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Closed Loop Tracking Systems for Naval Applications

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Abstract
Naval Weapon Closed Loop Tracking systems require adequate sensor availability, suitable algorithms to provide d appropriate system response and a modelling capability that allows evaluation of candidate designs and algorithmic techniques under representative conditions. This paper outlines some of the issues surrounding these capabilities and provides an overview of a system level modelling capability that allows the investigation of the performance of closed loop tracking systems for naval applications.

Introduction
In the naval environment, Closed Loop Target Tracking systems are used extensively as part of both gunfire and missile based weapon systems.

To perform this role, Naval Weapon Closed Loop Tracking systems require the following capabilities:

- Adequate sensor availability balancing the strengths and weaknesses of possible complementary sensor solutions
- Development of suitable algorithms to provide data fusion and appropriate system response
- A modelling capability that allows evaluation of candidate designs and algorithmic techniques under representative conditions

This paper explores the factors influencing the selection of the sensor fit for a Naval Tracking Sensor System and the development of a suitable modelling capability to allow algorithm development and evaluation of candidate system designs

Sensor Selection and Fusion
The design of a Naval Tracking System is generally based around a combination of the following key drivers:

- Sensor Type(s)
- All weather performance
- High and Low Level Performance
- Update Rates/Latencies

Single Sensor Solutions
The selection of sensors for Naval Tracking Systems generally falls into two regions of the Electromagnetic spectrum. RF Sensors and IR (Electro-Optic) sensors. These two types of sensor have individual benefits and drawbacks when considered in isolation as a sensor solution for a Naval Tracking System.

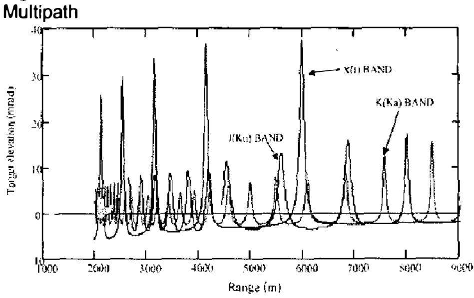
Radar sensors provide an all weather day and night performance capability that enables a satisfactory solution to the Naval Tracking System problem in appropriate environmental conditions. However, there are a number of limitations in using a radar as a single sensor solution.

Tracking Radar typically operate in the frequency region of I-Band (8-10 GHz) to K Band (30 - 35 GHz). For practical purposes these frequency bands offer the best trade off between measurement resolution and antenna aperture size. The Radar beamwidth for a given antenna aperture is inversely proportional to the Radar Operating Frequency. To put this into context, for an antenna dimension of 1 metre, a typical beamwidth at I Band is ~2 degrees. At K band, this is reduced to ~0.5 degrees.

At low level, radar sensor capability is influenced by multipath effects. Multipath effects are caused by the inability of the radar receiver to distinguish between a received signal that is reflected directly from a target and the received signal from an indirect path via the surface of the sea. These reflected signals, when combined with signals received directly from the target can cause a significant error to be introduced into the elevation measurements generated by the radar.

In addition to the variation in Radar beamwidth and hence the angular measurement resolution,
the change in operating frequency will modify the multipath effects upon the returned signal. The effects of multipath upon elevation measurement error for appropriate radar frequencies are shown in Figure 1.

Figure 1 Radar Elevation Measurement Error Due to Multipath



An additional factor to take into account when considering a single sensor, radar solution for a Naval Tracking System is the effect of the external environment. As the Radar operating frequency is increased, the signal attenuation due to propagation factors such as the atmosphere, cloud and rainfall increase dramatically. This, along with the antenna aperture/beamwidth relationship implies that the selection of Radar Operating Frequency is a trade off between measurement resolution and performance in high attenuation (poor weather) conditions.

Performance in poor weather conditions is also a factor for the other sensor type identified as a potential Naval Tracking System Solution.

IR sensors have a significant weakness in poor weather conditions such as fog, cloud and rainfall. Target detection performance is significantly degraded under these conditions.

The primary benefit of IR Sensors over Radar is the improved angular measurement resolution achieved by IR sensors. Typically, IR sensor measurement resolution is of the order of ten times better than that of and I Band Radar tracker. Therefore, in favourable weather conditions, an IR sensor provides a highly accurate angular measurement in both azimuth and elevation planes. Of particular note here is the fact the IR sensors are not susceptible to the multipath effects suffered by Radar sensors.

Despite the excellent angular measurement capability offered by an IR sensor, there is a fundamental limitation that impacts the practicality of using an IR sensor as a single sensor Naval Tracking Solution. IR sensors are passive, that is, they do not transmit a signal, this makes range measurement impossible by an IR sensor operating in isolation. As a result of this limitation, an IR sensor can only really offer a viable solution if used in conjunction with a range measurement sensor. Usually this range measurement sensor is a laser rangefinder device, but a multiple sensor solution employing both Radar and IR sensors is also a viable approach.

