved Conventional Munitions (ICM) ammunition. These munitions require a prohibitively large volume of rounds fired to effectively defeat armored vehicles. The addition of autonomous, terminal homing munitions to the Field Artillery's inventory may effectively combat the armored threat.

One candidate munition currently being investigated within the artillery community is a Terminally Guided Warhead (TGW) for the Multiple Launch Rocket System (MLRS). Recent studies have indicated that a MLRS/TGW concept has the potential for significantly enhancing the Field Artillery's capability against the armored threat to include moving targets.

On-going terminal homing hardware demonstration programs are advancing the technology and data base required for the MLRS/TGW concept. However, different technologies (with perhaps significantly different costs) are of interest because of their maturity and potential capability to meet different operational mission requirements. This paper highlights some of the results of a study recently conducted by the United States Army Materiel Systems Analysis Activity (AMSAA) that examined the effectiveness of a MLRS/TGW concept under a spectrum of anticipated battlefield weather environments in an European setting. The AMSAA Technical Report No. 353, to be published by mid 1982, documents the results of the overall study.

2. METHODOLOGY

A modified version of the United States (US) Army Missile Command (MICOM)/US Army Materiel Systems Analysis Activity (AMSAA) Terminally-Guided Submunition (TOSM) Model served as the primary analytical tool for this study. The model was used to generate effectiveness results against selected typical targets for several anticipated battlefield weather environments.

The TOSM Model was developed to evaluate the potential effectiveness of terminally-guided submunitions against vehicular targets. The model was originally developed by AMSAA in the early 1970's. Subsequent modifications were incorporated by industry and the MICOM.

The program is a Monte Carlo, end-game effectiveness model that simulates in detail the functioning of a TOSM weapon system from the delivery system warhead event over the target, through the individual submunition searching process, to impact. Figure 1 presents an overview of the model's logic flow.
The TGSM model does not directly play the influence of weather conditions, such as precipitation, fog, relative humidity, on the performance of infrared or millimeter wave sensing devices that are employed in terminally homing munitions. The potentially degrading effects of weather are taken into account in the model through the probability of acquisition versus slant range data required as input to the model.

To simulate the effects of weather conditions on MLRS/TGW effectiveness, the following general approach was developed:

- For potential geographical areas of system deployment (Central Europe), weather "snapshots" were developed for seasonal conditions (winter and summer).
- Mild, typical, and severe conditions corresponding to approximately the 95th, 50th, and 10th percentiles of occurrence of weather parameters (cloud cover and ceiling altitude, precipitation, relative humidity, and fog) were developed for each seasonal "snapshot."
- For each weather snapshot, acquisition probabilities against a selected set of target vehicles were calculated using an AMSAA developed probability of acquisition model. These acquisition data were used as part of the necessary input to the TGSM model.

The effectiveness results, under the conditions of these weather "snapshots," represent the basecase performance of the system. As time permitted, sensitivity analysis were conducted on parameters expected to critically affect system performance, such as Command, Control and Communication (C3) response time.

3. INPUT DATA AND ASSUMPTIONS

The TGW will be launched by the MLRS launcher using launch procedures similar to those for the Improved Conventional Munition Warhead and the Scattered Mine Warhead. To maximize commonality of hardware, the TGW design shall be ballistically similar to the mine warhead for the system. Hence, the most recent mine warhead accuracy estimates were used in this accuracy to represent TGW accuracy. Each TGW (single rocket) had an assumed payload of six Terminally Guided Submissiles (TGSM). The optimum pattern dispersion (shape and size) between submissiles is not known at this time. A 200 meter warhead dispersal radius with random submissiles placements was assumed based on earlier studies.

Once dispersed, the TGSM's should be oriented so that the onboard seeker or sensor has the greatest opportunity to acquire the target. A drag device was assumed for each submissile to provide deceleration of the TGSM and thus accomplish proper orientation in a near vertical trajectory for the search process. If a vehicle was acquired, the drag device was then assumed to be jettisoned and the submissiles would attempt to guide to the target. Vehicle aimpoints coincided with the vehicle centroids in the study.

The seeker examined in this study is a two color, infrared (IR) device that operates in the 2-3 and 3-5 micron wavelength bands. The search pattern is an outside-in spiral trace.

Three typical targets were examined in this study and are described in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Range (Km)</th>
<th>Status</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Defense</td>
<td>19</td>
<td>Firing Position</td>
<td>4 Launchers, 1 Radar</td>
</tr>
<tr>
<td>Artillery</td>
<td>16</td>
<td>Firing Position</td>
<td>6 Howitzers</td>
</tr>
<tr>
<td>Armor</td>
<td>32</td>
<td>Column March</td>
<td>33 Tanks</td>
</tr>
</tbody>
</table>

Each target was attacked with a six round volley of TGW, i.e., 36 submissiles.

As previously mentioned, the TGSM model does not directly play the effect of weather on seeker performance. The following approach was taken to develop the probability of acquisition data for the TGSM model that reflected the performance of the seeker in different types of weather environments.

First, European weather "snapshots" were developed upon which to base the acquisition data.

