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Coalition Transformation: An Evolution of People, Processes and Technology to Enhance Interoperability

Topic: Investigating the network enabled conventional submarine II: A summary of Australian simulation research

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Investigating the network enabled conventional submarine II: A summary of exploratory Australian research

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Abstract

This paper reports on simulation studies conducted by Maritime Operations Division at Australia's Defence Science and Technology Organisation (DSTO) to investigate network enabling of conventional submarines. Previously, Mansell et al (CCRT, 2002) defined aims and objectives of this program. Here, we present summary outcomes of that work. Results suggest that networking enabled a virtual submarine to detect priority targets sooner, and track them more continuously. It was also determined that workload on typical track management tasks was substantially greater when Network Enabled (NE) capability is available. The Commander of our virtual submarine saw the advantage of his network capable submarine as enabling him to analyse and assess low-bearing rate contacts (a difficulty for non-NE submarines).

1. Introduction

1.1 Overview

One of the most influential concepts in Defence in recent years has been the notion of Network Centric Warfare. The concept offers a number of benefits, by way of reduced decision times, but it also poses a challenge for maritime command and control. Careful analyses are required to exploit advantages of operational networks while avoiding potential pitfalls. This paper presents outcomes of investigations exploring undersea NE Operations. The approach adopted was to employ simulation in a practical and limited manner. Experimentation continues, with international collaborative studies termed Virtual Battle Experiments (VBE) undertaken as activities of TTCP MAR TP-1. Overall, the simulation programme has taken an incremental course of development toward larger scaled experiments in future [1,2,3].

1.2 Picture Compilation

A central focus of the VBEs is the process of picture compilation. This is a complex set of tasks performed by the submarine control room team and its supporting technologies. Picture compilation involves piecing together a representation of the surrounding water space using onboard sensors together with the processing capabilities of the combat system. At sea, passive and occasional active information is passed to the combat system which is used to detect, classify, localise and track particular contacts. The estimated range, course and speed characteristics of a contact held by the combat system, is referred to as its *solution*.

The geometry of passive sonar detection can make the final localisation of a target ambiguous. Submarines employ Target Motion Analysis (TMA) to refine the solution for priority contacts. Once a solution has been assigned it is monitored constantly. In addition, situational clues from sonar, visual (periscopes), radar or Electronic Support Measures reports as well as knowledge of the operational environs can be used constrain the uncertainty surrounding the solution for any particular track. This eases the TMA process somewhat.

A simplified activity diagram of current Picture Compilation activities is shown in Figure 1. In the VBEs the roles of Track Manager (TM) and TMA are central to simulation and provide activities against which augmented processes can be directly compared. The role of an Officer Of the Watch (OOW) is actually played by the submarine Commanding Officer (CO). The diagram was derived from observations of picture compilation both in the Submarine Squadron's training simulator and at sea. Note that Figure represents Track management for just one track. In reality the picture is much more complex. It proved to be very important for the simulation environment that the richness of the process was recognised. Until we implemented the input of situational and contextual cues to operators they had great difficulty dealing with detection geometry.

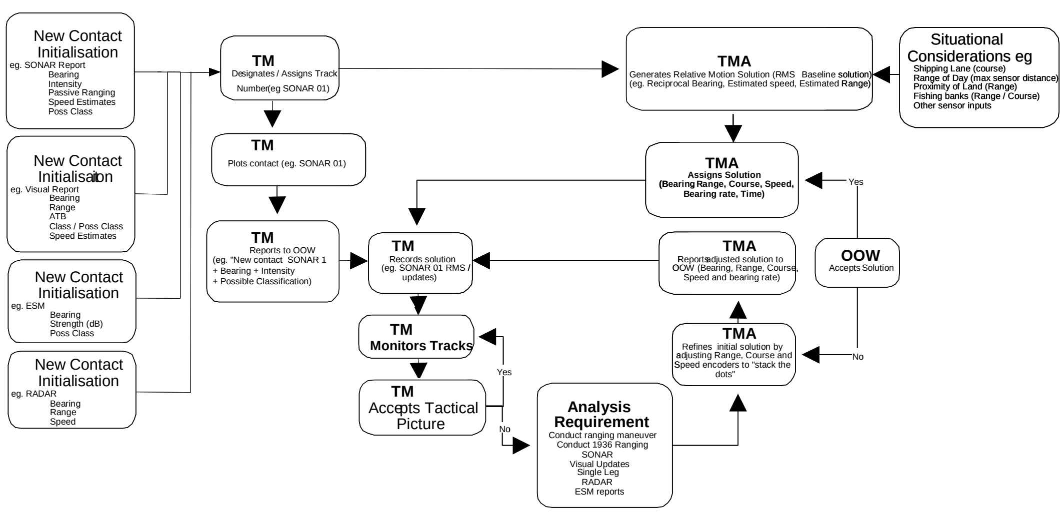


Figure 1 Basic Picture Compilation Process [4]

In the VBEs operators performing the process above, are immersed within a realistic synthetic environment and are provided with a suite of tactical and related track management applications that allow them perform tactical picture compilation.