Like Radar, selection of the correct IR sensor operating frequency (or wavelength) for the required application can enhance the performance of an IR sensor in certain conditions. There are two main frequency bands of interest within the IR spectrum that are used for tracking sensor applications. These two bands are the 3-5 µm band (for applications where performance in high humidity conditions is required) and 8-12 µm (for applications where performance in the presence of smoke effects is required).

Summary of Potential Single Sensor Solutions
A summary of the potential single sensor solutions for a Naval Tracking System is given in **Error! Reference source not found.**.

Table 1 Summary of Potential Single Sensor Solutions for a Naval Tracking System

Sensor Type	Advantages	Disadvantages
Radar	• All weather (Varying performance) • Provides Range and Angle Measurement	• Poor angular measurement quality, particularly in multipath conditions
IR	• High resolution angle measurement • No multipath effects	• No range measurement • Severe performance degradation in poor weather

Multiple Sensor Solutions
Having considered single sensor solutions and identified the advantages and disadvantages of both Radar and IR sensors in isolation we now look at combinations of these sensor types to look to produce a Naval Tracking System which has a complementary sensor suite.

The combinations to be considered are:

1) 2 Radar Sensors with different operating frequency bands
2) A single Radar Sensor and a single IR Sensor

The strengths of each of these solutions are considered below.

Combination 1 (Multi Radar Solution)
The performance of a Naval Tracking System using Radar Sensors can be improved by the use of multiple radar sensors in complementary frequency bands.

The use of an I Band Tracking radar to provide an all weather capability, supported by the higher resolution measurement of a Ku or K band radar sensor can provide a viable solution to the Naval Tracking System sensor selection problem. As discussed previously, the radar sensors at Ku/K band frequencies are very susceptible to a degradation in performance in poor weather conditions. This limitation can be mitigated by the fusion of K Band data with I Band data.

By using an appropriate measurement weighting strategy, the multiple radar approach can also provide a suitable solution to the multipath problem discussed earlier.

The multipath characteristics shown in Figure 1 can cause a significant degradation in elevation measurement performance.

Figure 1 shows that the position of the multipath nulls varies with operating frequency and hence by using appropriate weighting the Naval Tracking System can use the measurements from the two sensors to generate an improved elevation measurement. Such a system can provide a satisfactory performance solution at low level in all weather conditions.

Combination 2 (Radar/IR Solution)
Another potential Naval Tracking System solution brings together the all weather capability and high accuracy range measurement capability of an I Band radar solution with the high accuracy angular measurement capability of the IR sensor.

This solution provides a more robust solution to the radar multipath problem, enabling the fusion of Radar range data with IR angular data. An appropriate data fusion mechanism allows a smooth transition between the two sensors in scenarios where the radar sensor has a greater detection capability than the IR sensor.

The limitation of this combination is the poor performance of the IR sensor in adverse weather conditions (e.g. Rainfall). In these circumstances, the IR sensor performance is degraded further than that of the higher frequency radar sensors described earlier in this paper.

Data Fusion and Sensor Response
Data Fusion techniques can be used to improve the performance of single and multiple sensor naval tracking system solutions. A common approach to this problem is to use techniques based around a Kalman Filter. This is augmented for low level tracking systems by a manoeuvre detector used for multipath detection. A potential architecture for such a track filtering system is shown in Figure 2.

Figure 2 Kalman Filter Based Tracking Filter Architecture

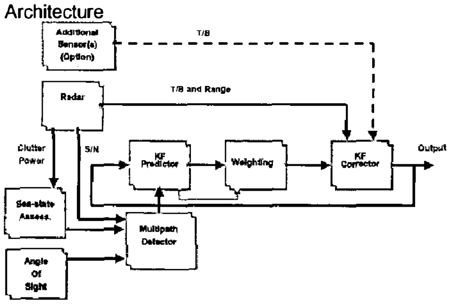


Figure 2 shows a track filtering solution based around a single radar sensor (potentially augmented by an additional sensor). Such an approach could be further enhanced to provide filtering of ship motion data and vibration effects.

Performance Evaluation
The modelling approach taken within BAE SYSTEMS, Integrated System Technologies is summarised in Figure 3.

Figure 3 Modelling Approach

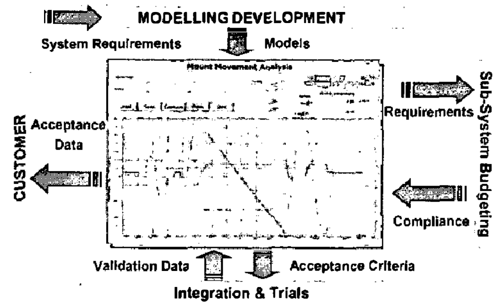
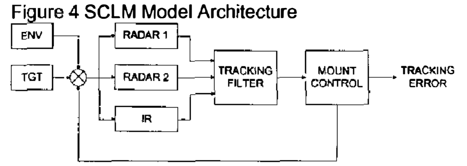


Figure 3 shows how the approach to performance modelling and model validation are linked into the fundamental systems engineering activities of requirements and acceptance criteria definition, functional partitioning, system integration and acceptance.