For these snapshots, the two generic time periods chosen were a winter morning (to represent the highest likelihood of bad weather), and a summer afternoon (to represent the highest likelihood of good weather). For each of these two time periods, three specific severity levels of weather conditions, i.e., mild, typical, and severe, were defined to permit examination of a broad set of weather conditions.

The specific criteria for each severity level were defined as follows:

- Mild: The 95th percentile of each weather parameter taken independently.
• Typical: Except for rain, the 50th percentile of each weather parameter taken independently. For rain, the 50th percentile of rain is no rain, and it was believed that an assumption of no rain would be an unreasonably optimistic modeling approach for the MLRS/TGW. Therefore, the rain rate value used is exceeded only 5 percent of the time. This is roughly the 50th percentile for periods when it is raining.

• Severe: The 10th percentile of each weather parameter taken independently. Precipitation exceeds the value used only .5 percent of the time.

There are numerous sources of Central European weather data currently available. Since the frequency of measurements and the duration of the weather measurement and data collection period were not identical for all sources, variations and inconsistencies in some of the data sources were found to exist.

Table 2 lists the values of the weather parameters that comprise the European weather "snapshots" developed in this study.

<table>
<thead>
<tr>
<th>Weather Variable</th>
<th>Summer</th>
<th></th>
<th>Winter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mild</td>
<td>Typical</td>
<td>Severe</td>
<td>Mild</td>
</tr>
<tr>
<td>Clouds Base (m)</td>
<td>--</td>
<td>1500</td>
<td>750</td>
<td>1350</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>500</td>
<td>1000</td>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>Density (g/m²)</td>
<td>.3</td>
<td>1.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Probability of CFLOS* to 2500m</td>
<td>.7</td>
<td>.7</td>
<td>.7</td>
<td>.34</td>
</tr>
<tr>
<td>Precipitation (mm/hr)</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>35</td>
<td>75</td>
<td>95</td>
<td>70</td>
</tr>
<tr>
<td>Surface Visibility @ .55 m (Km)</td>
<td>50</td>
<td>13</td>
<td>.5</td>
<td>20</td>
</tr>
<tr>
<td>Vertical Fog Depth (m)</td>
<td>--</td>
<td>--</td>
<td>100</td>
<td>--</td>
</tr>
</tbody>
</table>

*CFLOS is Cloud Free Line-of-Sight

It is emphasized that the independence of the weather parameters, assumed in the development of the "snapshots," is unrealistic. There are subtle correlations between various weather parameters, e.g., cloud cover and relative humidity, which are not captured by this formulation. For this reason, it would be a mistake to infer that the weather described here as "typical" summer afternoon in Central Europe is exactly representative of "average" conditions for that area.

Some of the IR energy radiating from an energy source (target vehicle) to a seeker is lost due to scattering and absorption by constituents of the atmosphere through which the energy passes. A number that is indicative of the amount of energy dissipated is the extinction coefficient. The Beer/Lambert Law,

\[ T = e^{-\sigma R}, \]

where

- \( T \) is the percent transmission of source energy over range;
- \( \sigma \) is the extinction coefficient (km\(^{-1}\));
- \( R \) is the range (km) over which the transmission is sought;

relates extinction to percent transmission.

To determine the amount of energy attenuated by the atmosphere, an AMSAA developed model was employed. The Infrared Acquisition Model (IRAM) uses the following relationship to determine the amount of infrared energy reaching the seeker dome from the target vehicle (source):

\[ H = \frac{J}{R^2} e^{-\left[ \sum_{i=1}^{N} \sigma_i r_i \right]}, \]
24-4

where

\[ H \] is the amount of energy (watts/cm\(^2\)) reaching the seeker.

\[ J \] is the amount (watts/steradian (SR)) of source energy.

\[ R \] is the range (cm) from source to seeker.

\[ N \] is the number of atmospheric states (for a given "snapshot") through which the energy passes.

\[ q_i \] is the extinction coefficient for the \( i \)th atmospheric state.

\[ r_i \] is the range (km) through the \( i \)th atmospheric state.

Values used for \( J \) in Eq. (1) are a function of the altitude of the seeker, the Instantaneous Field-of-View (IFOV), and the vehicle signature data.

The altitudes, at which the amount of energy reaching the seeker dome is to be checked, are inputs to the acquisition model. For each such altitude, the area (\( A \)) in the ground plane instantaneously "seen" by the seeker is computed. It is assumed that if \( A \) passes over the target at all, it passes over the "hot spot." Thus, the signature is computed as a function of \( A \) as follows:

\[ J = (S_H - S_B) \cdot A, \text{ if } A < 1 m^2, \quad (2) \]

or

\[ J = (S_H - S_B) + (A - 1) \left( \frac{(S_T - S_H)}{(TGT - 1)} \right) - S_B \],

\[ \text{if } A > 1 m^2 \quad (3) \]

where

\[ A \] is the area \((m^2)\) in the ground plane "seen" by the seeker.

\[ S_H \] is the signature (watts/SR) of the target's "hot spot" \((1 m^2)\).

\[ S_B \] is the signature (watts/SR) of the background \((1 m^2)\).

\[ S_T \] is the total signature (watts/SR) of the target.

\[ TGT \] is the total area \((m^2)\) of the target as viewed from above.