1.3 Exploratory Metrics: Single Integrated Air Picture Attributes

The US Single Integrated Air Picture (SIAP) project has developed a methodology [5,6] for attempting to evaluate a common representation of airspace available to coalition partners in a network. The project has proposed a hierarchy of system attributes and metrics. The SIAP attributes provide dimensions upon which the adequacy and fidelity of information used to compile a picture can be assessed. A set of eight attributes that can be measured using various metrics in order to characterise overall picture quality have been defined. These attributes are related to the Key Performance Parameters drawn from two related Capability Requirement Documents for the SIAP project. The attributes we have focussed upon most recently include:

- **Completeness –** The degree to which particular information includes every entity of interest.
- **Continuity –** A picture is continuous when the track number assigned to a RWO does not change and its attributes over time are maintained.
- **Accuracy –** A reflection of the measurement errors or estimation errors of physical variables (e.g. position, kinematics and identity).

2. Infrastructure

A representation of the infrastructure for VBE-B is shown in Figure 3. The Virtual Maritime Systems Architecture [8] simulation environment models kinematic data of all platforms within a scenario as well as track data arising from coalition sensors. Ownship C2 applications within the virtual submarine receive data corresponding to its own sensors direct from the simulation. However track data from the coalition platforms is transmitted via dedicated TCP / IP links. Although this data could be passed directly to ownship within the simulation, the use of an external communication route is preferred within VBEs because it allows different NE communication methods and protocols to be investigated. This configuration also readily supports the modelling of communication bearers within future VBEs.

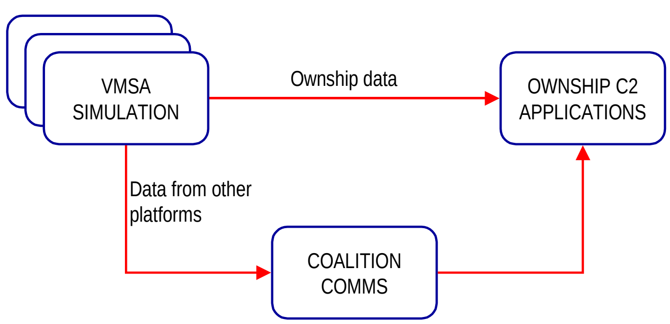


Figure 3 High level view of VBE infrastructure

A VBE communications protocol manipulation concept is under development to simulate possible architectural characteristics but was not implemented in VBE-AS4.

3. Conduct of VBE-AS4 [9]

3.1 Key comparisons: Current vs NE capability

For VBE-AS4 the control room of the virtual submarine was simulated using a set of displays that enabled direct comparison of picture compilation as shown in Figure 4. Three track manager roles were *played*. In essence, data flows and display layout enabled comparison of the picture compilation task undertaken using current practices (detection, localisation and tracking using ownship only processing) against a NE process (sensor data available from coalition vessels). Note that data from coalition vessels was input to the Networked displays subsequent to refinement of individual track solutions performed by manual TMA upon ownship detected tracks.

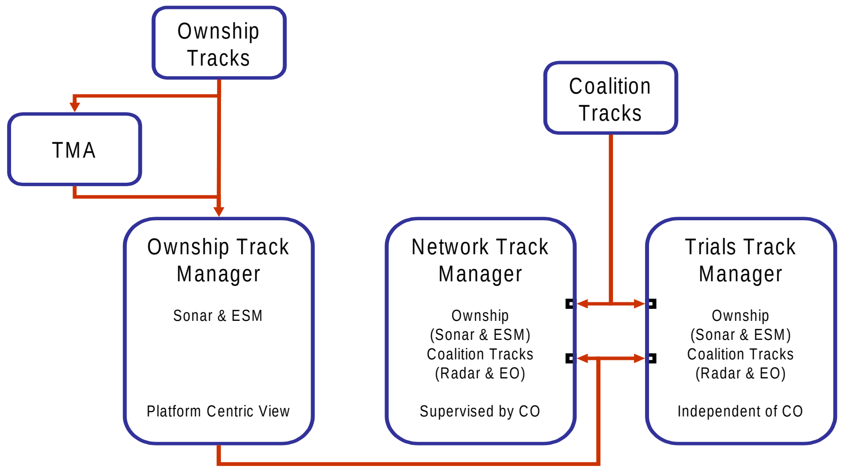


Figure 4 VBE-AS4 Data Flows

The major roles identified above were:

- **Ownship Track Manager** (OSTM)
  Management of tracks resulting from simulation of Ownship sonar and ESM sensor detections at typical ranges.
- **Network Track Manager** (Net TM)
  Management of tracks resulting from Coalition sensors as well as those resulting from Ownship sonar and ESM sensors at typical ranges (supervised by CO)
- **Trials Track Manager** (Trials TM)
  Management of tracks resulting from Coalition sensors as well as those resulting from Ownship sonar and ESM sensors in addition at typical ranges (unsupervised track management – employing augmented track management techniques)
- **Track Motion Analysis** (TMA) Operator
  Utilised DSTOs custom operator supported TMA tool ITMA, to refine the range, course and speed solution on individual tracks (employs contextual information).

