Surveillance Radar and IRST Contact Level Fusion: Practical Aspects and Results from Live Experiments

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1 Introduction
Fusing data of surveillance radar and an Infra Red Search and Track (IRST) system in the process that composes an environmental picture, offers a wide range of possible benefits. E.g., accurate angular information provided by the IRST can be exploited to improve track accuracy, radar performance degradation due to multipath fading can be compensated, the radar transmit scheme can be trimmed (EMCON) without seriously degrading the quality of the picture. We are investigating such claims using ‘live’ data that was gathered in September 1992 with a coherent medium-range 3D surveillance radar and, co-located, a long-wave IRST system. Results are presented in this communication.

A variety of topics that are related to this research are discussed. Firstly, attention is paid to the assessment of (possible) surplus value of sensor fusion (Chapter 2). Measuring sensor fusion gain can be rather troublesome and a series of measures of performance are described that can be considered to determine this gain. In Chapter 3, several approaches to fuse the data of these dissimilar sensors are presented. The phrase ‘dissimilar’ refers to the incongruity of measured features; as passive sensor, an IRST is not capable to determine range, the radar obviously does. Subsequently, details of the contact-level fusion architecture that we have implemented are presented (Chapter 4). The setup of the measurements and descriptions of the sensors involved are briefly discussed in Chapter 5. Results are presented and discussed in Chapter 6. Conclusive remarks are made in Chapter 7. Finally, references are given and abbreviations are clarified.

2 Assessing sensor fusion effectiveness
With the present emphasis on research related to sensor fusion, the subject of sensor fusion performance assessment is accordingly eminent. The availability of a comprehensive set of indicators is essential to determine the possible benefit of fusion, to compare results obtained with different fusion levels or algorithms, and to obtain optimal settings of specific signal processing algorithms. An overview of a series of measures of performance (MOP’s) has recently been given by Theile e.a. [1]. In that paper, MOP’s are described with which three processes that are usually encountered in a sensor’s signal processing chain can be judged, namely the processes detection, tracking and classification. In principle, sensor fusion can be carried out within these three processes. When dealing with dissimilar sensors, however, fusion in the detection process is generally not practical and in this communication we therefore focus on MOP’s that are related to the tracking process.

To illustrate the topic, Figure 2.1 presents true and estimated positional information for a scene in which six targets travel in a square area, during a specific time interval. The end of the target’s trajectory is indicated by a dot. The left panel shows the ground truth, i.e., true trajectories of true targets. The right diagram shows trajectories as estimated by the tracking process. Ideally, the number of tracks that the system produces during a specific time span, corresponds with the number of targets. Also, the estimated kinematic information should closely match the true motion. In practice, however, deficiencies can occur and several of these are illustrated in Figure 2.1.
Three categories of MOP’s that described the quality of the picture as provided by the tracking process can be distinguished. The following MOP’s belong to the category track statistics:

- **The number of tracks**
  Note the discrepancy in the figure; the tracker produces nine tracks whereas there are only six targets.

- **The number of missed tracks**
  A missed track occurs if a target is not tracked. In Figure 2.1 there is one missed track, namely that of target I.

- **The number of false tracks**
  A false track corresponds with a non-existing target or with an object that does not bear one’s interest, e.g. a sea spike track. In the right hand diagram of Figure 2.1, track 1 represents a false track.

- **The number of track (inter)changes**
  When targets get close together, correct contact to track association may fail, see Figure 2.1, tracks 8 and 9 of targets IV and V.

- **The number of track breaks**
  A broken track occurs if the system is not capable to track a target continually in time, which results in intermittent tracking. In the example, target II is represented by three tracks: 4, 5 and 6.

The following MOP’s belong to the category track quality:

- **Feature quality**
  This comprises the precision of both kinematic (position, course, velocity) and non-kinematic features that are being estimated. As an example: the positional error, $\varepsilon$, considers positional information and is given by

  $$
  \varepsilon = \frac{1}{N} \sum_{i=1}^{N} |\hat{z}_i - z_i|
  $$

  (2.1)

  with $\hat{z}_i$ and $z_i$ the estimated and true position vectors at time $i$ and $N$ the number of track updates, see Figure 2.2.

- **Track purity**
  This is the percentage of correctly associated contacts in a track. An example is shown in Figure 2.3.
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Figure 2.3: Track purity of 7/8 (87.5%) due to association of one non-target contact.