The extinction coefficients \( (q_i) \) required in Eq.(1) are input to the model as a function of atmospheric state.

By use of Eq.(1), IRAM computes the quantity of energy reaching the seeker at given input altitudes for each weather "snapshot" played. Data from captive seeker tests was then used to compute acquisition probability as a function of the quantity of energy reaching the seeker. The seeker tested had an energy ratioing algorithm embedded in its logic to aid in discriminating false targets.

4. RESULTS

T GW effectiveness results against the three targets for each of the weather "snapshots" were generated using the TGSM model. In addition to these "base case" results, model runs were made to investigate the sensitivity of effectiveness to variations in individual performance parameters. Results for two of these sensitivities, response time and target signature are discussed.

Base case results for the European summer and winter "snapshots" are given in Figures 2 and 3. In each case the results have been normalized with respect to the effectiveness versus the artillery target in the mild weather environment. These results indicate the degree of sensitivity of TGW effectiveness to variations in the weather conditions. The lack of capability in the severe winter conditions can be attributed to the occurrence of heavy fog or heavy snow. The significant difference in effectiveness between the air defense or artillery targets and the armor target results from three factors. First, the armor target is the hardest of the three targets examined; second, the target location errors associated with the attack of a moving target are larger than for stationary, and third, the submissile-to-target ratio in attacking the armor target is approximately one to one (versus 6 to 1 for the other two targets).

The first sensitivity examined the impact of system response time on TGW effectiveness. Against maneuvering or moving targets, the time from target acquisition to munitions or targets, i.e., response time, is extremely important. The sensitivity of effectiveness to the time variable was examined against the moving armor target. Response times distributions with medians from approximately 75 seconds to a maximum of 600 seconds (10 minutes) were examined for the European summer typical weather condition. These results, normalized to the assumed base line value (6 minutes) results are presented in Figure 4. These results indicate two conditions for engaging moving targets with this TGW concept. First, the command, control, and communications (C3) system and the organizational and
The second sensitivity presented herein investigated the impact of target vehicle signature reduction on TGW effectiveness. Reductions of 25 and 50 percent in the vehicle hot spot (hottest square meter) signature for each of the three targets were made. It was assumed that the reduction in energy was totally dissipated from the vehicle and not redistributed over the remaining upper surfaces of the vehicles. Thus, a reduction in total vehicle signature was also accomplished. Figure 5 presents these results for the European summer typical "snapshot." TGW effectiveness is sensitive to variations in vehicle signatures. Additionally, the degree to which effectiveness is degraded is target vehicle dependent, with the "cooler" vehicle (artillery) being sensitive to small reductions in signature. Although expected damage versus the air defense and artillery targets is still relatively high at the 50 percent reduction level, effectiveness levels are expected to be lower for more severe weather environments.

5. SUMMARY AND FUTURE EFFORTS

This study examined the effectiveness of a TGW concept for the MLRS under several environmental conditions. TGW effectiveness sensitivity to several performance parameters was also investigated. Efforts to enhance and extend this methodology are ongoing at AMSAA. One major effort over the last six months is the development of a computer model that simulates the critical events that occur in the conduct of a TGW fire mission beginning with target acquisition. Statistical play of the weather environment, a definitive characterization of the background clutter environment, and countermeasures are the primary methodology enhancements envisioned in this simulation.
Figure 1

TGSM MODEL

READ INPUT DATA

SAMPLE LOOP

REAL TARGET ROUTINE

FALSE TARGET ROUTINE

VOLLEY LOOP

DELIVERY ERROR ROUTINE

WARHEAD DISPER SAL ROUTINE

SEARCH ROUTINE

EFFECTS ROUTINE

OUTPUT ROUTINE

LAST REPPLICATION

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Figure 2. MLRS/TGW Effectiveness.

Figure 3. MLRS/TGW Effectiveness.
Figure 4. MLRS/TGW Effectiveness Response Time Sensitivity.

Figure 5. MLRS/TGW Effectiveness Signature Reduction Sensitivity.
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<td>ISBN 92-835-1434-3</td>
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5. Originator
Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title
PRECISION GUIDED MUNITIONS. TECHNOLOGY AND OPERATIONAL ASPECTS

7. Presented at
the Guidance and Control Panel 34th Symposium
held in Norway, 4/7 May 1982

8. Author(s)/Editor(s)
Various

9. Date
September 1982

10. Author’s/Editor’s Address
Various

11. Pages
108

12. Distribution Statement
This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors
- Precision guided munitions
- Laser designation
- Seekers
- Guidance law
- Sensors
- Weapon developments

14. Abstract
This publication contains part of the papers presented at the Guidance and Control Panel 34th Symposium on Precision Guided Munitions. Technology and Operational Aspects.

24 papers were programmed covering the following topics:
- Systems analysis
- Supporting technology
- Seeker technology
- Guidance and control
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