3.2 Display Layout

Each Track Management operator was supplied with two displays. One display was meant to be used as a "work bench" at which tracks were identified and compared and if possible fused to integrate with the tactical picture. The idea was that the operator would promote those tracks that were thought to be valid associations (or valid unassociated tracks) to a Tactical Picture Display (TPD). Hence each Track Manager had an associated TPD display (as in Figure 5). Information on the character of vessels being tracked (eg.

Classification by acoustic properties, best speed by sonar, visual contact and radar analysis) were supplied verbally by a sensor controller[1].

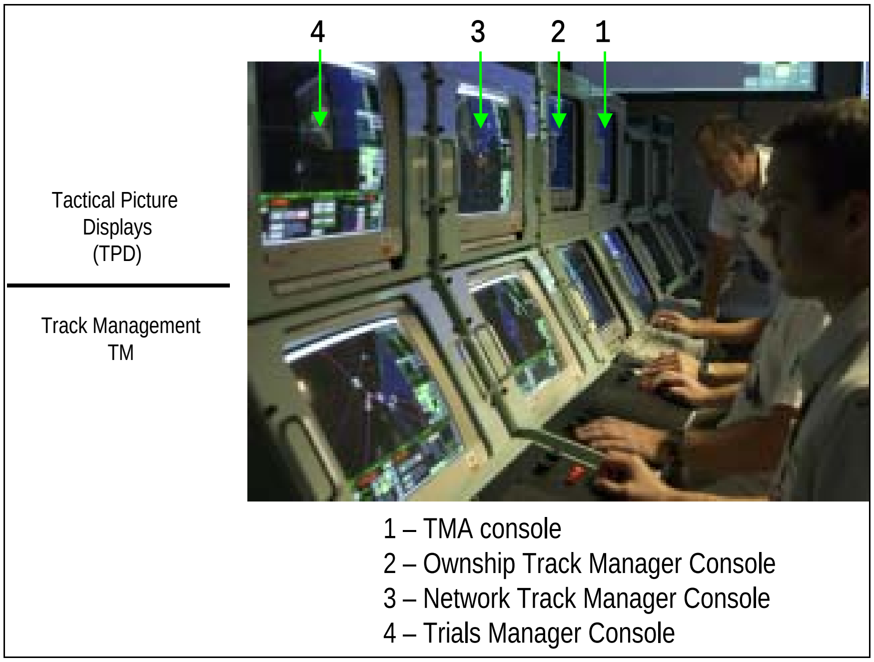


Figure 5 Console Layout

4. Summary findings

4.1 Completeness

This section presents a summary of example results that address the SIAP attributes of interest.

i. Detection Completeness is defined as the percentage of real world objects detected during each 30 second capture of sensor data (In calculating this metric, ownship and coalition partners were ignored).

$$\textbf{Detection Completeness} = \frac{\text{Number of RWOs within picture}}{\text{Total number of RWOs}} \times 100\%$$

The metric can be used to compare the relative completeness of the Tactical Picture compiled at each Track Manager Display. Figure 6 gives a general indication of the advantage of track sharing for detection. The two network capable pictures (NET TM and Trials TM) registered a greater percentage of possible detections overall than Ownship (OSTM) tactical picture.

[1] This role has been found, in previous studies, to be crucial to the task of tracking. It provides the human operator with a picture of the possible real world constraints that exist around constructed entities thus constraining the task of bearing only tracking (i.e. TMA) in particular.

It appears that the greatest advantage of track sharing arose early in the scenario (as previously noted in VBE-AS2). There was little difference between the Net TM and Trial TM displays. The overall reduction of Detection Completeness particularly towards the later part of the scenario is probably due to the movement of a large proportion of the contacts toward the Northwest. In the later stages of the scenario, the virtual submarine was evidently able to hold a greater proportion of new contacts entering its sensor range.