To enable the development and assessment of single and multiple sensor Naval Tracking Systems in a variety of conditions, BAE SYSTEMS, Integrated System Technologies have developed the System Control Loop Model (SCLM). This model has a modular structure for high flexibility and has been developed using an evolutionary lifecycle to provide an incremental performance assessment capability supporting the phases of the systems engineering lifecycle shown in Figure 3.

A top level block diagram of the SCLM is shown in Figure 4.

Figure 4 SCLM Model Architecture



Sample Performance Results
The SCLM has been used to obtain performance predictions for a typical set of Radar parameters in a number of system configurations. Each of these configurations has been evaluated against low-level targets in varying naval environmental conditions.

Examples of the output of this set of performance evaluations are given in Figures 5 to 7.

Figure 5 Single (Radar) Sensor Tracking Error Performance in a Low Sea State Environment

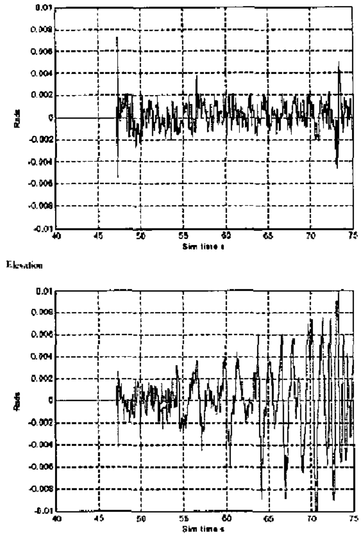
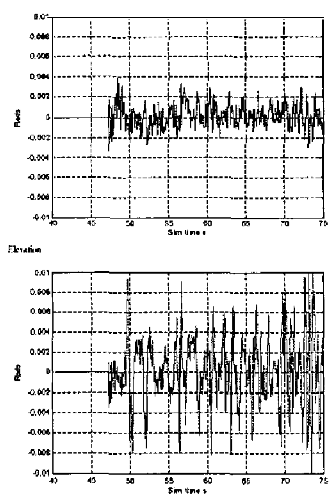


Figure 6 Single (Radar) Sensor Tracking Error Performance in a High Sea State Environment



For the single radar sensor in both high and low sea states, Figures 5 and 6 clearly show the errors introduced due to multipath when the azimuth errors (blue) are compared to the elevation errors (red).

Figure 7 Combined Sensor Tracking Error Performance (Radar + IR) in a Low Sea State Environment

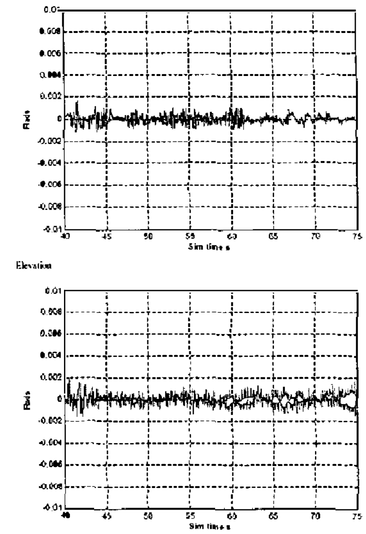


Figure 7 shows the clear improvement in measurement error that is achieved when the IR sensor is introduced into the sensor configuration. The introduction of the IR sensor shows some improvement in the measurement of the azimuth errors over that achieved with single or multiple radar solutions. However, there is a dramatic improvement in the elevation tracking performance when the IR sensor is introduced into the sensor configuration. This improvement is a clear indicator of the performance benefit that can be obtained through the inclusion of an IR sensor in the sensor configuration for a Naval Tracking System.

Future Development

Using the SCLM as a model framework for Naval Tracking Systems current and future activities within BAE SYSTEMS, Integrated Systems Technologies include:

- Algorithms to combat radar multipath
- IR sensor modelling using real and synthetic imagery sequences
- Enhancement of Kalman Filter based approach to consider more state of the art tracking algorithm techniques

Conclusions

In order to solve the Naval Tracking Systems problem consideration of the following issues is required:

- Target Characteristics
- Naval Environment Effects
- Consideration of Sensor Combinations and the balancing of Sensor strengths and weaknesses
- Appropriate filtering of sensor outputs to provide a smoothed 'system' output

Once each of the above considerations has been investigated and understood, a flexible, system level model is required to enable an evaluation of candidate solutions to be undertaken. This system level model should ideally be in place to support all phases of the Systems Engineering lifecycle to enable a robust solution to be delivered to potential customers.

The System Control Loop Model (SCLM) provides this capability in a framework that supports future growth within the field of Naval Tracking Systems.

The evaluation of candidate solutions using the SCLM demonstrates the benefits that can be gained from utilising a combination of sensors, particularly an IR sensor, supported by appropriate track filtering techniques to track typical targets within a Naval Environment.