In case of data that have been gathered experimentally, determining track purity can be problematic since it is not always possible to tell whether a contact originates from a target on the one side, or from noise or from clutter located in the vicinity of the target on the other side.

- Track accuracy
  When using a Kalman filter, the accuracies of the estimated parameters are calculated along with the estimates themselves, they appear in the diagonal elements of the state covariance matrix.

The following MOP’s belong to the category reaction time:

- Track initiation time
  This is the time span between the moment at which a target is detected and the moment at which its track appears.

- Track deletion time
  This is the time span between the moment at which a target is obscured or out of range and the moment at which its track is removed.

Which of these particular MOP’s are relevant, depends on the task the sensor system has to fulfil. E.g., MOP’s related to track statistics are likely to be of most importance if the system has to provide a recognised air picture for humanly interpretation by means of painting tracks on a graphical display. The operator must be presented a clean picture with very few false tracks and track breaks per unit of time. In case the sensor system automatically cues a self defence weapon system, timeliness and possibly also track accuracy are the key parameters.

3 Sensor fusion architectures

The approach one should follow to fuse data from dissimilar sensors is not trivial. As a consequence of the very dissimilarity of the individual sensors, low level fusion applied to non-processed (‘raw’) input data, e.g. image fusion, is not applicable since the data don’t match. As indicated in [2], contact extraction per sensor is required in order to obtain one or multiple features that provide the key for fusion. In our case, the prime features that are determined by the radar are range, azimuth, elevation, range rate, RCS and Doppler spectral width. The IRST provides information on azimuth, elevation and blob volume. The accuracy of the angular information provided by the IRST excels azimuth and elevation estimates provided by the radar by an order of magnitude. Furthermore, our sensors do not operate synchronously. Contacts are produced at different points in time and the rotation rates of the radar antenna and the optical head differ. The so-called fuse-while-track (FWT) architecture can be applied in such circumstances, see Figure 3.1.

Figure 3.1: Fuse-while-track architecture. The width of the arrows corresponds with the data rate, expressed in bits/s.
A central tracking process receives contacts from several sensors and associates these with tracks: contact-to-track-association. The quantities that are estimated by the track filter (e.g. kinematic properties) can be exploited to establish or refine the classification. Hence, the classification process is situated at the end of the signal processing chain.

A further decentralisation of processing is intrinsic to the track fusion architecture, as illustrated in Figure 3.2. The fusion process fuses tracks that are produced by the individual sensors: sensor-track-to-track-association. Owing to the false alarm reduction achieved by the individual trackers, the data rate on the input side of the fusion process is relatively low compared to the architectures previously discussed. Several authors have argued the inferiority of track fusion compared to contact fusion, due to mutual correlation of tracks.

Figure 3.2: Track fusion architecture.

Two examples of hybrid architectures are given in the Figures 3.3 and 3.4. In the upper scheme, local tracking is applied in one of the channels, merely to establish a reduction in the number of contacts; only contacts that associate with local tracks are being offered to the FWT algorithm. This recipe is attractive in case certain sensors produce significantly more false contacts than the other sensors. A mixture of FWT and track fusion is shown in Figure 3.4.

Figure 3.3: Hybrid sensor fusion architecture.

Figure 3.4: Hybrid sensor fusion architecture.
4 Description of the processing

The results presented in the next chapter have been obtained with an architecture that is in accordance with Figure 3.3. Because of the IRST’s massive contact rate, its data is first filtered before it is routed to the FWT process. The IRST tracker and the FWT process are based on a Kalman Filter and an Extended Kalman Filter, respectively, see for instance Kalman [3] and Lerro [4]. The IRST tracker uses a constant angular velocity model, implying a four dimensional state vector, given by:

\[ \bar{x} = \left( \phi \; \dot{\phi} \; \theta \; \dot{\theta} \right)^T, \] (4.1)

in which the four elements denote azimuth, azimuth rate, elevation and elevation rate. The FWT process uses a constant velocity model and the target motion is described in a 3D Cartesian co-ordinate system. Thus, the state vector is six dimensional and given by:

\[ \bar{x} = \left( x \; \dot{x} \; y \; \dot{y} \; z \; \dot{z} \right)^T. \] (4.2)

The design of both the IRST tracker and the FWT process is relatively straightforward. We have not applied multiple motion models like IMM and the contact to track association is according to the contact-oriented nearest neighbour approach. Merely kinematic properties are taken into account in this procedure. For details on the way the dissimilarity is dealt with we refer to Kester [2].