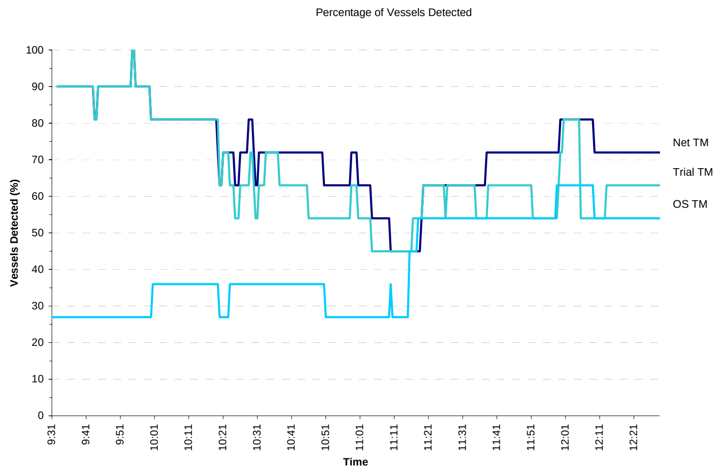


Figure 6 Comparison of Detection Completeness

ii. Solution Completeness is defined as the percentage of real world objects with position solutions. In calculating this metric ownship and coalition partners were ignored.

Solution Completeness = $\frac{\text{Number of RWOs within picture with position solutions}}{\text{Total number of RWOs}} \times 100\%$

Plotting this metric reveals that the NE Track Managers (Net TM and Trials TM) were able to generate solutions for more of the real world objects detected throughout the simulation. The output of the metric is plotted in Figure 7. The Net TM and Trials TM Displays appear to have been quite similar in holding contacts with solutions.

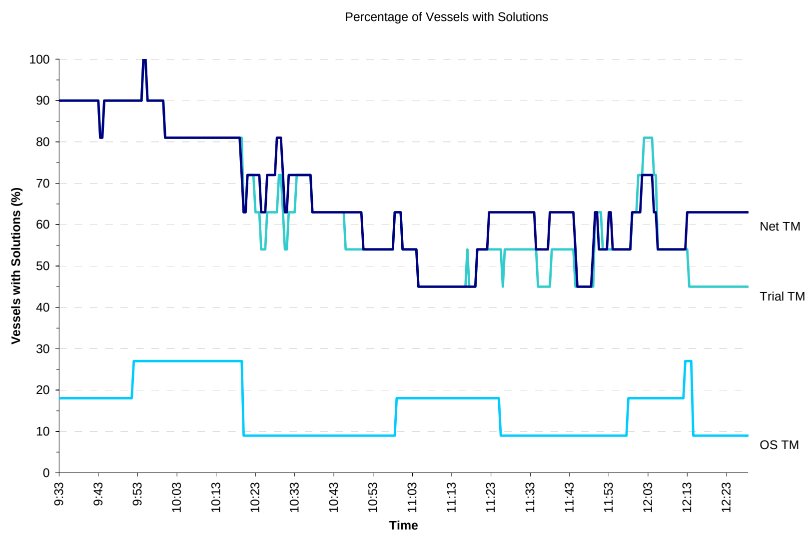


Figure 7 Solution Completeness

These findings are not altogether surprising given the extended range of sensor accessible by the NE track management operators. In practical terms of the tactical advantage of this enhanced picture completeness, several screen captures from the scenario are revealing. For example, in Figure 8 OS TM display reveals only three contacts while the NE capable Net TM display shows considerably more contacts, and in particular it shows hostiles vessels approaching from the S-South-East of the virtual submarine. The central circle on the Net TPD signifies ownship sensor ranges while NE capable displays are capable of holding all contacts outside of that small “field of view”.

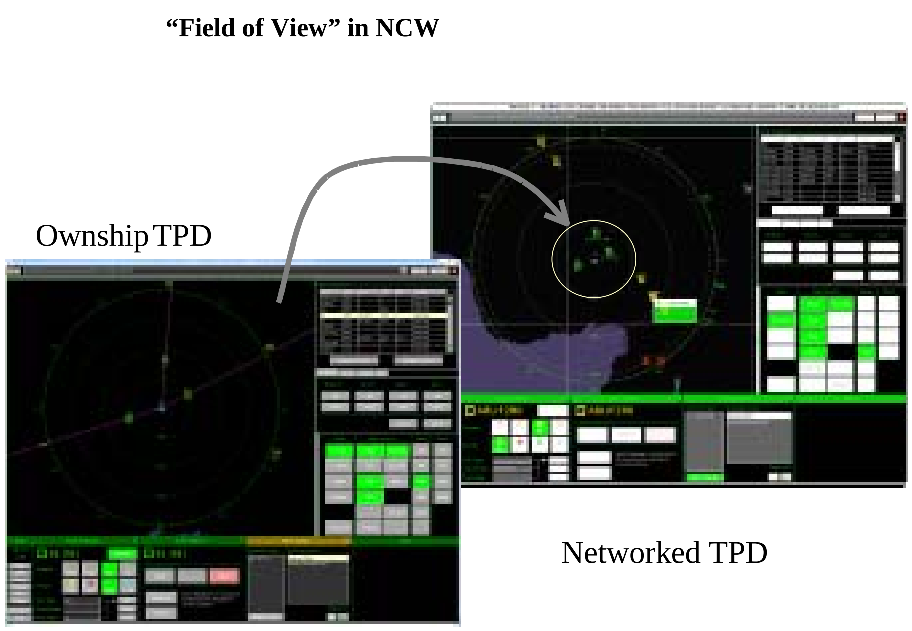


Figure 8 “Field of View”: Comparison of Tactical Pictures taken at 10.13am, VBE AS-4

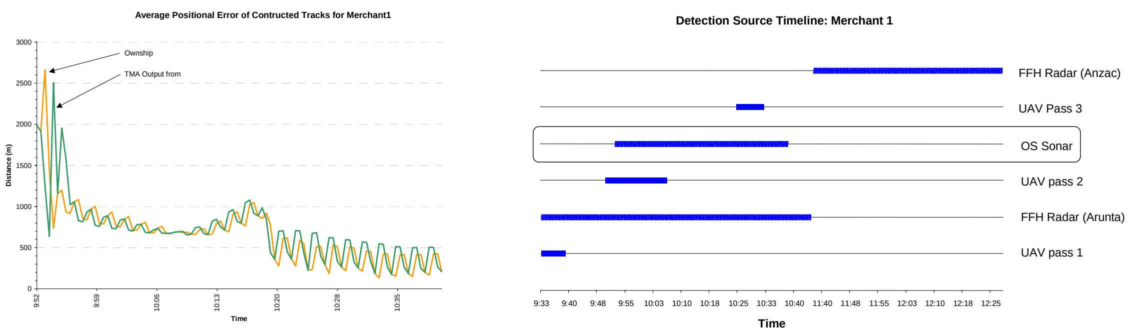
4.2 Accuracy

Another attribute of picture quality deemed important was the difference between estimated position and ground truth or **Position Error**. In sum position error was the difference between the best solution for any given track compared to the true position of the relevant RWO (clearly, care has to be taken as to the appropriate use of this metric for tracks that are the result of incorrect association).

$$\mathrm{PE} = \sqrt{(\hat{x}_k - x_k)^2 + (\hat{y}_k - y_k)^2}$$

where $(x_k,\ y_k,)$ and $\begin{bmatrix}\hat{x}_k & \hat{y}_k\end{bmatrix}$ are the ground truth and estimated coordinates respectively, of the real world object.

As an initial description of this metric, Figure 9a compares the overall TMA output and Ownship solution error for a particular very simple contact, in terms of its kinematic properties, Merchant 1. These are intimately related since OS TM receives TMA output as the basis of position localisation in picture compilation. Note that error initially is quite large and unstable at between 500 to 5200 meters compared to ground truth. However position-error then stabilises and is minimised during the first 25 minutes of the scenario.

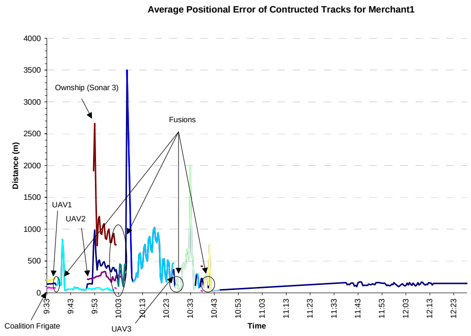


(a) (b)

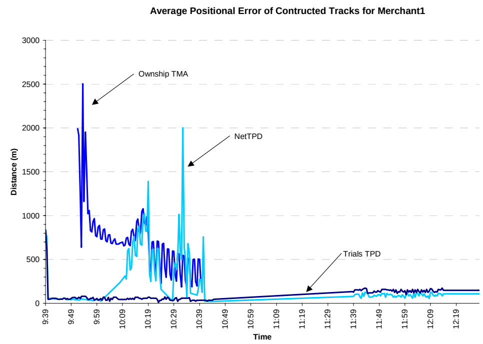
Figure 9 Merchant 1 – Detection

Tracks generated at the NET TM and Trials TM displays are derived from a number of different sensor sources. Figure 9b demonstrates the contribution of each sensor as a timeline. Note that ownship sonar held this particular contact for approximately 1/3 of the scenario. Several passes of the UAV and the FFH coalition vessels held the contact for a greater length of time.

A major task for the operators of the NE capable tools was to manage constituent tracks appropriately. A brief assessment of the manner in which position error revolved around the fusion and track management process is useful at this stage. For example, in the case of the contact Merchant 1, Sensors included Ownship, UAV radar tracks and coalition radar. Separate fusion identities were evident (these are the single line components of the line seen below). Four of the major fusion actions involving this track are shown below in Figure 10a. Note that fusion at times actually increased error relative to ground truth but then tended to quickly improve the overall error. Some means of filtering initial error generated by fusions and / or associations maybe useful: such as a simple error-bound filter.