In both trackers a 2-out-of-2 track initiation criterion is applied. In order to prevent track initiation in areas with an excessive contact density per unit of time, ‘clutter maps’ constructed from the contacts themselves are maintained. In the present implementation of the FWT process, only the radar can initiate tracks.

Based on the number of track updates, a distinction is made between ‘tentative’ and ‘confirmed’ tracks, with different track loss criteria.

A critical step in the architecture appeared to be the selection of IRST contacts that are routed to the FWT process. The most elegant solution is to accept all IRST contacts that associate with an IRST track. With this criterion, however, we (still) experienced an unacceptably high contact rate. We have therefore put a constraint on the number of updates of the track: IRST contacts that associate with tracks that have had two or more updates are let through.

5 Setup of the experiments

A picture of the sensor suite is shown in Figure 5.1. The sensors were located at the waterfront of Marsdiep near the town of Den Helder, in the north-west part of the Netherlands. Thales Naval Nederland (then Hollandse Signaalapparaten B.V.) provided the systems and recording equipment. The funds for the experiments were furnished by the Dutch ministries of Defence and Economic Affairs and by Thales. As one can see in the picture, a tracking radar was also present.

Characteristics of the sensors are as follows:

- 3D surveillance radar
  The system is a modified version of Thales’s medium range 3D radar Skyspy. The system operates at C-band and has stacked beams on receive. The antenna rotation rate is 2.2 s. The radar utilises a medium-PRF waveform. Hence, both unambiguous range and range rate are determined by combining responses from multiple pulse bursts. The radar’s instrumented range is 75 km. During the experiments, the radar did not transmit in an azimuthal sector from 90° (east) to -160°.

- IRST
  The system is a prototype of Thales’s LW-IRST IRSCAN. The total field-of-view (FOV) in elevation is 14.6°, the FOV per pixel is approximately 0.5 mrad. The rotation rate of the optical head is approximately 0.8 s. Unfortunately, several elements of the detector array were defective. Hence, this specific IRST had a
‘blind’ elevation sector from 4.32 to 4.54°.

- Tracking radar
  The system is part of Thales’s SHORAD system Flycatcher. Track updates are logged at a 3 Hz rate. With this specific model, operator interaction is required to initiate a track. The operator uses the picture provided by the 2D Flycatcher surveillance radar for this purpose.

Measurements on a wide variety of air targets were performed: helicopters, single and formations of fighter aircraft, airliners and propeller aircraft.

![Image of measurement site](3D surveillance radar, IRST, Tracking radar)

*Figure 5.1: Picture of the measurement site.*

## 6 Results

### 6.1 Trial description

In this paper results are shown of a single measurement conducted in the morning of October 15th 1992 that lasted for nearly 30 minutes. Within this period, the radar antenna and the IRST’s optical head made 801 and 2337 rotations, respectively. A helicopter was the invited target, the pilot was requested to fly a zigzag trajectory over the island of Texel, at a constant altitude of 400 m. During the recording, several commercial airliners and helicopters, commuting between Schiphol airport and oil rigs, flew by. A propeller aircraft took off from the airport on Texel, there was a circling helicopter, ships and birds were present as well. The weather conditions were adverse during this experiment: hail and a 6 Beaufort wind coming from the north-west.

### 6.2 Radar results

We have applied the tracking process to the radar contacts only and results are presented in this section. The mean contact rate of the 3D surveillance radar during this experiment was 36.4 per s. 46.2% of these contacts are, however, single-burst contacts which our tracker neglects. A mean contact rate of 19.6 per s therefore remains. Out of these, a radar-only tracker produces 80 confirmed tracks which are depicted in Figure 6.1.
Several aspects are noticeable:

- There are several track breaks, see for instance the propeller aircraft and the airliners. In fact, three distinct causes are responsible for this:
  - In order to limit the number of clutter contacts, contacts with absolute radial velocity less than 3 m/s are not issued by the radar’s contact extractor. This causes the track breaks which we have marked ‘A’ in Figure 6.1.
  - The radar was jammed during this specific recording, which causes the gap in Figure 6.1 marked ‘B’.
  - Ship tracks break due to the glint effect. Note that our tracker does not take into account specific target classes.
- Bird tracks show up within a range of approximately 10 km. The birds travel with the wind, their speed being around 15 m/s.
- The invited target is kept in track during the course of the run. This track contains 780 updates.