(a)



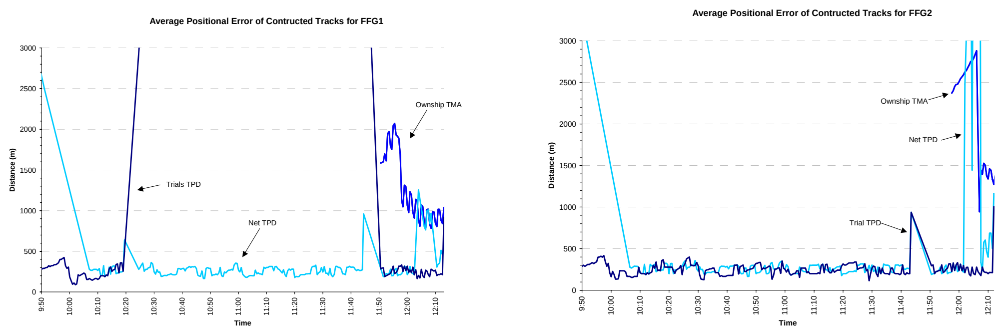
(b)

Figure 10 Position error for Merchant 1

Figure 10b compares the average positional error across all sensors for the contact Merchant 1 at each of the Track Manager Tactical Picture Display. Note firstly that there is substantial variability in errors generated at the level of Ownship TMA solutions. This error reduces from about 1500 meters to below 1000m then to below 500m as the Merchant vessel continues to travel past ownship and then fades from the sonar. The Net TPD error appears to increase dramatically when ownship TMA outputs are fused with other sensor source tracks. It is also interesting to note that as ownship sonar Loses the Merchant Track, the Radar track still holding the vessel has very low error indeed.

4.3 Priority Target Tracking

In the case of priority contacts, FFG1 and FFG2 (hostile Frigates) there are dramatic benefits evident in the latency of detection and holding contacts during the scenario (see Figure 11). This is to some extent scenario dependent. Though it would be entirely anticipated at sea that priority targets would come into range from a distance. In Figure 11a the Net TPD plot for average position error is dramatically more stable than that for the Trials TPD. The Trials TPD for, some reason, held the track for FFG1 in excess of 3000 m from its actual position and for a period of over an hour. Even so, ownship TMA only tracked the vessel for a very small proportion of the actual scenario (ownship TMA). Once again this points to potential risks inherent in the management of tracks made up of multiple components. Finally, in this series of examples, Figure 11b plots the average position error for the other hostile Frigate – FFG2. Once again, the radar detections that must comprise the contact FFG2 until about 11.55 (when Ownship sonar detections were initiated). Note that error in the NET TPD was greatly exacerbated as the virtual submarine's sonar federate detected this virtual Frigate. It also appears that the relative accuracy of Ownship TMA can represent a limiting factor upon the subsequent accuracy of fused or associated tracks (in turn, this suggests that the TMA solution uncertainty estimates were not accurate enough – generating errors on fusion).



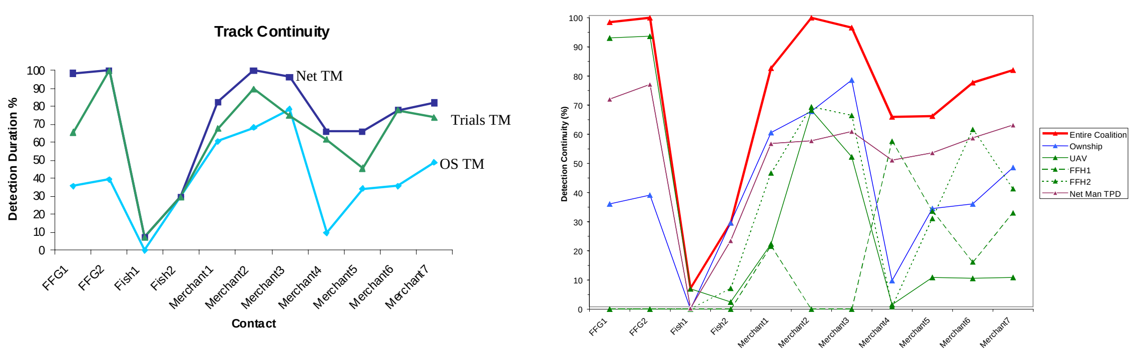
(a) (b)

Figure 11 Position Errors for Priority Targets

The pattern of errors above indicates some of the potentially difficult aspects of track management in NE operations. From our observations, it takes time for error to "normalise". Perhaps addition of reasonable bounding filters to fusion algorithms might assist.

4.4 Continuity of Tracking

Figure 12a outlines the Detection Continuity metric for each track in the scenario at each Track Manager. Clearly, the Net TM and Trials TM have held detection for most contacts for longer duration in this scenario. In particular, the priority contacts (hostile FFG1 and FFG2) were held with greater continuity when tracks were shared between coalition vessels (between 30 % - 60% longer). This finding is somewhat scenario dependent since the hostile Frigates approached the range of the virtual submarine's sensors only in the last half-hour of the scenario.



(a) (b)

Figure 12 Comparison of track continuity between Track Managers

Next, considering the relative advantage for continuity, Figure 12b compares the continuity metric across individual sensors and ownship against the combined continuity provided by all of these entities combined. Clearly, the combined impact of the coalition adds to overall continuity of tracking. This is particularly the case for contacts that enter the scenario from outside ownship sensor range.

5. Human Performance Factors

5.1 Workload

As a very simple guide to the workload to which the operators were subjected, a simple moment-to-moment workload measure was carried out. This involved a pop-up screen containing a rating scale (1 = low to 7 = high).

The findings for this measure are shown in Figure 13. The figure suggests that the NetTM (Networked track manager) perceived himself to be under quite a high workload in comparison to the other operators. Both Ownship and Trails TM indicated that their workload was very low. Given that the Net TM and Trials TM tasks were very similar, one possible explanation for the difference in their perceived workload might be involvement of the CO with Net TM Picture Compilation. The cognitive effort of paying attention to the CO in discussing the picture layout may have meant that perceived workload was high. This metric has been developed by van Orden [10] to be integrated with system performance attributes.

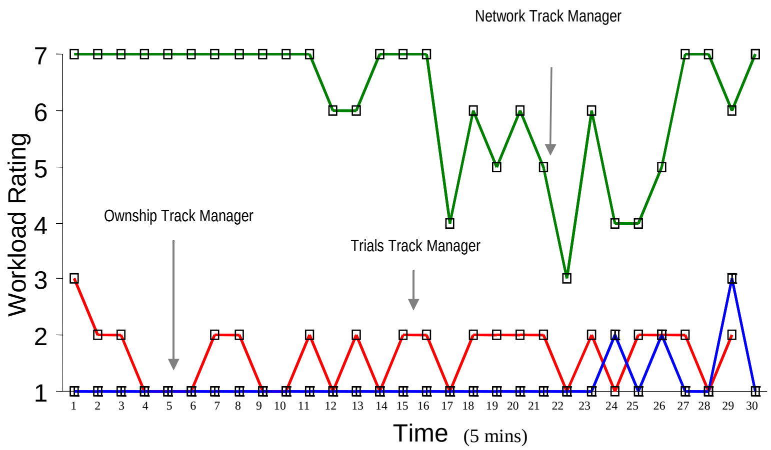


Figure 13 Moment-to-moment subjective workload

5.2 Situation Awareness Rating Technique (SART) [11, 12]

The SART scores taken after the simulation was run are shown in Figure 14. Participants in the study appear to have felt that they understood the situation quite well. They also believed they had sufficient resources with which to deal with the situation. Interestingly, the OS TM whose focus was upon his ownship sensors and TMA believed his understanding of the situation was high. That is quite possible, however, relative to the other TMs, his field of view was small.

The degree that participants found the tasks they performed to be demanding suggests that all participants thought the scenario did not challenge them. Only the Net TM rated Cognitive Demand as moderate.

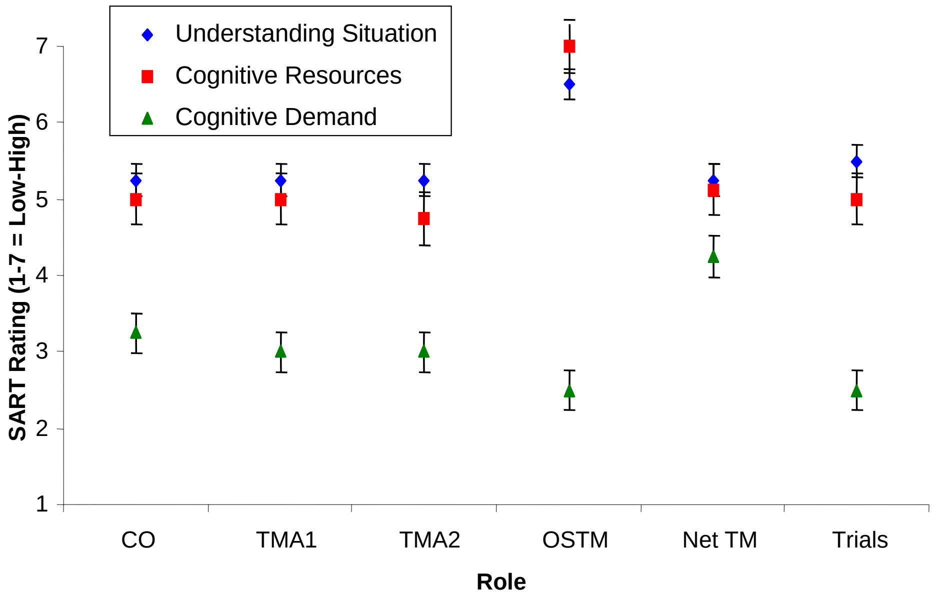


Figure 14 SART Scores Showing Standard Error Bars

Similarly, the number of incorrect associations made by these networked operators was also very low. This can be seen in Figure 15. Incorrect associations are defined as the total number of incorrect associations that are present in a picture at any given time over time. If an incorrect association is further compounded then these are currently ignored in the analysis of VBEs. In calculating this metric tracks arising from own ship and coalition partners are **not** generally ignored. Figure 15 suggests that both TM operators made the same total number of incorrect associations. Interestingly, the NetTM was able to correct all association errors during the simulation, while the Trials TM incorrectly created one association that remained associated throughout the scenario.