Figure 6.2 presents range, azimuth and elevation estimates versus time for the invited helicopter. These quantities have been derived from the Cartesian filtered state vectors. Note that time is expressed in ks.
6.3 IRST results

We have applied the tracking process to the IRST contacts only and results are presented in this section. The IRST’s contact rate at the input of the IRST tracker is 157.1 per s. The tracker produces a total of 137 confirmed tracks. The azimuth and elevation estimates versus time are shown in Figure 6.3. Tracks that correspond with the invited target are depicted in Figure 6.4.

Figure 6.2: Estimated slant range (left), azimuth (middle) and elevation (right) of the invited target. Only the radar contacts have been processed.

Figure 6.3: IRST tracks.

Figure 6.4: IRST tracks of the invited target.
As shown in Figure 6.4, there are four tracks that correspond with the invited target. Track breaks occur for a number of reasons:

- Between 420 and 1550 s, the helicopter’s range is more than 15 km. Given a vertical target dimension of 3 m, the angular extent in elevation is then less than 0.2 mrad, i.e., 40% of the FOV of a pixel. It is likely that the target is not detected.
- At the point marked ‘A’ the target is in the dead elevation sector.
- Incorrect contact to track association is the reason for the track to break at the point marked ‘B’. Furthermore, there is poor track continuity of the airliners as well.

### 6.4 Fusion results

The effect of the IRST tracker is that the contact rate of 157.1 per s is reduced to a manageable 2.7 per s. As said, the radar’s contact rate is 19.6 per s. Had we not put the constraint on the number of updates in the IRST tracker (see Chapter 4), the IRST contact rate at the input of the FWT process would be 20.7 per s.

The most noticeable result of the fusion process is depicted in Figure 6.5 showing elevation versus time of the helicopter track, for both the radar-only architecture (thin line) and the fusion architecture (bold line). The helicopter track produced by the latter architecture is composed of 780 radar contacts and 1611 IRST contacts.

![Figure 6.5: Elevation versus time of the helicopter track. Bold line: fusion is applied. Thin line: radar-only result.](image)

Clearly, the fluctuations have decreased considerably in the time spans where the helicopter is tracked by the IRST system, i.e. prior to 400 s and after 1500 s.

A comparison of the fusion result with the output of the tracking radar is depicted in Figure 6.6. Note that the tracking radar loses the target at \( t \approx 550 \) s, its range is then roughly 20 km (see Figure 6.2, left diagram). 450 s later, the target is acquired again.
Figure 6.6: Elevation versus time of the helicopter track. Bold line: fusion is applied. Thin line: track of the tracking radar.

For the periods where the IRST can detect the helicopter, we observe a close resemblance between the fused track and the output of the tracking radar. One exception, however, is the peak at $t \approx 130$ s. The dead elevation sector of the IRST is the reason for this discrepancy; for some 20 s the track is not updated with IRST contacts.

It is remarked that the track breaks of the airliners and the propeller aircraft are not mended by the fusion process. This is not surprising, given the fact the IRST does not provide continuous tracks of these targets.

Figure 6.7 presents tracks when contacts of one out of four scans of the radar antenna are removed, so that the amount of radiated energy is reduced with 25%. The left diagram shows results obtained with radar-only processing, the right diagram shows the picture when the FWT process handles both radar and IRST contacts.

Figure 6.7: Tracks when contacts of every fourth radar scan are removed. Left: radar-only. Right: radar plus IRST.
One can clearly see in the left panel that track continuity is affected in the nearby region, where the rate of clutter contacts is relatively high. The right diagram shows that the degradation is counterbalanced when the fusion with IRST contacts is engaged (right diagram).

7 Conclusions
Results presented in this communication show that the claim of increased track accuracy by fusing IRST and surveillance radar contacts is confirmed. Also, track continuity under EMCON conditions gains from the sensor fusion process. These benefits manifest themselves within the region that is bounded by the detection range of the IRST. Undoubtedly, this range will increase in the near future, as sensitivity of detector elements improves. Due to a high contact rate of the IRST, we were forced to utilise a local IRST tracker with a criterion on track life time. We expect that this criterion can be relaxed with a more advanced fusion tracker. Results with an IMM tracker and the MHT mechanism for contact to track association are forthcoming.

8 References


9 Abbreviations
EMCON Emission Control
FOV Field of view
IMM Interacting Multiple Models
IRST Infra Red Search and Track
MHT Multiple Hypothesis Testing
MOP Measure of Performance
PRF Pulse Repetition Frequency
RCS Radar Cross Section
SHORAD Short Range Air Defence