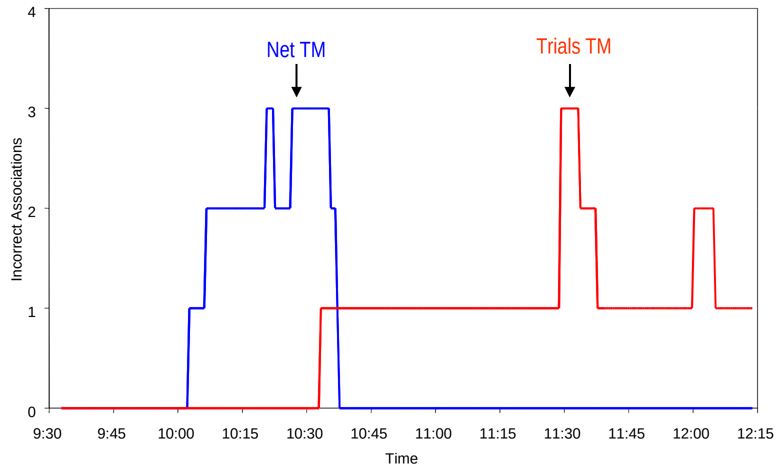


Figure 15 Incorrect associations performed by networked Track Managers

6. Conclusions

6.1 General Issues

The focus of VBEs to date has concerned the applications, algorithms and information exchange requirements that are required to support picture compilation within the NE environment. Although the transitioning of research output through to equipment procurement programmes is rarely straightforward, the complex domain of NE operations can make this process especially difficult. Simulation studies such as VBEs have the potential to assist greatly in minimising the risks that may arise in attempting to introduce technologies into NE operations. Much effort is required to expand upon the activities and analyses developed in the current VBE program toward a mature line of research and, potentially, evolution of technical and human that might augment Australia's Defence.

6.2 Algorithm Performance

It is clear from our analyses that the act of inception of track fusion has reliably created a degree of error. This error appears to reduce as the algorithm data sample accumulates (as iterations increase). Hence, it appears that it will be useful to filter the output of fusion algorithms somewhat. This might be done in two ways:

- Apply maximum error bounds to position data (based on real world constraints)
- Apply a time period filter where initial outputs of an algorithm are ignored.

Clearly, based upon our observations there is a requirement upon us to review this work and so:

- Validate implementation of fusion algorithms
- Validate the data input variables to those algorithms

6.3 Tactical Picture Quality (or Benefits of a Network Enabled Capability)

VBE AS-4 once again found evidence that picture quality – in terms of completeness (detection and total number of RWOs with solutions) and continuity of tracking is enhanced in an NE operation. It appears that this benefited the CO during the present scenario however we cannot be sure of this yet. It is clear that the design of the experiment, in terms of the picture compilation comparisons meant that the benefits of NE capability were quite clear at the level of picture compilation. At the tactical level however, more complex scenarios will be required. Of course we must also recognise the limitations in our studies to date where communications systems are assumed to be almost perfect. The key to these studies though is not necessarily to pursue to operational fidelity but to derive useful dimensions of understanding and test useful comparisons that will inform us on future possibilities.

6.4 Operator Performance

In this study we did not find a great deal of difference between the two NE operators except in the workload dimension. One possible reason for this is that the scenario was at a tempo so low as to fail to generate the sort of stress that one might expect in a wargame. Once the work of picture compilation becomes more hectic then there is a good chance that operators will rely more upon the assistance of automation to cope.

6.5 Toward realisation of a Network Enabled Capability

On the face of it, the potential benefits of supplying a networked submarine with tracks shared by a coalition seem clear. The most obvious outcome is a greatly expanded “field of view”. How this might augment the tactical advantage of such a vessel, however, is less than clear. From our analysis of positional error in particular, we have found that it is difficult to transpose algorithms developed in constrained laboratory conditions (such as MatLab) to a synthetic domain. These algorithms may require adaptation to deal with some of the variability that exists in the synthetic environment. Needless to say, the variability found is magnified manyfold at sea. Hence, there seems to be much work to be done in automating many of the currently “handrolic” submariner activities on the road toward a Network Enabled Capability.

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